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The deep-burrowing earthworm *Lumbricus terrestris* ingests and transports microplastic fibres of a wide length range in soils

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ABSTRACT

Microplastic (MP) exposure of the terrestrial environment is increasingly reported, but exposure levels may change due to transport processes. MPs occur in different shapes. Particularly MP fibres can affect soil structure and soil organisms. Earthworms are important contributors to particle movement in soils, yet their influence on the redistribution of MP fibres remains poorly understood. This study investigated if the deep-burrowing earthworm *Lumbricus terrestris* enhances vertical MP fibre transport and whether fibre length affects ingestion and transport distance. We measured the mass-based redistribution of MP fibres by *L. terrestris* using repacked soil columns spiked with metal-doped polyethylene terephthalate (PET) fibres (median length 0.750 mm). Additionally, number concentrations and MP lengths were determined by optical microscopy. The transported MP mass-fraction increased from two to four weeks (5.7 to 9.0 % of MP mass), with most transport occurring during the first two weeks. *L. terrestris* preferentially transported smaller MP fibres, indicated by a depth-dependent decrease in MP fibre lengths, likely due to easier ingestion. However, absolute differences in MP fibre lengths across depth ($<$0.170 mm) and effect magnitudes were small (Cohen's $d < 0.2$). Another experiment with homogeneously spiked soil confirmed instead that this earthworm species can ingest long MP fibres (up to 4.8 mm in casts; median 0.700 mm) that are otherwise often considered immobile in soils. The observed transport underscores that bioturbation is a relevant transport mechanism leading to a vertical redistribution of MPs entering soils. A broader range of bioturbating organisms in more complex systems need to be considered for establishing realistic transport rates.

Abbreviations: MP(s), Microplastic(s); *L. terrestris, Lumbricus terrestris*.

1. INTRODUCTION

Earthworms are important ecosystem engineers that affect soil processes and contribute to key soil ecosystem services (Blouin et al., 2013). As an integral part of carbon and nutrient cycling, earthworms ingest and break down organic matter, making nutrients more available to plants (van Groenigen et al., 2014). They also regulate air and water movement as they create large biopores when they burrow through and re-work the soil (Capowiez et al., 2011). While this so-called bioturbation is essential for maintaining healthy soils, it can also lead to the redistribution and deeper incorporation of persistent pollutants that are emitted to the soil (Jarvis et al., 2010; Rillig et al., 2017). Microplastics (MPs) are plastic particles between 1 μm and 5 mm that are of increasing environmental concern due to their persistence and increasing abundance in soils (Chamas et al., 2020; Crawford and Quinn, 2017). Similarly to other soil particles, earthworms may ingest MPs, push them aside (Arrázola-Vásquez et al., 2022) or create pathways that enable transport with preferential water flow (Jarvis et al., 2016). However, earthworm-driven transport of MPs remains a particularly understudied fate process despite its known importance for the rearrangement of soil particles in general (Larsbo et al., 2024; Taylor et al., 2018).

MPs can be formed *in situ* in the soil from fragmenting agricultural plastics (Steinmetz et al., 2016) or they can enter soils from external

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sources through littering (Braun et al., 2023), atmospheric deposition (Allen et al., 2019), or with soil amendments that are enriched in MPs (Porterfield et al., 2023), particularly sewage sludges (Corradini et al., 2019). Depending on their source, MPs can vary in terms of their chemical composition, but they also occur in a range of sizes and shapes (Harley-Nyang et al., 2023). These physical MP properties are often considered key determinants for potential effects on the soil ecosystem (Ju et al., 2019; Khalid et al., 2020; Lahive et al., 2022; Lozano and Rillig, 2020), but also for their mobility within the soil (Gao et al., 2021; Han et al., 2022; Ranjan et al., 2023; Zhang et al., 2022). Generally, MPs are classified according to their largest size dimension, i.e. the major diameter (hereafter length), and their aspect ratio for shapes: ranging from irregular fragments to spherical particles and elongated fibres (Liu et al., 2023). Of the different shapes, MP fibres have been associated with more negative effects on soil organisms (Lahive et al., 2022; Prendergast-Miller et al., 2019) and changes in soil structure and hydraulic properties (de Souza Machado et al., 2018), which can, in turn, affect plant growth (de Souza Machado et al., 2019). MP fibres are particularly abundant in soils amended with sewage sludge (Corradini et al., 2019; Ding et al., 2020; Harley-Nyang et al., 2023) owing to shedding of synthetic textiles during the washing process (Cai et al., 2020; Yang et al., 2023). Given that the European textile industry alone generated an estimated 3 million tonnes of synthetic fibres in 2020 (Manshoven et al., 2021) and approximately 39 % of sewage sludge in Europe is applied to agricultural soils (EEA, 2025) MP fibres are a distinct MP subgroup whose long-term accumulation and spatial distribution in soil raises concern.

Studies on the transport behaviour and the potential redistribution of MP fibres within soils remain scarce as compared to other MP shapes. MP fibres are often considered less mobile than other MP shapes, due to their potential entanglement with other soil constituents that hinders water-driven transport (Waldschläger and Schüttrumpf, 2020). In contrast, such shape-effects remain elusive for earthworm-driven transport as studies on MP fibre transport remain scarce. Initial studies with deep-burrowing earthworms confirmed that spherical MPs were transported by earthworms (Huerta Lwanga et al., 2017, 2016; Rillig et al., 2017). However, findings on MPs spheres or fragments cannot be readily transferred to MP fibres as their elongated shape and typically small(er) width might have currently unknown consequences for their transport potential by earthworms. The few existing earthworm studies with MP fibres were instead aimed at quantifying potential effects of MP fibres on earthworms rather than studying transport dynamics (Lahive et al., 2022; Prendergast-Miller et al., 2019). One recent study has taken a comparative approach with different MP shapes (Zhang et al., 2025), but the limiting factors of MP fibre transport by earthworms remain poorly understood.

The aim of this study was to investigate whether relatively long MP fibres are susceptible to transport by bioturbation and the extent to which fibre length determines their transport potential. For this purpose, we measured the depth-dependent transport of MP fibres in soil columns by a deep-burrowing earthworm, i.e. *Lumbricus terrestris (L. terrestris)*, and determined the size distribution of transported and ingested MP fibres to elucidate the underlying transport mechanism for MP fibres and how length affects their mobility. We hypothesized, firstly, that earthworms contribute to the vertical transport of MP fibres in the soil and secondly, that smaller MP fibres are preferentially transported. Understanding how MP size and shape affect interactions with soil fauna may provide insights into the mechanisms driving MP redistribution in soils and thereby inform long-term predictions of MP exposure levels in soils.

2. MATERIALS & METHODS

2.1. Overview of experiments

A first experiment aimed to quantify vertical MP fibre transport by earthworms (E1), supplemented by a second experiment to assess which MP fibre lengths were ingested and egested by earthworms (E2). Microcosms were constructed for both experiments using repacked soil, earthworms of the species *L. terrestris* and metal-doped MP fibres. For the transport study (E1), MP fibres of varying lengths were spiked to the top of the soil columns before earthworms were introduced, and the depth-dependent mass redistribution of MP fibres measured after 2 and 4 weeks. Additionally, depth-dependent MP number concentrations and fibre lengths were determined for one soil column after their isolation from the soil using an optical microscope (E1). To determine which MP fibre lengths were most readily ingested by earthworms, MP fibres were homogeneously mixed into the soil of the entire column, earthworms extracted after two weeks and MP fibres isolated from their casts (E2).

2.2. Metal-doped MP fibres

We used indium (In)-doped polyethylene terephthalate (PET) MP fibres which facilitated mass-based quantification via inductively-coupled plasma mass-spectrometry (ICP-MS) after microwave-assisted acid digestion of soil samples, using the metal dope as a proxy for MPs. PET is a type of polyester, which is the most commonly used polymer type for synthetic textiles (Manshoven et al., 2021) and commonly detected in sewage sludge-amended arable soils (Heinze et al., 2024; Klemmensen et al., 2024). The metal-doped fibres were produced by first melting PET preproduction pellets and mixing it with indium oxide nanoparticles to achieve a homogeneous distribution of In throughout. After re-palettization, the product was introduced into an extruder to create an endless fibre filament (see Schmiedgruber et al., 2019; Tophinke et al., 2022 for details). The MP fibres used in this study contained In concentrations of 0.48 ± 0.04 % m/m ($n = 6$). Fibre filaments (mean width ± standard deviation: 38 ± 10 μm, $n = 142$) were then manually cut and sieved (4 mm mesh) to obtain a wide size distribution representative of what would be expected in the field, achieving mean lengths of 890 ± 665 μm (median 750 μm; range 0.030–9.0 mm; $n = 33\,752$). It is important to note that the sieving step did not fully exclude larger MP fibres, as they may by-pass the sieve owing to their small width. MP fibre length, rather than width, was expected to be the most constraining factor for earthworm-driven transport and therefore focused on in the analysis of MP sizes. Overall MP fibre lengths and widths were determined on MP fibres that were extracted from soil after the experiments; see section 2.8 for the extraction and measurement procedures and section 2.9 for calculations.

2.3. Soil

The soil was a sandy loam with 60 % sand, 28 % silt, 12 % clay, from the plough layer of a former agricultural field (Sprowston, UK; WGS 84:387724, 5835408), sieved to 2 mm. The soil was relatively rich in organic matter (5 % m/m) with a pH of 7.2-7.6, providing favourable conditions for earthworms. The water holding capacity (WHC) of the soil was 0.42 g g^{-1} and determined gravimetrically by placing dry soil in a funnel, wetting it and measuring the remaining water content in the soil after drainage (following ISO:11268–2; ISO, 1998). MP mass concentrations were determined based on the In metal-dopant quantified with ICP-MS following a microwave-assisted acid digestion (section 2.7). Therefore, the In-background concentration of the soil (12.1 ± 0.3 μg kg^{-1}, $n = 4$) was used for In-background correction before quantifying MP mass concentrations in soils. Background particle concentrations of MPs were not assessed because the spiked MP fibres were easily distinguished by width, surface and overall appearance using optical microscopy (Fig. 1).

2.4. Earthworms

L. terrestris is a predominantly deep-burrowing earthworm species with a preference for semi-permanent vertical burrows and was chosen because of its expected contribution to deep vertical transport.

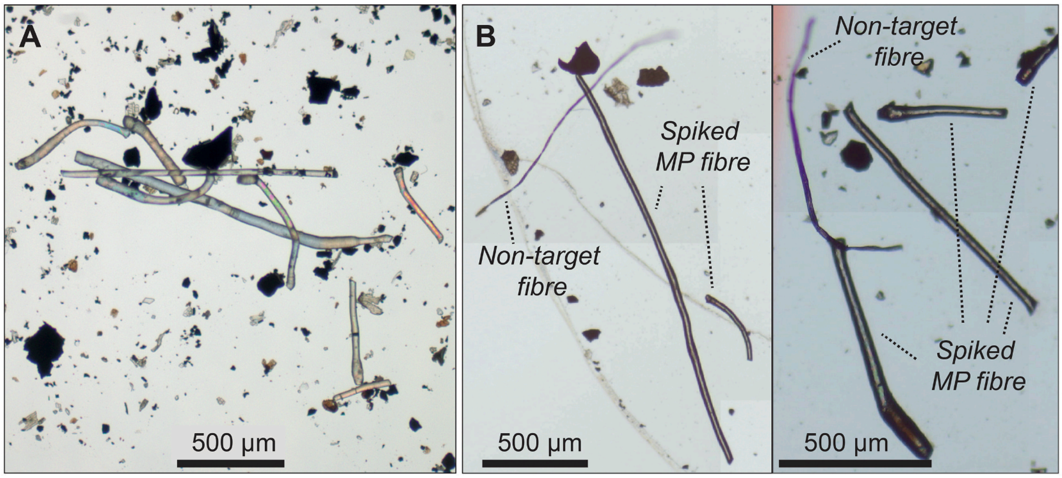

Fig. 1. Examples of spiked MP fibres (A) and a comparison of spiked target MP fibres with non-target fibres extracted from soils (B).

According to Bottinelli et al. (2020), the species is considered epi-anecic (92 % anecic, 8 % epigeic); or a burrower according to a recent more functional classification by Capowiez et al (2024). The same species was used in a number of previous studies on MP and nanoplastic transport (Heinze et al., 2021; Huerta Lwanga et al., 2017; Rillig et al., 2017), which facilitated the comparison of transport dynamics between studies. The adult earthworms were purchased (E1: Wormsdirect, UK; E2: Wurmwelten, GER), acclimatised for two weeks, depurated in petri dishes with wet cellulose paper for 48 h to achieve gut clearance, weighed (E1: 5.7 ± 0.4 g wet weight (WW), $n = 18$; E2: 4.7 ± 0.6 g WW, $n = 30$; Supplementary Table S1) and then introduced to the prepared soil columns. At the end of each experiment, the procedure was repeated to assess weight changes over the duration of the experiment as an indicator for earthworm fitness.

2.5. Soil column setup and sampling for MP fibre transport (E1)

The setup of the soil columns followed a design previously described by Heinze et al. (2021), with minor adjustments. Topsoil was packed to a depth of 30 cm inside polyvinylchloride (PVC) cylinders (10 cm diameter), with the top 2 cm of soil mixed with MP fibres (Fig. 2A). The soil was moistened to 40 % of its water holding capacity (WHC) prior to packing and then added to the cylinder in layers by successively adding ca. 200 g WW of soil with gentle tapping in between for the soil to settle. MP fibres were mixed with the last top 2 cm of the soil (180 ± 0 g DW) at dry conditions to prevent entanglement, then moistened, added on top and covered with a leaf litter layer (*Tilia cordata*; 5.0 g DW). The mean total soil depth across columns at the start was 30 cm, with an mean soil weight of 2.83 ± 0.05 kg dry weight (DW), corresponding to a dry bulk density of 1.21 ± 0.01 g cm^{-3} ($n = 3$ soil columns per treatment, $n = 9$ total). A total of 1.58 g of PET MP fibres were added to each column, corresponding to an average concentration of 558 ± 1 mg kg^{-1} (0.06 % m/m DW) across the entire soil column. Note that all MP fibres were initially added to the top 2 cm at the onset of the experiment leading to locally higher concentrations (8.77 ± 0.06 g kg^{-1} or 0.9 % m/m DW). While this local concentration exceeded most concentrations currently reported for agricultural soils, we argue that the insights into transport mechanisms gained from this mechanistic study remain relevant. After 24 h, three adult earthworms (*L. terrestris)* were introduced to each soil column. The stocking density, i.e. 380 individuals m^{-2}, was selected to ensure observable effects within the given timespan. This earthworm density is high for arable soils that often have less than 200 individuals m^{-2}, but are within ranges of other land uses such as pastures (Fründ et al., 2010). The initial soil moisture was maintained throughout the experiment by spraying water on top of the column at low enough rates to avoid water saturation (9.5 ± 1.5 mm week^{-1}).

We destructively sampled the soil columns after two and four weeks ($n = 3$ per timepoint). Additionally, three control columns with MP

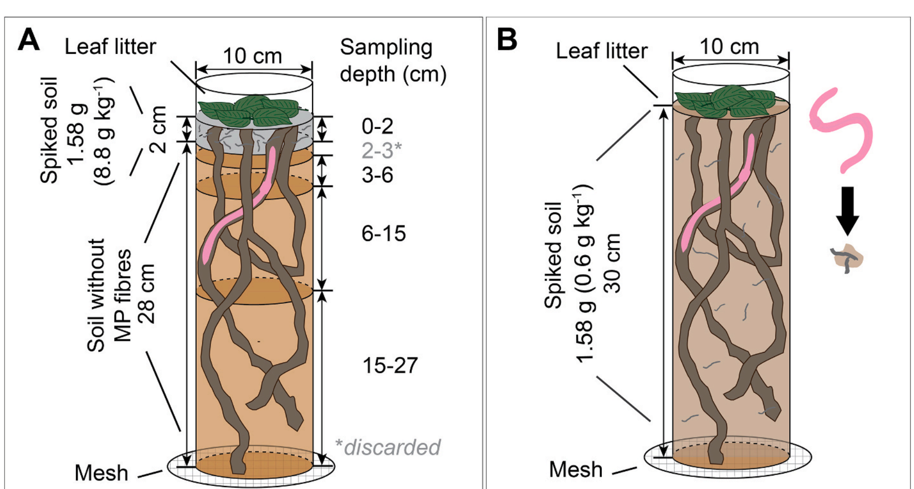

Fig. 2. Schematics of the microcosm setups, including: (A) the setup and sampling depths for the transport study (E1, note that the depth layer 2–3 cm was discarded after sampling) and (B) the setup for determining ingested MP fibre lengths (E2).

fibres but without earthworms were sampled after four weeks. To sample the columns, the remaining leaf litter layer was removed, and soil columns were completely pressed out of the cylinder towards the bottom and onto a semicircle-shaped sample carrier to minimize potential MP fibre contamination of the lower depth layers while keeping the soil column intact. The soil column thickness was measured before and after extraction from the PVC cylinders, ensuring that no compaction occurred during sampling. After extraction, the soil column was segmented into 5 different depth segments starting at the soil surface: 0–2 cm, 2–3 cm, 3–6 cm, 6–15 cm and 15 cm to the bottom (Fig. 2A). The depth layer 2–3 cm was discarded to more clearly distinguish between the initially spiked layer and layers that were initially free of MP fibres. The deepest sampling layer deviated in its thickness because of soil settling during the experiment (10–12 cm, mean 11.2 ± 0.7 cm; Supplementary Table S2). After oven-drying (105 °C for 48 h), the soil was ground with a mortar and pestle prior to further analysis.

2.6. Soil column setup and sampling for length-dependent MP fibre ingestion (E2)

For the second set of soil columns, all MP fibres were mixed with the dry soil of the entire soil column to ensure a homogeneous exposure of earthworms to fibres at the same overall concentration as during the transport study (1.58 g MP fibres per column; 558 ± 1 mg kg^{-1}; 0.06 % m/m DW). After mixing the dry soil with MP fibres, the spiked soil was moistened to 40 % WHC and packed to soil columns of 30 cm height similarly as in E1 (Fig. 2B, $n = 6$; 2.78 ± 0.05 kg DW; 1.19 ± 0.03 g cm^{-3}), also with a litter layer on top (*Tilia cordata*; 5.0 g DW). Five earthworms (640 individuals m^{-2}) were introduced into each soil column to ensure sufficient replicates (total $n = 30$ earthworms) and that sufficient cast material could be collected from treatments with spiked MP fibres for statistical analysis (total 18.4 g). To assess potential effects on earthworm fitness at this density, we added 5 earthworms to a control column without MP fibres. Earthworms were collected from the soil after 2 weeks and their casts were collected during depuration. The casts were pooled per column and dried (105 °C, mean 3.0 ± 0.6 g DW per column) before MP isolation.

2.7. Analysis of MP fibre mass concentrations (E1)

MP fibre mass distributions in samples collected during E1 were quantified by analysing the In-dopant following microwave-assisted acid digestion and quantification using ICP-MS (PerkinElmer, Nexion 350D). In brief, soil samples were successively halved to obtain representative subsamples of approximately 5 g, of which 0.5 g were added to a digestion vessel. The soil was then treated with 1 mL of hydrogen peroxide (H_2O_2, 30 vol%) and 8 mL nitric acid (HNO_3, 65 vol%) and then digested in a closed-vessel microwave system (Milestone Ethos Easy, PTFE vessels). After a 15 min ramping time to 200 °C, the temperature was maintained for 30 min, followed by cooling to room temperature. Three technical replicates were analysed per soil column and sampling depth. Measured In concentrations were corrected using the procedural blank of the respective digestion batch (negative control, $n = 3$ per digestion batch; $n = 12$ in total with mean 0.01 ± 0.03 μg L^{-1}) and soil-containing samples corrected for the mean natural In background in the soil (12.1 ± 0.3 μg kg^{-1}, $n = 4$). Each digestion batch included three spike recoveries with solutions of known In added as positive control ($n = 12$, 99 ± 4 %). The recovery of fibre-incorporated In in the presence of soil was 94 ± 2 % ($n = 3$). The analytical limit of detection (LOD) was 0.10 μg L^{-1} and limit of quantification (LOQ) 0.31 μg L^{-1}, based on all negative control samples. After correction for the natural In-background of the soil, this corresponded to an equivalent MP fibre mass of 2.08 mg kg^{-1} soil for the LOD and 6.46 mg kg^{-1} soil for the LOQ (Supplementary Materials S1).

2.8. Analysis of MP fibre number concentrations and MP fibre lengths

Depth-dependent number concentrations and MP fibre lengths from the transport study (E1) were determined for one soil column which was selected as it showed the highest mass-based transport of MP fibres from the top layer. MP fibres were first isolated from the soil as commonly done for environmental MP samples (Hurley et al., 2018; Liu et al., 2019; Löder et al., 2017). A subsample of the soil (70 g for 0–2 cm, 95 g for other layers) underwent density separation ($ZnCl_2$, >1.6 g cm^{-3}, one time, 48 h), followed by impurity removal with a sequence of hydrogen peroxide (10 % H_2O_2, 24 h at 50 °C) and sodium dodecyl sulphate (SDS, 5 % m/m, 24 h at 50 °C) as detailed by Heinze et al. (2024). The sample was density-separated and treated with H_2O_2 a second time, ethanol-rinsed, dried and suspended in a fixed volume of ethanol (25 mL, except for 0–2 cm: 15 mL). Between each step, the samples were vacuum filtered onto a stainless-steel filter (nominal mesh size 10 μm) and rinsed with ultrapure water. For the exact sample weights, volumes and detected MP fibres see Supplementary Table S7.

After extraction, a subsample of the isolated MP fibres was taken while the sample was kept in motion with a magnetic stirrer (16 % of the total sample volume) and deposited onto microscope slides with intermittent drying before analysis with an optical microscope (Nikon, Eclipse 80i Upright Microscope). Identification of spiked MP fibres was possible due to their relatively distinct width and surface compared to other soil components (Fig. 1; Supplementary Figs. S1 for further examples). Images were taken for each microscope slide and MP fibre lengths were manually measured for all detected MP fibres (number of measured MP fibres $n = 33\,752$) using the software ImageJ/FIJI (Schindelin et al., 2012; Schneider et al., 2012) in single images or merged images using a stitching tool (Preibisch et al., 2009). Detected MP fibre particle concentrations (particles kg^{-1}) were then extrapolated to the total sample, soil layer and column to derive the estimated total number of MPs added (Supplementary Table S7, section 2.9). MP fibre widths were determined for a smaller random subsample of MP fibres extracted from the initially spiked layer ($n = 142$; 0–2 cm).

The procedure was shortened for the isolation of MP fibres from earthworm casts (E2) to a single density separation step followed by a single organic matter removal with H_2O_2 due to the small sample mass (3.0 ± 0.6 g DW casts). All MP fibres extracted from earthworm casts were measured ($n = 4899$). Casts collected from the control were not analysed since no MP fibres were added to the control column.

2.9. Data processing and statistical analysis

We observed substantial settling of the soil after the onset of E1 in response to earthworm bioturbation, resulting in different soil bulk densities across sampling time points and replicates (mean decrease 3.7 ± 0.7 cm; Supplementary Table S2). As sampling was performed from the top to bottom layers, this led to deviating thicknesses of the lowest layer, i.e. 15 cm to bottom of the columns. We thus converted MP fibre concentrations from mass or number per mass (mg kg^{-1}, particles kg^{-1}) to mass or number per volume of soil including pore space (mg cm^{-3}, particles cm^{-3}) to make the results comparable across all replicates (see Supplementary Table S3 and S4). This conversion to volume rather than mass was further considered appropriate as the focus of the study was on transport distances.

The length distribution of MP fibres was analysed using R (see Supplementary Table S5 for a list of packages used). The initial MP fibre length distribution was determined by calculating the weighted mean of means from MP fibres extracted from the different depth layers (E1). Extracted MP fibres showed no signs of fissures, cracks or abrasion that would suggest fragmentation over the duration of the experiment (Supplementary Fig. S1). We thus considered length distribution estimates based on the large number of extracted and measured MP fibres ($n = 33\,752$) as robust and representative for the initial length distribution. Specifically, we used the detected number concentrations and soil weight per depth layer to approximate the total number of MP fibres added (Supplementary Table S7), and determined the weighted mean of medians, mean of means and weighted standard deviation for an overall characterisation of MP fibre length (section 2.2). For E2, we used the derived total numbers of added MP fibres and soil weight per soil column to estimate expected MP fibre number concentrations in soil when homogeneously mixed (Supplementary Table S8).

We used Welch's *t*–tests ($\alpha = 0.05$) for assessing statistical significance, reporting the respective *p*-value following recommendations (Wasserstein et al., 2019), except for *p*-values below 0.001. Sample numbers were very large for MP fibres which can result in low *p*-values despite minor differences. We therefore supplemented *p*-values for fibre lengths comparisons with Cohen's *d* tests (confidence intervals = 95 %) to assess the practical magnitude of the effect.

3. RESULTS AND DISCUSSION

3.1. Earthworm bioturbation causes downward transport of MP fibres

MP fibres are generally considered less mobile than MPs of other shapes because of their potential entanglement hindering their water-driven transport through the soil (Waldschläger and Schüttrumpf, 2020). In contrast, our results highlight that MP fibres can be readily transported by deep-burrowing earthworms as shown by the time-dependent vertical transport of MP fibres to deeper layers of the soil columns (Fig. 3A). In terms of MP fibre mass, approximately 5.7 % was transported away from the initially spiked layer after 2 weeks of bioturbation, and approximately 9.0 % after 4 weeks (Supplementary Table S6). Consequently, most downward transport occurred during the early phases of experiment when earthworms created their burrows (Fig. 3A). At the beginning of E1, earthworms had to penetrate the soil layer spiked with MP fibres to create the first burrows and were, thus, inevitably most exposed to MPs fibres, leading to most transport occurring during this initial exposure. With increased bioturbation time, MP fibre concentrations in previously fibre-free layers increased notably for all but the deepest soil layer (Fig. 3A). For the deepest soil layer, the increase in MP fibre concentrations from week 2 to week 4 was negligible due to relatively high variability between replicates (Welch's *t*-test: $p = 0.4$).

The overall decrease of transport rates with increasing soil depth may be, in part, related to the burrowing behaviour of the earthworm species: *L. terrestris* scavenges near the surface where it creates many horizontal burrows but takes refuge in semi-permanent deep vertical burrows that it reuses (Capowiez et al., 2024). This pattern was also observed in previous work on nanoplastic transport by *L. terrestris* where the burrow system development was monitored (Heinze et al., 2021). Transport rates observed in this laboratory-based study were likely faster than under field conditions due to high earthworm densities, ideal soil moisture and temperature, and finally earthworms being restricted in space. In field conditions, however, MP fibres will be affected by

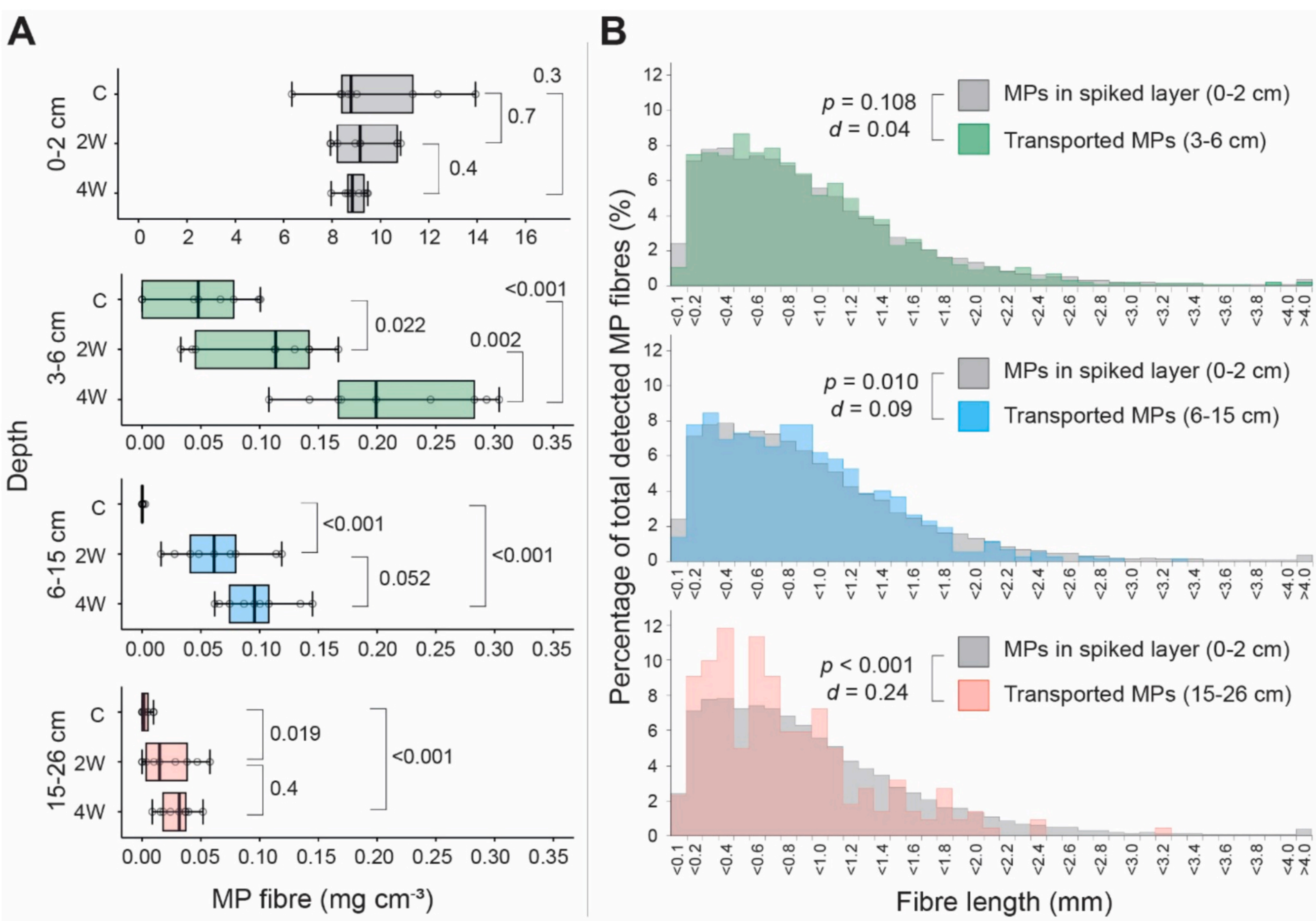

Fig. 3. Depth-dependent mass and length distributions of MP fibres. (A) Including control columns (C: no earthworms), and in bioturbation columns sampled after 2 and 4 weeks (2 W, 4 W). Boxplots represent the interquartile range (IQR), where the median is represented as a vertical bar and points showing the individual data points ($n = 9$). Horizontal error bars indicate the range excluding outliers (1.5 times IQR). (B) Length distribution of transported MP fibres in comparison to the initial size distribution. Displayed numbers are *p*-values based on Welch's *t*-tests comparing the length of all detected MPs; d-values represent the calculated Cohen's *d* indicating effect magnitude.

earthworm bioturbation by a range of different earthworm species and for much longer times than in this current study. Disturbances by weather events, roots, other soil biota and anthropogenic activities, such as ploughing in arable soils, for instance, will lead to burrow refilling and collapse, forcing earthworms to create more new burrows. As a result, more surface soil is turned over to deeper soil in the long-term (Leuther et al., 2023), which will likely result in a successive downward transport of MP fibres and to potentially greater depths. Earthworm ecology will also affect the maximum transport depths that are possible in the field. For instance, earthworms respond to very high or low temperatures and moisture contents by retreating into deeper soil which would promote deeper transport of MPs in the field. Burrow systems of *L. terrestris* can indeed be more than 2 m deep (van de Logt et al., 2023). We therefore propose that earthworm bioturbation could be one factor explaining the presence of a wide range of different MP shapes and sizes in deeper parts of soil profiles as has been reported in field studies (Weber et al., 2021).

3.2. The deep-burrowing *L. terrestris* ingests and transports even relatively large MP fibres

L. terrestris transported MP fibres of a wide length distribution to the deeper soil (E1, Fig. 3B) and MP fibres present in earthworm casts suggested particle ingestion and excretion as the driving transport mechanism (E2, Fig. 4). Near-surface ingestion of MPs by earthworms and their subsequent movement to deeper soil layers was previously identified as a major transport mode for small plastic particles (Heinze et al., 2021; Rillig et al., 2017). The current study confirms that

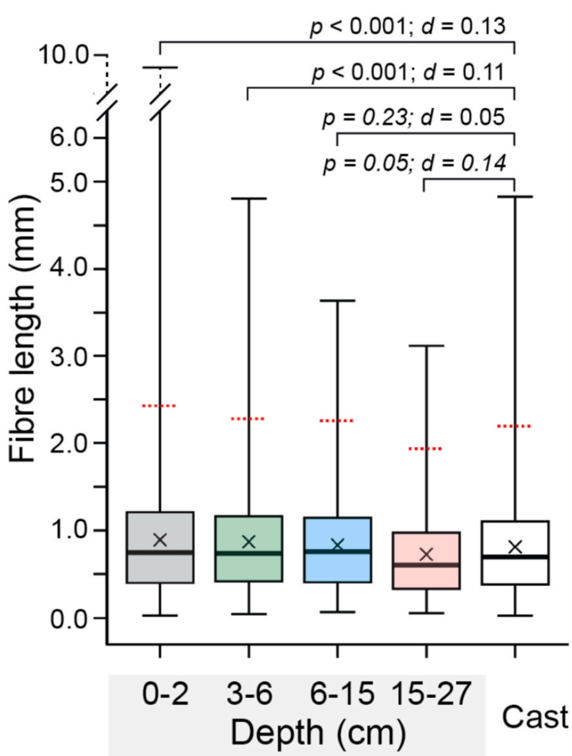

Fig. 4. MP fibre lengths for the different depth layers in the transport study (E1) for one replicate in comparison to MP fibre lengths in earthworm casts (E2). Boxplots represent the interquartile range (IQR), where the median is represented as a horizontal bar and the mean as a cross. The black error bars indicate the total minimum and maximum lengths of MP fibres detected and the red dotted line represents the spread excluding outliers (1.5 times IQR). Displayed *p*-values are based on Welch's *t*-tests comparing the length of all detected MPs (numbers shown in Table 1); *d*-values represent the calculated Cohen's *d* effect magnitude.

earthworms ingest and excrete much larger MP fibres than previously reported (i.e. 2.8 mm MP spheres; Rillig et al., 2017), as MP fibres found in earthworm casts were up to 4.8 mm in length (Table 1, Fig. 4). Moreover, MP fibre concentrations in earthworm casts corresponded to the expected concentrations in the homogeneously mixed soil surrounding them (Table 1), suggesting that MP fibres were ingested indiscriminately together with other soil constituents. Other studies have shown no signs of avoidance behaviour of earthworms for smaller MPs (Heinze et al., 2021). Consequently, wherever MP fibres are present in the soil, earthworms inhabiting the soil are likely to ingest and be exposed to these persistent particles.

MP fibres are likely susceptible to ingestion and excretion by *L. terrestris* owing to their comparatively small width (in our case 38 ± 10 μm) and the correspondingly small volume relative to the earthworm size. Epi-anecic earthworms, such as *L. terrestris*, are known to drag litter material and ingest seeds of several millimetres in length (5 mm) and widths of up to 1.3–1.7 mm (Eisenhauer et al., 2010; McTavish and Murphy, 2021). In these previous experiments on plant seed ingestion, seed width and volume played an equally important role as seed length (Eisenhauer et al., 2009). The likelihood of ingesting MP fibres and other MP particles likely depends on the interplay between MP size dimensions and earthworm traits, such as overall body size and mouthpart dimensions. Systematic measurements of mouthparts of *L. terrestris* would elucidate if there are specific width limitations for particle ingestion but are currently lacking. Shape parameters of MPs are often considered key determinants for their potential mobility in soil, generally stipulating a lower mobility of fibres in comparison to other shapes concerning water-driven transport. In the case of bioturbation, in contrast, MP fibres of small width and volume may in fact be more mobile than spherical or fragmental particles of the same major length because they are more easily ingested and transported by earthworms due to their small width and potential flexibility. In line with this, Zhang et al. (2025) found that earthworms transported larger fibres than spheres pointing out their greater flexibility as a determining factor. Complementing their findings, the longest transported MP fibres in our study were up to 4.8 mm (Table 1), which to date are the largest MPs for which transport by earthworms has been observed. This length coincides with the lengths of plant seeds ingested by earthworms (Eisenhauer et al., 2010; McTavish and Murphy, 2021), but it remains unclear if this represents a general threshold for ingestible particle lengths. Taken together, our and recently published results by Zhang et al. (2025) thus challenge the assumption that MP fibres are less mobile than other MP shapes in soils (Table 1).

3.3. MP length by itself does not suffice to predict MP fibre transport

Given the length range of transported MP fibres, we propose that MP transport by earthworm bioturbation might be affected but less sensitive to particle size than previously assumed, provided the particles are within the ingestible range in at least one dimension. Decreasing MP fibre lengths with increasing soil depth indicate that smaller MP fibres were transported somewhat more easily by *L. terrestris* than longer fibres (Table 1, Fig. 3B). Changes in MP fibre length and diameter due to ingestion and grinding of MPs within the earthworm gut are unlikely to explain this size decrease because the shape, width and surface of MP fibres extracted from earthworm casts appeared visibly unchanged from their original appearance (Supplementary Fig. S1). Instead, preferential transport of shorter MP fibres seems intuitive given their greater ingestion potential by earthworms: The smaller the particles, the more easily they are ingested as earthworms burrow through the soil. Initially, our study reaffirms previously observed size-dependency of MP transport as reported by Rillig et al. (2017) for spherical MPs (710–2800 μm). Moreover, only half as much of the MP fibre mass was transported to the lower layers compared to much smaller nanoplastics (256 nm diameter) used by Heinze et al. (2021) in a previous study, even though spike concentration, earthworm species and density, soil, initial soil column

Table 1
MP fibre lengths and corresponding MP fibre particle concentrations in soil (E1) and earthworm casts (E2). +Overall MP fibre length was based on the calculated weighted mean of medians, weighted mean of means and weighted standard deviation. *Signifies expected MP fibre particle concentrations in the homogeneously spiked soil columns that were estimated based on total MP fibre numbers added divided by soil weight per soil column (see section 2.8).

Experi-ment	Sample description	Median (mm)	Mean ± Stdev (mm)	Max (mm)	Min (mm)	Number (n)	MP fibres (particles g^{-1})
E1	0–2 cm	0.750	0.900 ± 0.680	9.7	0.03	30 836	2 598
	3–6 cm	0.740	0.870 ± 0.620	4.8	0.05	1 890	124
	6–15 cm	0.760	0.840 ± 0.540	3.6	0.07	804	52
	15–26 cm	0.610	0.730 ± 0.520	3.1	0.06	222	15
	Overall	0.750^{+}	$0.890 \pm 0.665^{+}$	9.7	0.03	33 752	NA
E2	Casts	0.700	0.810 ± 0.590	0.03–4.8	0.03	4 899	271 ± 33
	Soil						247 ± 4*

dimensions, moisture and temperature were the same (Supplementary Table S9).

However, although MP fibre transport rate was somewhat influenced by length, the magnitude of this effect was relatively modest (Cohen's $d < 0.5$) suggesting that it is not necessarily as size-restricted as previously assumed. This current and other laboratory studies suggest a decrease in MP size with soil depth (Fig. 3B), but the absolute difference in mean and median MP fibre lengths across sampling depths was small (< 0.170 mm; Table 1) relative to the fibre lengths themselves (overall mean 0.890 mm). This trend was similarly observed for MP fibres isolated from earthworm casts: mean MP fibre lengths were statistically different (Fig. 4) but absolute values of this difference were small as shown by negligible effect magnitudes (Cohen's $d < 0.2$). In this context, a recent two-year field experiment demonstrated that MP fragments (65–125 μm) and MP fibres (0.5–2.0 mm length, 30 μm width) had similar transport depths and speeds, despite their markedly different size dimensions (Schefer et al., 2025). While water-driven transport is generally considered size-limited and influenced by particle shape, bioturbation – as observed in our case – offers a plausible explanation for the comparable depth distribution of such differently sized and shaped particles, since it appears to be less size-selective. Accordingly, the practical implications of the widely stipulated size-dependency of MP transport may require careful re-evaluation of the underlying transport mechanisms and other influencing factors.

One influencing factor, besides MP length, may be related to subtle alterations of egestion dynamics by the presence of large MP fibres in the earthworm gut which could lead to lower transport rates (Lahive et al., 2022). We did not observe an effect of MP fibre presence on earthworm weight before and after exposure, neither during the transport nor during the cast experiments (Supplementary Table S1). However, earthworm weight, by itself, is not always an indicator of more subtle or indirect effects, including alterations in earthworm burrowing activity. MP fibre concentrations were especially high in the initial spike layer, nearing or exceeding some of the currently reported effect values of MP fibres for earthworms. In two recent eco-toxicological studies, *L. terrestris* exposed to MP fibres demonstrated signs of stress expressed in molecular genetic biomarkers and a reduced cast production, already occurring at lower levels than in this current study (Lahive et al., 2022; Prendergast-Miller et al., 2019). Larger particles may cause more severe physical constrains, thereby impeding egestion. The MP fibres used in those two studies were 630 ± 280 μm and 360 ± 390 μm respectively (Lahive et al., 2022; Prendergast-Miller et al., 2019), i.e. smaller than in the current study. Hence, the slower transport rates of MP fibres here as compared to other bioturbation studies could be a combined result of reduced ingestion potential and an overall reduced egestion.

4. CONCLUSIONS

MP fibres are generally considered less mobile in soil than other MP shapes because of their potential entanglement with other soil constituents. However, we found that bioturbation by the deep-burrowing *L. terrestris* led to the successive vertical dispersal of even relatively long MP fibres via ingestion and excretion. Bioturbation is therefore an important transport process to consider when predicting MP dispersal in soils, especially for MP fibres. Our results highlight that wherever MP fibres are present in the soil, earthworms are likely to ingest and be exposed externally and internally to these persistent particles with currently unknown long-term effects. Given that MP fibres are amongst the MP morphologies for which physical toxicity effects are most anticipated, ingestion of large fibres may have important long-term implications for earthworm populations in exposed soils, such as soils receiving municipal sewage sludge as an amendment or where agricultural fleeces are utilised. In agreement with other studies assessing other MP shapes, earthworms transported shorter fibres more readily, but this size-dependence may have limited practical relevance, as the overall change in MP fibre length with depth was comparatively small as indicated by small effect magnitudes. While it is intuitive that shorter MPs are likely easier to ingest for earthworms, large MP fibres may also have affected the casting activity which would further lead to slower transport rates than previously observed for smaller MPs. More investigations are necessary for disentangling physical constraints for ingestion of MPs from reduced transport caused by adverse effects on the earthworms. *L. terrestris* transported MP fibres up to several millimetres in length, suggesting that major particle size is not the only factor determining MP transport by earthworms. Focusing on the major particle size alone neglects the potential effect of particle width and volume on their further dispersal in the environment. Thus, a more nuanced evaluation of MP mobility that expands beyond the major particle size may be necessary for assessing MP fate in soil. Potentially decisive MP properties need to be evaluated in conjunction with the underlying transport mechanism as driving factors may differ between bioturbation and water-driven transport. Importantly, earthworms are one component of bioturbation, but in soils there is a host of soil biota and plant roots that can further contribute to MP redistribution, either directly, by ingesting particles, or indirectly by creating transport routes for water-driven transport which may lead to combined transport processes. A broader range of different soil biota in more complex and dynamic systems need to be considered for establishing field-realistic transport rates and assessing the long-term distribution of MPs in soils.

Disclosures

Denise M. Mitrano has since moved to employment in industry. The research described in this manuscript was conducted and fully funded during her previous academic affiliation. The current employer was not involved in the study design, data collection, analysis, interpretation, or the decision to publish.

Data statement

Supplementary information is available for this manuscript. The data that support the findings of this study is openly available via the Swedish National Data Service at: https://doi.org/10.5878/kx3v-8w58.

CRediT authorship contribution statement

Wiebke Mareile Heinze: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Elma Lahive:** Writing – review & editing, Methodology, Investigation. **Kathrin Leicht:** Writing – review & editing, Methodology, Investigation, Conceptualization. **Denise M. Mitrano:** Writing – review & editing, Resources, Methodology. **Geert Cornelis:** Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.geoderma.2026.117768.

Data availability

The data that support the findings of this study is openly available via the Swedish National Data Service at: https://doi.org/10.5878/kx3v-8w58.

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