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Microplastic Accumulation in Earthworms and Its Effects on Soil Health

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Abstract
Microplastics , those tiny plastic particles smaller than 5 mm have shown up as one of the most everywhere contaminants in land ecosystems over the last twenty years or so. In many regions, agricultural soils are now carrying noticeable amounts of these particles, mostly coming from plastic mulch films, the use of sewage sludge, and also from what settles out of the atmosphere. Earthworms, usually described as nature's most powerful soil engineers, seem especially sensitive to microplastic exposure, because they basically keep swallowing soil and organic matter while they burrow and feed. In both lab and real-world studies, microplastic ingestion repeatedly links to physical harm in the earthworm gut, oxidative stress gets turned on, intestinal microbial communities get thrown off balance, and growth plus reproduction tends to fall. But it does not stop there, the consequences can ripple through the whole soil system, changing how aggregates hold together, dimming microbial variety, messing with nitrogen and carbon cycling, and in the end putting the fertility and long-term resilience of farm land at risk. This piece brings together current findings on how microplastics collect in earthworm tissues and their burrows, what biological mechanisms drive the harm, and the larger knock-on effects for soil health. It also covers regulatory and clean-up routes, plus what research should focus on next.
Keywords: *microplastics, soil contamination, soil microbial communities, terrestrial ecotoxicology, earthworms, oxidative stress*

I. Introduction

Imagine digging into a garden bed that looks perfectly healthy from the top — dark crumbly soil, a few worms turning under the trowel and then, somehow, you find out the soil holds hundreds to thousands of microscopic plastic fragments per kilogram. That's the reality for a growing share of the world's farming land, and the earthworms living in it are basically paying a cost that researchers are still kind of piecing together, a lot at a time but not fully yet.

The term "microplastics" was formally brought in by Thompson and colleagues in 2004(Thompson et al., 2004), to cover plastic debris and particles smaller than 5 mm. Since then, the whole area has expanded quickly. Out of all plastic waste generated globally, only 9% gets properly recycled, 50% lands in landfills, 19% is incinerated, and 22% is mismanaged, per the OECD Global Plastics Outlook. And it's that mismanaged slice that soil scientists have their eyes on, because it's the part most likely to end up inside living systems.

The soil environment has, historically, received way less attention than oceans in the microplastics conversation, yet a bunch of evidence suggests it could actually be an even bigger reservoir(Rillig, 2012). The United Nations Environment Programme (UNEP) has already flagged microplastics as a significant emerging pollutant because they're small in size, spread everywhere and they persist for a long time, in different compartments of the environment. In land based settings, the organisms most directly exposed to these particles are those that live and feed inside the soil matrix, and none more than earthworms really.

Earthworms are in the phylum Annelida; they're found on every continent except Antarctica. They provide an extraordinary range of ecological services, like improving aeration by burrowing, boosting organic matter breakdown, promoting water percolation, and also stimulating microbial activity through their gut passages. Those services, taken together, are collectively worth billions of dollars in ecosystem functioning(Jones, Lawton, &Shachak, 1994; Lavelle, 1988) and they basically rely on earthworm populations staying healthy and abundant. Now once microplastics enter the picture, every one of those services is at risk of being undermined.

This article looks at what occurs when earthworms run into microplastics— how the particles manage to get in, what kinds of damage show up, and how that damage might ripple through the wider soil system. The evidence is pretty sobering, though it also suggests some clear routes toward mitigation.

II. Sources and Pathways of Microplastic Entry into Soil

2.1 Agricultural Practices as Primary Routes

Soil doesn't just spontaneously generate microplastics, the particles come in from human doings, and agriculture is basically at the top of that list. Sewage sludge application and plastic film mulching are the main, inputs that bring microplastics into soil—especially in agricultural settings. Plastic mulch is quite widely used on farms because it conserves water in the ground, keeps the temperature steadier and suppresses weeds. The issue is that, after harvest, farmers often leave fragments behind, and over the years of cultivation those bits get progressively smaller, until they are sort of lost in the soil matrix and become hard to tell from the soil itself. This matters, because there is a real gap in recycling infrastructure that can handle plastic retrieved from field soils that have already been contaminated. Wastewater irrigation makes it worse too, it transports microplastics from urban waste streams straight into crop areas.

Microplastic concentrations in farmland soils varied a lot between regions, in Iran it was 67–400 particles per kilogram, in Chile 600–10,400 per kilogram, and in southeast Germany the average was 0.34 ± 0.36 particles per kilogram. This pattern points to local differences in farming practices and the intensity of plastic use. The variation sounds striking, but even the low end of those ranges still creates a meaningful ecological burden for soil organisms.

2.2 How Particles Move Through the Soil Profile

Once microplastics settle on or near the soil surface, they dont really just stay put. They drift deeper, sort of migrate downward through a mix of physical processes and, more importantly, biological ones. Earthworms, in particular, are kinda key for this vertical movement. They can transport microplastics via eating and then passing them out, by having particles stick to their outer body surface, and by moving those particles down along burrow walls while water flows, plus there is also casting activity.

Because of this bioturbation way of doing things, what might otherwise stay as surface contamination actually gets redistributed through the soil column in a more active manner. It can then turn up at depths where it starts to influence organisms and soil processes that would otherwise be out of reach for the pollution that only sits on top.

III. Earthworm Ingestion and Accumulation of Microplastics

3.1 The Mechanics of Uptake

Earthworms do this basically by chewing their way through soil, or at least that's the idea—ingesting organic leftovers, mineral bits, microorganisms, and in polluted sites, microplastic particles too. But it's not like they take everything, not quite. They tend to prefer smaller microplastics, which is probably because they fit better with what's in the oral cavity and the gut's sort of filtering ways. That matters because smaller particles are often thought to be more toxic in a toxicology sense, having higher surface area compared to their mass, and they can also more easily pass through biological membranes.

In mesocosm trials, Huerta Lwanga et al. showed that microplastics under 50 μm were up to 65% more abundant in the soil after earthworms had been active, compared with what was seen at the soil surface. So yeah, it suggests those finer fractions are being pulled downward through bioturbation in a kind of selective way.

After microplastics are inside, they move through the gut, and then a fraction is either kept there or ends up causing some harm while moving along. Fourier-transform infrared spectroscopy along with intestinal pathology checks back this up, showing that microplastics can injure the intestinal tract of earthworms during transit. The mechanical rubbing from tougher plastic pieces against the soft gut lining kicks off a sequence of cellular reactions that end up being a main foundation for microplastic toxicity in these animals.

3.2 Evidence from Key Experimental Studies

The landmark study by Huerta Lwanga and colleagues, published in Environmental Science & Technology, was among the first attempts to quantify microplastic impacts on Lumbricus terrestris in a fairly systematic way, and sort of more direct. Their work suggested that being exposed to polyethylene laced litter led to higher mortality and less growth in Lumbricus terrestris, also, earthworms can move meaningful amounts of microplastics from the surface so they end up in the burrow walls, with a kind of selective downward movement of smaller particle portions.

Across every microplastic treatment, L. terrestris displayed weight loss, and the strongest weight loss showed up at the lowest plastic concentration that they tested, which was like 7% w/w of the litter, and at the same time burrow formation looked different versus the controls. These kinds of dose response connections matter too because they indicate that effects can still be detected even when contamination is only moderate, not just when using those very extreme lab concentrations.

As shown in Figure 1, the pathway from ingestion to downstream soil impacts involves multiple interacting biological and chemical processes that compound the initial physical harm.

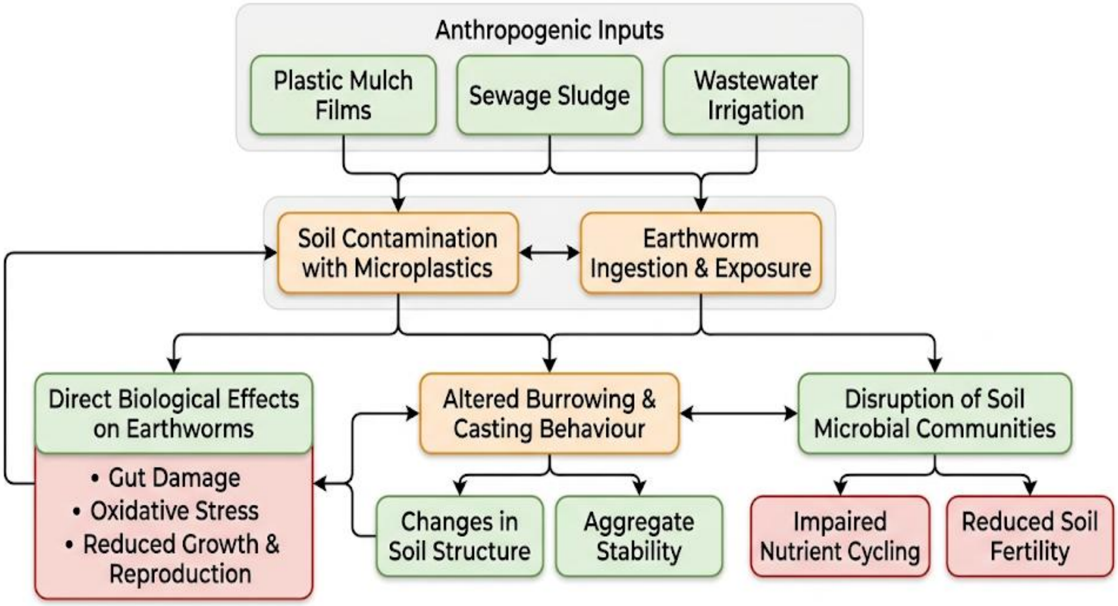

Figure 1: Conceptual Flowchart of Microplastic Accumulation and Effects in Earthworm-Soil Systems

This flowchart shows the sequential pathway of microplastic pollution in soil, starting with anthropogenic inputs (like plastic mulch films, sewage sludge, wastewater irrigation) at the top, then moving into soil contamination and earthworm ingestion in the middle tier, and finally splitting into three converging outcome routes at the bottom. Those routes are: (1) direct biological effects on earthworms, including gut damage, oxidative stress, reduced growth and reproduction, (2) altered burrowing and casting behaviour, which then changes soil structure and aggregate stability, and (3) disruption of soil microbial communities, which ends up feeding back into impaired nutrient cycling and reduced soil fertility. Arrows suggest bidirectional interactions between the pathways, so it is not just one way. The main point is that earthworms can act as both the victims and, kind of, unintentional carriers of microplastic harm within the soil system.

IV. Physiological Effects on Earthworms

4.1 Gut Damage and Inflammation

The gut wall is basically the first real interface where the earthworm has contact with ingested microplastics, and you can see that the kinds of damage reported there look pretty consistent across species, and also across different polymer types. For example polyethylene microplastics seem to harm the mucus lining and can drive inflammation in the earthworm intestine, but then polystyrene and polyethylene microplastics also show they can get the earthworms' antioxidant defence working, like scavenging free radicals and offering protection against oxidative harm. That second part matters, because it suggests the organism senses "something is off" and is trying to counteract it, only… the counter measure is not free, it takes metabolic energy, and that cost matters too.

Microplastics can also block the gastrointestinal tract and as a result, kick off local inflammatory reactions. Gut injury then feeds into oxidative stress cascades. And when those inflammation responses keep going, energy gets rerouted away from growth and reproduction, which is pretty much what the experimental observations on earthworm biomass and cocoon production are showing.

4.2 Oxidative Stress: A Central Mechanism

Oxidative stress is probably the most consistently observed physiological reaction to microplastic exposure across many species, and, also across polymer types. Microplastics seem to push earthworms into oxidative stress, and this comes with shifts in several enzyme activities, like superoxide dismutase (SOD), peroxidase (POD), lipid peroxidation (LPO), 8-hydroxy-2′-deoxyguanosine (8-OHdG), catalase (CAT), and glutathione S-transferase (GST). Basically these enzymes are the bodies front line antioxidant defences, and when they get activated it can mean cell injury is happening, or it's being countered in a more proactive way.

When microplastic content in soil goes above about 0.1%, earthworm growth gets affected, and oxidative stress is triggered, which then results in neural damage and DNA damage too. That 0.1% threshold is not just some abstract upper limit— in field surveys from heavily managed farmland soils, concentrations have been reported that are close to, or even reaching, this level in certain areas.

4.3 Effects on Growth, Reproduction, and Survival

Besides cellular harm, microplastic exposure also seems to mess with the overall performance of a whole organism, like more than just inside the cells. A bunch of studies agree that microplastics can be swallowed and then accumulate in earthworms and that, in turn, can lower their growth, their reproduction rate, and their lifespan. Polypropylene microplastics, when used at high concentrations, have been reported to cut down biomass and fecundity quite a bit, and the negative effects tend to get worse the longer the animals are exposed(Spurgeon et al., 1994; Spurgeon & Hopkin, 1996).

The co contamination angle is kind of especially concerning, because microplastics aren't only a standalone issue— they also work like carriers for other pollutants, so they can hold heavy metals and organic compounds on their surfaces, and then deliver those compounds into earthworm tissues more efficiently than would happen without microplastics involved.

V. Effects on Soil Structure and Physical Properties

5.1 Aggregate Stability and Porosity

Earthworms kinda shape the soil structure by burrowing and leaving casts, ya know, the way they move matters. They also secrete mucus that sort of binds soil particles up so they clump into more stable aggregates. On top of that their burrows open up macropores, so water can move and air can circulate, rather than staying stuck. But when their physiology and usual behaviour get disrupted from microplastic exposure, these contributions get weaker, like the whole setup slowly falters.When microplastics were present, the size distribution of water-stable soil aggregates changed. With HDPE microplastics specifically, soil pH dropped as well, which hints at possible changes in soil stability. Aggregate stability is not just some abstract metric in soil science — it matters for erosion resistance, water retention, and even the physical space where plant roots and soil organisms can live.

Microplastics, including HDPE, PES, PET, PP, and PMMA, can cause decreases in bulk density in non-rhizosphere soil. At the same time, bulk density increases in rhizosphere soil, and the overall effect seems linked to how much microplastic is around. Bulk density, like it directly impacts compaction, drainage, and how well roots can push through. So if the direction shifts because of plastic contamination instead of normal natural processes, then the soil ends up losing its inherent functional balance.

5.2 Earthworm Burrowing as a Distribution Mechanism

One of the more counterintuitive findings in this field is that earthworms, while being clearly harmed by microplastics, somehow also help spread them deeper into the soil profile through their everyday burrowing routine, like it's just part of the job. Soil incubation experiments suggested the best vertical transport efficiency at about 28.5 earthworms per square meter, and the whole depth dependent burrowing thing forms biological channels. In those trials small PET particles also made it down to deeper soil layers around 13.5–19.5 cm more efficiently than larger fragments.

So, in a way, earthworm activity in contaminated fields ends up working against remediation efforts. The very same burrowing that can improve drainage and aeration is also relocating the plastic pollution farther down, where it then becomes harder to detect, or even remove.

VI. Effects on Soil Microbial Communities

6.1 Diversity Losses and Community Shifts

Healthy soil has this kind of astounding mix of bacteria, fungi, and other little microorganisms, and like, estimates say that one teaspoon of healthy soil may hold more microbes than there are humans on Earth. That microbial web works behind the scenes for nutrient cycling, decomposition, disease suppression, and carbon sequestration. But microplastics seem to mess with it, on a few different angles too.

For example, both the plastisphere, (that microplastic-microbe alliance) and microplastic-affected soils showed a clearly different, and lower microbial diversity compared with non-contaminated soils. There were also changes in soil physical-chemical traits, and the microbial connections inside the plastisphere appear to help plastic-degrading organisms get enriched. Meanwhile, broader functionally diverse communities get crowded out somehow.

When earthworms are not around, small polyethylene microplastics can sharply reduce the Shannon diversity of soil bacteria, fungi, and protists by 4.3%, 37.0%, and 9.1% respectively. Fungi get hit the hardest, and that's pretty alarming because soil fungi are especially important for decomposition, and they also form mycorrhizal collaborations with plant roots.

6.2 Disruption of Nitrogen and Carbon Cycling

The functional consequences of microbial community disruption are, honestly, most clearly seen in nutrient cycling. Microplastics come with a noticeable rise in the relative abundance of soil nitrogen fixing and phosphorus solubilizing bacteria, but they also bring down the abundance of soil nitrifiers and ammonia oxidisers. At first glance, more nitrogen fixers might seem kinda helpful, yet the same time suppression of nitrifiers messes with the step by step transformation of nitrogen into plant-usable forms, so nutrient delivery becomes inefficient even if total nitrogen looks adequate.

Then there's the carbon, nitrogen, and phosphorous cycles, all affected by microplastics microbe interactions—like via the leaching of dissolved organic carbon, and also through changes in denitrification. Microplastics can decrease soil microbial enzyme activity, shift coding genes, lower microbial biomass carbon and reduce microbial carbon use efficiency. So, even though the microplastics aren't directly "feeding" plants, the whole thing indirectly reshapes how nutrients are cycled in soil.
As shown in Figure 2, the cascading effects of microplastic contamination on soil microbial function illustrate just how interconnected biological and chemical soil processes are.

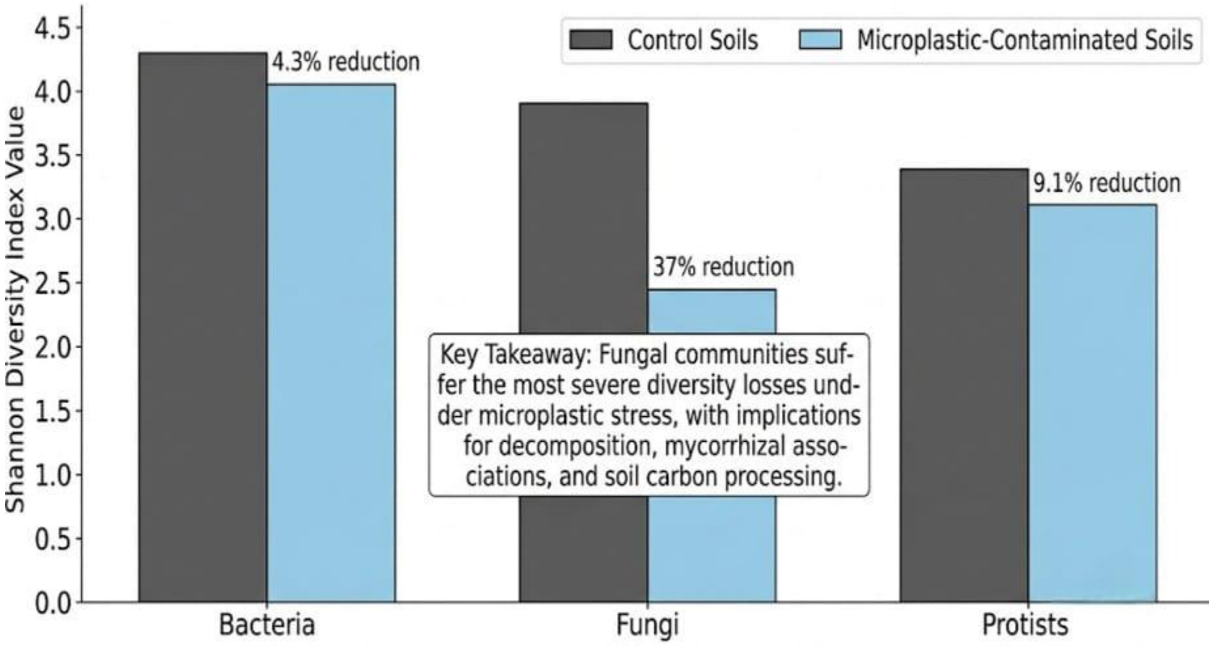

Figure 2: Comparative Bar Chart — Shannon Diversity Indices of Soil Microbial Groups in Microplastic-Contaminated vs. Control Soils

This bar chart sort of compares Shannon diversity index scores for three big microbial groups, bacteria, fungi, and protists, across two different setups. On one side we have the control soils with no microplastic added (dark grey). On the other side it shows the contaminated soils with small polyethylene microplastics, but specifically without earthworms (light blue). The vertical axis is the Shannon diversity index, running from 0 up to 4.5, roughly. For bacteria theres only a modest decrease, about 4.3% from that initial higher diversity. For fungi it looks like a much stronger drop, around 37%, and for protists the reduction is in between at about 9.1%. So the main point kinda is that fungal communities take the hardest hit in terms of diversity under microplastic stress, and that could matter for decomposition rates, mycorrhizal ties, and the way soil carbon gets processed.

6.3 A Partial Counterbalance: Earthworms as Buffers

There is an important nuance inside the microbial story. While microplastics suppress microbial diversity, earthworms— when they are healthy enough to stay active— can partially counteract it, kinda like a backstop. The earthworms mitigated diversity losses that were caused by microplastics, boosting diversity and also reshaping the composition of microbial communities. At the same time they increased the niche width, and the stability of the soil microbial food web network. The issue is kinda circular, microplastics harm earthworms, and that lowers their activity, which then removes one of the key buffers against the microbial disruption triggered by microplastics. So, if earthworm numbers decline, contaminated soils get less microbial protection.

VII. Microplastics as Vectors for Co-Contaminants

One thing about microplastic toxicity that kinda deserves its own spotlight is the hitchhiker problem, because plastic particles are not really chemically inert, you know. On their surfaces sit additive chemicals that were built in during manufacturing (things like plasticisers flame retardants UV stabilisers), and at the same time they can also sponge up pollutants that were already hanging around in soil, such as pesticides, heavy metals, and polycyclic aromatic hydrocarbons.

Some work indicates that microplastics can make bioaccumulation and trophic transfer of other contaminants happen more easily, which might make the overall toxic impact worse. Still, how toxic microplastics themselves are inside the soil system, and whether they truly act as vectors for pollutant bioaccumulation, is not a settled topic, and research is still going on.

In one study, simulated earthworm digestive fluids caused the herbicide atrazine to desorb from aged polyethylene microplastics that had been bound to it earlier. That basically suggests that if earthworms ingest these contaminated particles, pesticide exposure and toxicity could increase. This desorption-in-gut idea is extra worrying, because it implies that even microplastics taken from soils with only relatively low contamination could still carry and release concentrated doses of those adsorbed toxins straight into earthworm tissue.

VIII. Earthworms and Microplastic Transport to Groundwater

Microplastics moving through soil usually don't just sit put in the root zone, it can keep going. Biogenic activities, and here I mean earthworm burrowing plus litter incorporation, could create a real chance for microplastics to leach downward toward groundwater. This is especially true for particles smaller than 50 μm, and for nano-sized material, which seems to travel in a more preferential manner along the walls of earthworm burrows.

Once groundwater gets contaminated with microplastics, the whole issue gains a new layer. It no longer only affects agricultural productivity; it also touches drinking water safety. Even if this article mainly highlights soil-side processes, the idea that earthworms can help drive microplastics into deeper water resources is a good reason why controlling microplastic inputs at the agricultural source is, honestly, urgently important.

IX. Conclusion

Earthworms have sort of shaped the soils that feed us for millions of years. They are, in the words of Charles Darwin who devoted his final book to them — some of the most important animals on Earth really. The growing body of evidence reviewed here makes it clear that microplastic contamination is a genuine threat to these creatures and through them, to the soil functions they keep going.

When earthworms ingest microplastics, it can lead to gut damage, oxidative stress, smaller growth and weaker reproduction across species and polymer types. Then there is the whole burrowing thing they do, which basically spreads plastic particles through the soil column and maybe even into groundwater. At the same time, the microbial communities that depend on and work alongside earthworms lose diversity and also functional capacity when microplastic stress ramps up. That messes with nutrient cycling processes, and those processes are what underpin soil fertility. Taken together, all of it looks like a slow, steady erosion of the biological engine room that keeps cropland productive, not just a small inconvenience.

The urgency is partly about scale — hundreds of millions of hectares of agricultural land worldwide get plastic mulch films every year — and partly about persistence. Unlike many chemical pollutants that break down over time, plastic fragments in soil keep splitting into tinier and tinier pieces, potentially for centuries. Getting ahead of the issue will mean policy action on plastic use in agriculture, investment in monitoring, and ongoing scientific attention to the long-term destiny of plastic in terrestrial ecosystems. The earthworms are already kind of telling us, something is off. If we listen to that warning now it will cost far less than dealing with the fallout later.

References

[1]. Andrady, A. L. (2011). Microplastics in the marine environment. *Marine Pollution Bulletin*, *62*(8), 1596–1605. https://doi.org/10.1016/j.marpolbul.2011.05.030

[2]. Barnes, D. K. A., Galgani, F., Thompson, R. C., &Barlaz, M. (2009). Accumulation and fragmentation of plastic debris in global environments. *Philosophical Transactions of the Royal Society B*, *364*(1526), 1985–1998. https://doi.org/10.1098/rstb.2008.0205

[3]. Blouin, M., Hodson, M. E., Delgado, E. A., Baker, G., Brussaard, L., Butt, K. R., Dai, J., Dendooven, L., Peres, G., Tondoh, J. E., Cluzeau, D., & Brun, J.-J. (2013). A review of earthworm impact on soil function and ecosystem services. *European Journal of Soil Science*, *64*(2), 161–182. https://doi.org/10.1111/ejss.12025

[4]. Bouché, M. B. (1972). *Lombriciens de France: Écologie et systématique*. Institut National de la Recherche Agronomique.

[5]. Browne, M. A., Galloway, T. S., & Thompson, R. C. (2007). Microplastic—an emerging contaminant of potential concern? *Integrated Environmental Assessment and Management*, *3*(4), 559–561. https://doi.org/10.1002/ieam.5630030412

[6]. Cole, M., Lindeque, P., Halsband, C., & Galloway, T. S. (2011). Microplastics as contaminants in the marine environment: A review. *Marine Pollution Bulletin*, *62*(12), 2588–2597. https://doi.org/10.1016/j.marpolbul.2011.09.025

[7]. Curry, J. P., & Schmidt, O. (2007). The feeding ecology of earthworms – A review. *Pedobiologia*, *50*(6), 463–477. https://doi.org/10.1016/j.pedobi.2006.09.001

[8]. Darwin, C. (1881). *The formation of vegetable mould through the action of worms, with observations on their habits*. John Murray.
[9]. Edwards, C. A., & Bohlen, P. J. (1996). *Biology and ecology of earthworms* (3rd ed.). Chapman and Hall.
[10]. Jones, C. G., Lawton, J. H., &Shachak, M. (1994). Organisms as ecosystem engineers. *Oikos*, *69*(3), 373–386. https://doi.org/10.2307/3545850
[11]. Lavelle, P. (1988). Earthworm activities and the soil system. *Biology and Fertility of Soils*, *6*(3), 237–251. https://doi.org/10.1007/BF00260820
[12]. Lavelle, P., Bignell, D., Lepage, M., Wolters, V., Roger, P., Ineson, P., Heal, O. W., &Dhillion, S. (1997). Soil function in a changing world: The role of invertebrate ecosystem engineers. *European Journal of Soil Biology*, *33*(4), 159–193.
[13]. Lee, K. E. (1985). *Earthworms: Their ecology and relationships with soils and land use*. Academic Press.
[14]. Mato, Y., Isobe, T., Takada, H., Kanehiro, H., Ohtake, C., &Kaminuma, T. (2001). Plastic resin pellets as a transport medium for toxic chemicals in the marine environment. *Environmental Science & Technology*, *35*(2), 318–324. https://doi.org/10.1021/es0010498
[15]. Rillig, M. C. (2012). Microplastic in terrestrial ecosystems and the soil? *Environmental Science & Technology*, *46*(12), 6453–6454. https://doi.org/10.1021/es302011r
[16]. Six, J., Bossuyt, H., Degryze, S., & Denef, K. (2004). A history of research on the link between (micro)aggregates, soil biota, and soil organic matter dynamics. *Soil and Tillage Research*, *79*(1), 7–31. https://doi.org/10.1016/j.still.2004.03.008
[17]. Spurgeon, D. J., & Hopkin, S. P. (1996). Effects of metal-contaminated soils on the growth, sexual development, and early cocoon production of the earthworm *Eisenia fetida*, with particular reference to zinc. *Ecotoxicology and Environmental Safety*, *35*(1), 86–95. https://doi.org/10.1006/eesa.1996.0085
[18]. Spurgeon, D. J., Hopkin, S. P., & Jones, D. T. (1994). Effects of cadmium, copper, lead and zinc on growth, reproduction and survival of the earthworm *Eisenia fetida* (Savigny): Assessing the environmental impact of point-source metal contamination in terrestrial ecosystems. *Environmental Pollution*, *84*(2), 123–130. https://doi.org/10.1016/0269-7491(94)90094-9
[19]. Teuten, E. L., Saquing, J. M., Knappe, D. R. U., Barlaz, M. A., Jonsson, S., Björn, A., Rowland, S. J., Thompson, R. C., Galloway, T. S., Yamashita, R., Ochi, D., Watanuki, Y., Moore, C., Viet, P. H., Tana, T. S., Prudente, M., Boonyatumanond, R., Zakaria, M. P., Akkhavong, K., ... Takada, H. (2009). Transport and release of chemicals from plastics to the environment and to wildlife. *Philosophical Transactions of the Royal Society B*, *364*(1526), 2027–2045. https://doi.org/10.1098/rstb.2008.0284
[20]. Thompson, R. C., Olsen, Y., Mitchell, R. P., Davis, A., Rowland, S. J., John, A. W. G., McGonigle, D., & Russell, A. E. (2004). Lost at sea: Where is all the plastic? *Science*, *304*(5672), 838. https://doi.org/10.1126/science.1094559