ORIGINAL RESEARCH ARTICLE

Effects of microplastics and earthworm burrows on soil macropore water flow within a laboratory soil column setup

Miao Yu1,2 | Martine van der Ploeg3 | Xiaoyi Ma | Coen J Ritsema2 | Violette Geissen3

1 Key Lab. for Agriculture Soil and Water Engineering in Arid and Semi-arid Areas, Ministry of Education, Northwest A&F Univ., Yangling, Shaanxi Province 712100, PR China
2 Soil Physics and Land Management Group, Wageningen Univ. & Research, PO Box 47, Droevendaalsesteeg 3, Wageningen 6700 AA, the Netherlands
3 Hydrology and Quantitative Water Management Group, Wageningen Univ. & Research, PO Box 47, Droevendaalsesteeg 3a, Wageningen 6700 AA, the Netherlands

Abstract
Several earlier studies reported that microplastics (MP) accumulated on soil surfaces could be transported into the subsoil and ingested by soil biota, such as earthworms. The present study explores how networks of earthworm burrows and MP (low-density polyethylene, LDPE) in subsoil affect the soil hydraulic properties and saturated water flow. A repacked and saturated sandy soil column experiment was conducted in an environment-controlled laboratory with earthworms (anecic, Lumbricus terrestris) inoculated into the soil columns to form networks of macropore. The macropore network parameters (i.e., number, length, volume, diameter, soil saturated conductivity, and tracer breakthrough curves of soil columns) have been determined. The relative arrival times of the tracer mass (i.e., T5%, T25%, and T50%) were determined in order to describe the shapes of the breakthrough curves. The results show that in some breakthrough curves for the treatments with earthworms, there are two peaks. This is an indication that water was flowing faster in the macropores than in the soil matrix. There is a significant correlation between 5% arrival time and the median burrow volume, and the correlation coefficient was .571 (at the level of p < .05). The formation of macropores due to the burrowing activities of earthworms is considered the main cause of nonequilibrium water flow in the present study. The MP did not show any significant effect on the saturated water flow. This may be attribute to the low concentrations of MP used in the present study.

INTRODUCTION

Soil, a porous media, can be considered as a natural filter for many solutes and contaminants (Keesstra et al., 2012). Water and solutes infiltrating from the soil surface into the subsoil can be classified as equilibrium or nonequilibrium flow (Hendrickx & Flury, 2001). When water flows...
with a stable wetting front that is parallel to the soil surface, it is classified as equilibrium flow. Nonequilibrium flow is the phenomenon where a volume of water flows or solute dissolves faster through certain pathways, thereby bypassing part of the soil matrix (Jarvis, Moey, Koestel, & Hollis, 2012). Nonequilibrium water flow in the vadose zone is also denoted as preferential flow. Preferential flow can cause volumetric water or solutes accumulating rapidly at a certain location such as deep soil layers or even the ground water layer, without wetting the whole soil matrix (Jarvis, Koestel, & Larsbo, 2016; Zhang, Zhang, Niu, & Zheng, 2016). Pollutants (e.g., herbicides, pesticides, and heavy metals) or nutrients (e.g., P and N) can be transported by volumetric water through preferential flowpaths, which may end up in the groundwater, thereby causing groundwater pollution (van der Heijden et al., 2013). As soil is an opaque porous media, dye tracers have been used to stain the pathways to make them visible (Alaoui & Goetz, 2008; Allaire, Roulier, & Cessna, 2009; Sander & Gerke, 2009). Furthermore, the breakthrough curve (BTC) method has been applied to laboratory soil columns to investigate macropore flow in soil (Jarvis, 2007; Koestel, Moey, & Jarvis, 2012). This method examines the tracer concentration in effluent from soil as it changes over time. The water source can be artificial rainfall, irrigation, or constant water head infiltration (Aquino, Aubeneau, & Bolster, 2015; Zhang, Peng, Zhou, Lin, & Sun, 2015). By plotting the BTCs with the tracer concentration in leachate on the y axis and time on the x axis, the soil preferential flow can be determined. Today, computed tomography (CT) and X-ray medical tomography technologies are used to investigate preferential flowpaths without disturbing the soil (Luo, Lin, & Halleck, 2008; Sammartino et al., 2015; Sammartino, Michel, & Capowiez, 2012). For instance, Koestel and Larsbo (2014) used X-ray to visualize KI transporting in an undisturbed saturated soil column under a steady water supply. The results revealed that I− solute flow mainly occurred in two cylindrical macropores, and the solute diffusion was also observed in these macropores.

According to the identified mechanisms, there are three classification of preferential flow patterns: (a) unstable flow, (b) funnel flow, and (c) macropore flow (Hendrickx & Flury, 2001). Unstable flow often occurs in dry coarse-textured materials with stable water irrigation rates. Sometimes water repellence and air entrapment can also cause unstable flow. Funnel flow is typically observed at textural boundaries. In this circumstance, water may be redirected along less permeable layers in the soil. Macropore flow refers to preferential water movement along biopores (e.g., earthworm burrows and root channels), cracks, or fissures. Water moves along the least resistance macropores and bypass the less permeable soil matrix (Jarvis, 2007). Recently, water movement through biopores, and specifically earthworm burrows, has received increasing attention (Capowiez, Sammartino, & Michel, 2014; Schneider et al., 2018). Earthworm burrowing not only affects the number of soil macropores in soil but also the soil structure (Kavdir & Ilay, 2011), nutrient uptake by plants (Vos, Ros, Koopmans, & van Groenigen, 2014), and biodiversity (Plaas et al., 2019). Different types of earthworms generate different effects on the formation of preferential flow pathways. Earthworm species can be classified into three main ecological types, depending on their burrowing activities: (a) anecic, (b) endogeic, and (c) epigeic earthworm species (Butt & Lowe, 2011). Anecic earthworm species are deep-burrowing species that can form permanent, continuous burrows that run vertically from the soil surface to the subsoil. Endogeic earthworm species live in and reside under the soil surface and create burrows, which they then refill with cast. Epigeic earthworm species live on the soil surface or litter and most of them do not dig burrows (Chatelain & Mathieu, 2017; Lamandé et al., 2011). Capowiez et al. (2014) used X-ray to visualize the characteristics of endogeic earthworm burrowing activities in the soil cores and identified the burrow parameter that was the key factor affecting water transfer. Using the univariate partial least squares regressions (i.e., the shorter the distance, the sooner the breakthrough), the results showed that the mean geodesic distance had the most significant effect on the soil water transfer.

Yu et al. (2019) showed that the burrowing and casting activities of anecic earthworms (Lumbricus terrestris) could influence the redistribution of microplastics (MP) in repacked soil columns vertically and accumulated in draining water as water flowed through macropores within burrow systems. Microplastics as a contaminant in aquatic and terrestrial environments are receiving increasingly attention (de Souza Machado, Kloas, Zarfl, Hempel, & Rillig, 2018; Jiang, 2018; Mahon et al., 2017). Microplastics mainly originate from human activities such as industrial manufacturing (Lei et al., 2017), solid waste landfill (Andrady, 2017), agriculture plastic mulching (Gao et al., 2019), sewage irrigation (Li et al., 2018), and sludge fertilizer (Mahon et al., 2017). They are a type of plastic

Core Ideas

- Breakthrough curve with two peaks indicates nonequilibrium flow in soil.
- Median of total burrow volume is significantly correlated with 5% arrival time.
- Application of microplastics on the soil surface did not affect saturated conductivity.
debris, with a typical particle size between 1 μm and 5 mm (Crawford & Quinn, 2017a). They can be classified into primary and secondary MP based on their sources (Lots, Behrens, Vijver, Horton, & Bosker, 2017). Primary MP are particles of plastic from objects manufactured for the purpose of satisfying specific uses, such as clothing fibers and personal care products (Andrady, 2011). Large plastic pieces mainly contribute to secondary MP sources through photodegradation and mechanical abrasion in natural environments (Siegfried, Koelmans, Besseling, & Kroeze, 2017; Van Cauwenberghe, Devriese, Galgani, Robbens, & Janssen, 2015). There are many studies documenting the disadvantages caused by MP particles accumulated in aquatic systems, and the results revealed that not only were MP a good carrier of toxic chemicals in water (Andrady, 2017, Crawford & Quinn, 2017c), but they could also enter into food chain, which may develop into a new threat to many species including human beings (Crawford & Quinn, 2017b; Lusher, Welden, Sobral, & Cole, 2017). On the other hand, there were few documents on the interactions among MP, water, and soil particles in terrestrial systems. In one of the documents, it was reported that terrestrial storage accounted for 21–42% of the world’s plastic waste, and the terrestrial system may contain more MP than that in aquatic systems (Nizzetto et al., 2016). Many researchers predicted that MP pollution in terrestrial systems will be worse in the near future (Geyer, Jambeck, & Law, 2017).

As a porous media, soil is recognized as a good filter for plastic particles. For instance, when the sizes of soil pores are smaller than the sizes of most plastic debris, soil can retain these plastic particles and lower the risk of polluting groundwater (Bläsing & Amelung, 2018). However, MP accumulated in topsoil and litter can be transported into subsoil layers by soil biotas. For example, 65% of MP particles <50 μm were found in the soil samples from biopore walls when compared with the MP particles originally applied to the soil surface in an experiment with anecic earthworm species (Huerta Lwanga, Mendoza Vega, et al., 2017). In a control treatment without earthworms, MP was present on the soil surface throughout the experiment, and Rillig, Ziersch, and Hempel (2017) found that earthworms (anecic species, L. terrestris) could transport MP (polyethylene) particles sized 710–2,800 μm from topsoil to subsoil layers, reaching as deep as 10.5 cm from the soil surface. However, leaching of MP and soil contaminants adsorbed to MP surface could be a groundwater contamination risk. Benhabib, Simonnot, Faure, and Sardin (2017) indicated that hydrophobic contaminants like polycyclic aromatic hydrocarbons (PAHs) were not only leaching in solution but also affected by colloidal transport. Bradford, Yates, Bettahar, and Simunek (2002) investigated the transportation of polystyrene colloids in saturated sand column with the diameters of 0.45, 1.0, 2.0, and 3.2 μm. The results revealed a potential for plastic colloids leaching in sands. Using CT techniques, Soto-Gómez, Pérez-Rodríguez, Vázquez-Juiz, López-Periago, and Paradelo (2018) investigated how the tillage management affected transport of the solute and polystyrene colloids (1 ± 0.11 μm in diameter). The results showed that bromide tracer movement parameters were mainly affected by porosity. Bläsing and Amelung (2018) assumed that when leaching occurs, only very small plastic particles (size <5 μm) are likely to go through preferential flowpaths. Although the preceding literature review shows that MP can be transported into subsoil from the soil surface by bioturbation, the potential influences of the MP migration on the soil properties and water infiltration, especially with preferential flowpaths, have not been investigated.

The objectives of the present study are as follows: (a) to investigate whether MP accumulated in subsoil layers has effects on saturated water flow; (b) to determine the key factors that influence water flows through macropores in soil; and (c) to determine the correlations among the relative arrival times of tracer mass, MP, and parameters of burrow systems.

## 2 MATERIALS AND METHODS

### 2.1 Experimental setup

A laboratory soil column experiment was set up with sandy soil (94.4% sand, 3.2% silt, and 2.4% clay), a controlled temperature of 16 ± 1 °C, and humidity of 40 ± 5%. The average soil organic matter content was 3.37% (w/w). Using duct tape and five small, clean polyvinyl chloride (PVC) rings in which four rings were 10 cm high × 12 cm in diameter, and one cylinder was 20 cm high × 12 cm in diameter, each of eight soil columns was assembled (Figure 1). A perforated metal plate covered with a mesh cloth was placed on the base of the columns so as to prevent the soil from being flushed out. Seven kilograms of air-dried sandy soil was sieved through a 2.00-mm-wide mesh and mixed with 1 L of nonchlorinated tap water. After filling with the prepared soil, the columns were saturated with 5 L of tap water supplied by Marriot bottle (Figure 1) and compacted to the final height of 50 cm of soil. Then, by measuring the electrical conductivity (EC) of drainage water, the background EC was determined. This background EC was used to correct the BTCs in the latter part of this study. The saturated hydraulic conductivity was determined by establishing a fixed a depth of water layer above the soil column, and the resulting flux was measured for each soil column. When saturating or leaching, the depth of water layer, flux of drainage, and time from each soil column were recorded. Then, Equation 1 was used to calculate the
soil column setup depicting the measurement of saturated hydraulic conductivity prior to start of treatment

saturated hydraulic conductivity:

\[ K_s = \left( \frac{Q}{A} \right) \frac{L}{(L+D)} \]  

(1)

where \( K_s \) is the saturated hydraulic conductivity (cm min\(^{-1}\)); \( Q \) is the flux of drainage (cm\(^3\) min\(^{-1}\)); \( A \) is the area of soil column (cm\(^2\)); \( L \) is the height of soil column (cm); and \( D \) is the depth of water above the soil column (cm).

The MP (low-density polyethylene, Riblon, Ter Hell Plastics) was prepared in the laboratory by grating large pieces of plastic into powder and then sieving the plastic powder into powders of different particle diameters. In this experiment, the size of the MP was classified into the following particle diameters: 50% of MP with diameters between 1 mm and 250 μm, 30% of MP with diameters between 250 and 150 μm, and 20% of MP with diameters <150 μm. The concentration of the MP was 7% (w/w) with litter, and the litter was just the food source for the earthworms (Huerta Lwanga, Gertsen, et al., 2017). The entire experiment consisted of four treatments with each treatment contained eight soil columns each as replicates (Table 1). More details about experimental setup can be found in Yu et al. (2019). For the soil columns subjected to treatment EW-L and MP-EW-L (where “EW” stands for earthworms and “L” stands for litter), earthworms were included. Anecic earthworm (\( L. \) terrestris) were introduced to create burrows within the incubation period of 14 d. At the same time, dry litter was put on the soil column surface as a food source for the earthworms. In order to determine whether the earthworms have any effect on the shapes of the BTCs and the saturated water conductivity, as the control to the soil columns subjected to the EW-L treatment, all the soil columns subjected to the MP treatment were also incubated in the same environment as those subjected to the EW-L treatment for 14 d. For the purpose of investigating how the MP affect the saturated water flow and the BTCs, the soil columns subjected to the EW-L treatment served as a control to the soil columns subjected to the MP-EW-L treatment. In order to describe the changes of saturated conductivity before and after leaching, the soil columns subjected to the soil only (SW) treatment were used as the control to the soil columns subjected to the other three treatments.

### Table 1

| Materials       | SW | MP | EW-L | MP-EW-L |
|-----------------|----|----|------|---------|
| Air-dry sandy soil (7.00 kg) | ✓  | ✓  | ✓    | ✓       |
| Tap water (1.00 L) | ✓  | ✓  | ✓    | ✓       |
| Microplastics (3.97 g) | ×  | ✓  | ×    | ✓       |
| Dry litter (52.98 g) | ×  | ×  | ✓    | ✓       |
| Earthworms (two adults, 7.14 ± 0.26 g) | ×  | ×  | ✓    | ✓       |

Note: SW is treatment only with soil; MP is treatment with microplastics; EW-L is treatment only with earthworms and litter; MP-EW-L contains microplastics, earthworms, and litter.

2.2 Earthworm incubation exposure

Earthworm (\( L. \) terrestris) was used in this study because it is able to create permanent vertical and open-surface burrows within a short incubation time. Furthermore, the BTC was used to investigate leaching and how burrow systems influence saturated water flow. Two clean adult earthworms of anecic species (\( L. \) terrestris) were inoculated in each replicate soil column subjected to the EW-L and MP-EW-L treatments. On the soil column surface, 52.78 g dry litter (\( P. \) nigra L.) mixed with 3.97 g MP was placed in the column subjected to the MP-EW-L treatment. For the soil column subjected to the EW-L treatment, only dry litter (52.78 g per replicate) was placed on top of the soil column. The \( P. \) nigra litter was collected from a clean open area in Wageningen, the Netherlands. Thereafter, the litter (\( P. \) nigra) was prepared in the laboratory by washing in nonchlorinated tap water and air dried at 60 °C to remove the soil particles. Then, on the first and eighth day of
incubation, tap water (20 ml) was sprayed onto the surface of each column. In order to prevent the earthworms from escaping, PVC lids with 10 holes (2 mm in diameter) covered the soil column surfaces. All the columns subjected to the MP, EW-L, and MP-EW-L treatment were placed on a wooden shelf (i.e., one column in Figure 1 in the laboratory for 14 d under controlled environmental conditions (16 ± 1 °C temperature and 40 ± 5% humidity; Huerta Lwanga, Gertsen, et al., 2017; Yu et al., 2019).

2.3 Tracer leaching experiment and relative tracer arrival times of breakthrough curves

At the end of incubation, eight 10-L Mariotte bottles were put on a wooden shelf to supply tap water to soil columns continuously. Potassium bromide solution (100 ml per replicate, 0.0167 M, EC = 2,430 μS cm⁻¹) was added to each replicate soil column before leaching starts. As a conservative tracer, Br⁻ is frequently used in the investigation of soil macroporosity and preferential flow (Masipan, Chotpantarat, & Boonkaewwan, 2016). It rarely exists in soils naturally, and the background concentration is low (Bero, Ruark, & Lowery, 2016). This is why KBr solution (100 ml per replicate, 0.0167 M, EC = 2,430 μS cm⁻¹) was used as a tracer in the present study. Monitoring the change in the concentration of tracer in the drainage water can show the progress of initial soil water replacement by leaching. For the purpose of calculating the saturated hydraulic conductivity, water flux, total time, and depth of the water layer in each soil column was recorded. During the leaching process, data were recorded regarding the EC as tracer concentration and the volume of effluent (free drainage). After the tracer concentration gradually increased to its peak and then decreased, the supply of water was then stopped when the tracer concentration reached its background value. In a few cases when the tracer concentration did not reach its background value within the laboratory operational period, the water supply was still stopped. Since the flow was saturated water flow, linear interpolation method was used to determine the missing EC data.

The application of a specific relative arrival time of the tracer mass (e.g., 5, 25, and 50%) has been proven to be a robust method to measure the strength of preferential flow in a tracer BTC (Karup et al., 2016; Koestel, Moeys, & Jarvis, 2011; Koestel et al., 2012). In order to compare the differences of shapes of BTCs between treatments in the present study, 5, 25, and 50% arrival times of the tracer mass were determined. By considering the period it takes for a specified percentage of the tracer mass to reach the bottom of the soil column, relative arrival time of the tracer mass was determined. Further details on relative tracer arrival times definition and calculation can be found in Koestel et al. (2012) and Karup et al. (2016). By fitting the travel-time probability density function (PDF) of the tracer with a Gaussian function (one peak) and Fourier function (double peak) ($R^2 > .95$), the relative 5, 25, and 50% tracer arrival time (i.e., T5%, T25%, and T50%) can be determined. Figure 2 shows an example of the cumulative distribution function (CDF) and the PDF of a BTC, and the determination of the 5, 25, and 50% relative tracer arrival times. The data are from Replicate 1, treatment MP. By fitting a Gaussian function to the data ($R^2 = .9838$, RESE = .0366), the times to recover 5, 25, and 50% of the tracer mass are determined from the fitted Gaussian function.

2.4 Determination of burrow system parameter

After the leaching experiment, each soil column was first cut into 10-cm layers. Then, each layer was cut vertically
into five to six pieces, and the soil samples and earthworm burrow samples were selected from the pieces. In the soil columns subjected to the EW-L and MP-EW-L treatments, for each 10-cm layer, earthworm burrows were separated carefully from the opened soil column. After removing the column rings, photographs of burrow formations, such as the position, diameter, and length of the burrows, in the soil columns were taken (Figure 3). The relevant earthworm burrow parameters are the number of burrows, the diameter, the total length, and the total volume of burrows per column. The number of burrows in each soil layer was counted; the length and the diameter of the burrows was measured (Figure 3). The volume of burrow was calculated based on the following equation:

\[ V = l \pi r^2 \]  

where \( V \) is the calculated volume of the burrow (cm\(^3\)); \( r \) is the measured radius of the burrow (cm); and \( l \) is the measured length of the burrow (cm). Within the earthworm burrows, more MP were detected than in the surrounding soil matrix (Huerta Lwanga, Gertsen, et al., 2017). Thus, each burrow in each 10-cm soil layer was removed in pieces and placed individually in a clean aluminum container. The dried burrow wall was collected by scaling the dry burrow soil samples after all the samples had been air dried at 60 °C for 24 h. The MP particles were collected through the floating method (Huerta Lwanga, Gertsen, et al., 2017; Zhang et al., 2017). More details about extracting MP from soil through the floating method can be found in Yu et al. (2019).

### 2.5 Data analysis

In this study, IBM SPSS Statistics version 23 was used to determine the statistically significant relationships among the soil columns subjected to different treatments. The data were examined with the Kolmogorov–Smirnov test to identify cases with normal distribution. One-way ANOVA with LSD testing (Duncan’s) was used when the data were normally distributed, and the variance of data was assumed to be equal. Otherwise, Kruskal–Wallis testing (nonparametric test) was used when the data were not normally distributed, even after log transformation. MATLAB version 2014 was used to calculate the relative 5, 25, and 50% tracer arrival times.

### 3 RESULTS

#### 3.1 Comparison of breakthrough curves and the correlations between burrow parameters and relative tracer arrival times

In order to investigate how MP and network of burrows affected saturated water flow in soil column, comparisons among soil columns subjected to MP, EW-L, and MP-EW-L treatments were made. The BTCs of each replicate soil column after subjection to the three treatments (MP, EW-L, and MP-EW-L) are displayed in Figure 4. For the soil columns subjected to the MP treatment, the BTCs of the eight replicates are symmetrical and have one peak (Figure 4a). However, the soil columns subjected to the EW-L and MP-EW-L treatments show very different BTCs from the soil column subjected to the MP treatment (Figures 4b, 4e). Figure 4c shows the BTCs for five replicates soil columns subjected to the EW-L treatment, which have two peaks. For the soil columns subjected to the EW-L treatment, all the first peaks occur around time 1.66 h, except for Replicate 8 whose first peak occurs at time 5.59 h (Figure 4c). Considering the soil columns subjected to the MP-EW-L treatment, the BTCs of the eight replicates show similar characteristics to those subjected to the EW-L treatment, such as two peaks (Replicate 1 and 2) and total breakthrough time (Figures 4d and 4e). Moreover, the total
FIGURE 4  Breakthrough curves for soil columns subjected to three different treatments; (a) breakthrough curves for soil columns subjected to microplastics (MP) treatment, (b) one-peak breakthrough curves for soil columns subjected to earthworm–litter (EW-L) treatment, (c) double-peak breakthrough curves for soil columns subjected to EW-L treatment, (d) one-peak breakthrough curves for soil columns subjected to MP-EW-L treatment, and (e) double-peak breakthrough curves for soil columns subjected to MP-EW-L treatment.
TABLE 2  Characteristics of breakthrough curves for soil columns subjected to microplastics (MP), earthworm–litter (EW-L), and MP-EW-L treatments

| Treatment     | Drainage flux (ml min⁻¹) | T5% | T25% | T50% | Total time (h) |
|---------------|---------------------------|-----|------|------|----------------|
| MP            | 13.01 ± 2.62a             | 1.59 ± 0.38b | 2.07 ± 0.37b | 2.38 ± 0.41b | 3.67 ± 0.61b   |
| EW-L          | 8.87 ± 2.60b              | 2.25 ± 0.99a | 3.62 ± 1.16a | 4.52 ± 1.21a | 7.19 ± 0.92a   |
| MP-EW-L       | 7.86 ± 1.46b              | 2.05 ± 0.77a | 3.12 ± 1.23a | 3.88 ± 1.48a | 7.04 ± 0.67a   |

Note. T5%, T25%, and T50% are the relative arrival times of 5, 25, and 50% tracer mass. The values are mean ± SD; the letters “a” and “b” indicate significance test of mean differences among three groups of soil columns. a > b (one-way ANOVA, p < .05)

leaching time or breakthrough time in the soil columns subjected to the EW-L and MP-EW-L treatments are all longer than that of columns subjected to the MP treatment.

For the purpose of finding out whether the BTCs are statistically different for the soil columns subjected to different treatments, the significant test of mean differences for the soil columns subjected to MP, MP-EW-L, and EW-L treatments have been determined (Table 2). The soil columns subjected to EW-L and MP-EW-L treatments are significantly different from that subjected to the MP treatment (Table 2). However, no significant difference was detected between treatment EW-L and MP-EW-L. Treatment MP had higher water flux and shorter tracer-experienced breakthrough time than treatments EW-L and MP-EW-L (Table 2).

In order to better determine the relationships between the burrow system and the BTCs, a correlation analysis was carried out for the soil columns subjected to the EW-L and MP-EW-L treatments. The earthworm burrows parameters (i.e., total number of burrows, total volume, total length, and diameter of burrows) were randomly distributed, and there were no significant differences between the soil columns subjected to the EW-L and MP-EW-L treatments. These results were reported in Yu et al. (2019). In this paper, we only present how the burrow parameters (i.e., total number of burrows, total volume, total length, and diameter of burrows) vary with the soil depth. The total number of burrows in the soil columns subjected to EW-L and MP-EW-L treatments decreased with increasing soil depth; not every replicate soil column had more than one burrow in the 20- to 50-cm soil layer (Figure 5a). As for the total volume of burrows in the soil columns subjected to the two treatments, they all decreased with increasing soil depth. The median of total volume of burrows in the soil column subjected to the MP-EW-L treatment was higher than that subjected to the EW-L treatment (Figure 5b). In the soil column subjected to the EW-L treatment, the burrows created by the earthworms were longer in the top soil layer (0–10 cm), whereas in the soil column subjected to the MP-EW-L treatment, the burrow system was longer in the 10- to 50-cm subsoil layer (Figure 5c). The median diameter of the burrows per 10-cm soil layer in the soil column subjected to the MP-EW-L treatment was smaller than that in columns subjected to the EW-L treatment (Figure 5d).

The results of the correlation analysis are shown in Table 3. Only the 5% relative tracer arrival time showed significant correlation with the volume of burrows when the correlation coefficient was .571 (at level p < .05, two-tailed). There were no significant correlations between the diameter of the burrows, total length of the burrows, and the 25 and 50% arrival times.

3.2 Saturated conductivity

Before leaching, the average saturated conductivity of the soil columns after subjection to the MP-EW-L treatment was significantly different from those after subjection to the SW, MP, and EW-L treatments (Table 4). After leaching, the saturated conductivity of all the soil columns after subjection to all these treatments were lower. Further, after leaching, the saturated conductivities of the soil columns after subjection to the EW-L and MP-EW-L treatments were significantly lower than that after subjection to the MP treatment. The average saturated conductivity of the soil columns after subjection to the SW treatment was significantly different from those the after subjection to the MP, EW-L, and MP-EW-L treatments and leaching. However, there were no significant differences between the average saturated conductivity of the soil columns after subjection to the SW treatment was significantly different from those the after subjection to the MP, EW-L, and MP-EW-L treatments and leaching. The standard deviation and standard error of the soil columns after subjection to the MP-EW-L treatment were smallest.

4 DISCUSSION

4.1 Relationships between burrow system and breakthrough curves

In the present study, BTCs of the soil columns after subjection to the EW-L and MP-EW-L treatments were
TABLE 3  Correlation analysis between parameters from earthworm burrows and breakthrough curves for the soil columns after subjected to earthworm–litter (EW-L) and microplastics (MP)-EW-L treatments

| Parameter | T5% | T25% | T50% | Total volume | Total length | Diameter | Total time |
|-----------|-----|------|------|--------------|-------------|----------|-----------|
| T5%       | 1   | .812*** | .765** | .571* | .460 | .919 | .703*** |
| T25%      | 1   | .974*** | .423 | .219 | .183 | .735** |
| T50%      | 1   | .482 | .260 | .246 | .674** |
| Total volume | 1 | .701** | .650** | .335 |
| Total length | 1 | .049 | .253 |
| Diameter | 1 | .066 |
| Total time | 1 |

Note. T5%, T25%, and T50% are the relative arrival times of 5, 25, and 50% tracer mass.
*Significant at the .05 probability level. **Significant at the .01 probability level.

TABLE 4  Saturated conductivity in the soil columns subjected to soil only (SW), microplastics (MP), earthworm–litter (EW-L), and MP-EW-L treatments

| Treatment period | Treatment | N | Mean conductivity | SD | SE |
|------------------|-----------|---|-------------------|----|----|
|                  |           |   | cm min⁻¹            |    |    |
| Before leaching  | SW        | 8 | 0.1638a           | 0.0594 | 0.0107 |
|                  | MP        | 8 | 0.1769a           | 0.0548 | 0.0194 |
|                  | EW-L      | 8 | 0.1363ab          | 0.0301 | 0.0106 |
|                  | MP-EW-L   | 8 | 0.1055b           | 0.0177 | 0.0062 |
| After leaching   | MP        | 8 | 0.1038b           | 0.0198 | 0.0070 |
|                  | EW-L      | 8 | 0.0712c           | 0.0205 | 0.0072 |
|                  | MP-EW-L   | 8 | 0.0642c           | 0.0125 | 0.0044 |

Note. The letters (a, b, and c) indicate significance test of mean difference among the four groups of columns. a > b > c (one-way ANOVA, p < .05).

significantly different from that after subjection to the MP treatment. In other words, the redistributed MP in subsoil did not show any influence on tracer breakthrough, and the key factor affecting saturated water flow was the biopores formed by the earthworms. This finding is consistent with an earlier study (de Souza Machado, Lau et al., 2018) that showed that low-density polyethylene (LDPE) MP did not significantly or demonstrably influence the soil water capacity. For the soil columns subjected to the EW-L and MP-EW-L treatments, some BTCs show double peaks. This is an indication that the water infiltration rates in two flow domains (soil matrix and macropores) are different. Considering the differences in BTCs from MP subjected to the MP, EW-L, and MP-EW-L treatments, causes of this phenomenon can be explained as follows.

For flow in a soil matrix, the processes of convection, dispersion, and diffusion can produce the BTC as shown in Figures 6a and 6c. Flow through the biopores (e.g., earthworm burrows) can produce BTCs with more variations, depending on the distribution of earthworm burrows (continuity, tortuosity, and connectivity) and how much tracer ends up in the burrows or in the matrix flow, as shown in Figures 6b and 6e. This may indeed lead to BTCs with two distinct peaks. The different timings of the two peaks may be attributed to the fact that not all of the earthworm macropores are efficient downward flowpaths (Capowiez et al., 2014). This can be due to their placement in the soil column, or because some of the burrows are refilled when earthworms move through the soil. Figure 6d shows a BTC with an early peak and a long tail. This can be attributed to the water flow rate in the preferential paths being rapid and much higher than that in the soil matrix.

Based on the correlation analysis results between the burrow parameters and the specific tracer arrival times, the total volume of burrows can be a good indicator of 5% relative arrival time of tracer mass in a soil column after subjection to the EW-L and MP-EW-L treatments. In brief, biogenic activities affected the shape of a BTC significantly. On the other hand, low concentration of MP applied on soil surface mixed with litter did not affect flow through macropores in soil.

4.2 Influence of burrow system on saturated conductivity

For the soil columns subjected to the EW-L and MP-EW-L treatments, the saturated conductivity is significantly
FIGURE 5 Distribution of burrow parameters for soil columns subjected to earthworm–litter (EW-L) and microplastics (MP)-EW-L treatments: (a) median number of burrows in the 10-cm soil layer (Replicate = 8) in treatments EW-L and MP-EW-L (the bars indicate median absolute deviation), (b) median of total burrow volume in the 10-cm soil layer (Replicate = 8), (c) median of total burrow length in the 10-cm soil layer (Replicate = 8), and (d) median of burrow diameter in the 10-cm soil layer (Replicate = 8)

lower than in columns subjected to the MP treatment. However, there are no significant differences in the saturated conductivity for the soil columns subjected to the EW-L and MP-EW-L treatments. This is an indication that MP at 7% (w/w) concentration used in the present study did not have a significant effect on the saturated hydraulic conductivity of the soil, especially when earthworm activities are a key factor. Although the earthworm activities provided preferential pathways for the solutes, the saturated hydraulic conductivity is lower. This may be attributed to the change in the bulk density of the burrow walls due to the tunnels dug by earthworms, which has been reported by Rogasik, Schrader, Onasch, Kiesel, and Gerke (2014). After using X-ray to conduct an investigation on the changes in the bulk density around the earthworm (*L. terrestris*) burrows, they concluded that the bulk density of burrow walls was >30% higher than that of the soil matrix. Thus, to a certain extent, a high bulk density of burrow walls could reduce the rate of water diffusion between the soil matrix and the burrows (Ellerbrock & Gerke, 2004; Jégou, Cluzeau, Hallaire, Balesdent, & Tréhen, 2000; Leue, Ellerbrock, & Gerke, 2010).

An additional explanation is the fact that the earthworms (*L. terrestris*) inoculated in this study belong to the anecic earthworm species that dig tunnels for permanent use deep into soil with high continuity but low connectivity (Pagenkemper et al., 2015). High continuity or lower tortuosity of burrow systems affects water infiltration rate in soil with biopores (Capowiez et al., 2014). Moreover, the diameter of critical pore is an important indicator of the macropore continuity, which affects the water flow through the connected pathways based on percolation theory (Koestel et al., 2018). Incubation time can also be a factor affecting the hydraulic conductivity in soil. In the present study, the incubation time is relatively short and not all the replicate soil columns subjected to the EW-L and MP-EW-L treatments contain burrows at the 40- to 50-cm soil layers, as shown in Yu et al. (2019), which confirms the finding of Capowiez et al. (2014) that macroporosity increases with earthworm incubation time. This leads to relatively low continuity and connectivity of burrow systems. Moreover, Francis and Fraser (1998) showed that in the topsoil and subsoil, saturated hydraulic conductivity varied when the inoculation rate and earthworm species changed. Finally, as we determined the saturated conductivity of the soil columns before and after the various treatments, we found a gradual decrease in the saturated conductivity for all the soil columns (Table 4). Saturating the soil twice (saturating the soil columns before incubation, and leaching the soil columns after incubation) could have led to the soil being settled more, which could have caused collapse of earthworm burrow from soil columns subjected to EW-L and MP-EW-L treatments.
latter was indeed observed in the subsequent slicing of the soil column.

5 | SUMMARY AND CONCLUSIONS

The present study investigated how the MP and biopores (earthworm burrows) affect BTCs and saturated conductivity. The results show that low concentration of MP does not have a significant effect on the water flow through macropores in soil columns, and the 5% relative arrival time of the tracer mass has a positive correlation with the total volume of burrows. On the other hand, low concentration of MP does not show clear effects on soil saturated conductivity, since earthworm activities are key factors. Microplastics, as a new pollutant, are widely found in terrestrial environments. Soil biotas are reported to increase the risk of leaching caused by MP, but the role of MP as a pollutant in terrestrial system is still unclear due to some technical limitations. To what extent do MP in soil matrix affect soil physical, chemical, and hydraulic properties of soil and the biota habitat, and the mechanisms behind these phenomena, still require further study. It is also necessary to find out the details of burrow formation and the main factors that affect the water flow and saturated conductivity when water flows through the macropores. This knowledge will help to prevent water loss and groundwater pollution especially when they are caused by MP particles accumulated in deep soil layers. Future works can be developed based on the results of the present study. For instance, CT is a recommended technique that can achieve three-dimensional visualization of macropores, changes in the bulk density around macropores, and water flow through macropores.

ACKNOWLEDGMENTS

This manuscript was edited by Mogo Editing. We thank Hennie Gertsen, Piet Peters, Harm Gooren, and Tamás Salánki for their technical support. This study was financially supported by the EU Horizon 2020 Project (ISQAPER: 635750), the National Natural Science Foundation of China (Grant no. 51279167), the Special Fund for Agro-scientific Research in the public interest (Grant no. 201503124), and the China Scholarship Council (201606300123).

CONFLICT OF INTEREST

The authors declare no conflict of interest.
REFERENCES

Alaoui, A., & Goetz, B. (2008). Dye tracer and infiltration experiments to investigate macropore flow. Geoderma, 144, 279–286. https://doi.org/10.1016/j.geoderma.2007.11.020

Allaire, S. E., Roulier, S., & Cessna, A. J. (2009). Quantifying preferential flow in soils: A review of different techniques. Journal of Hydrology, 378, 179–204. https://doi.org/10.1016/j.jhydrol.2009.08.013

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

Andrady, A. L. (2017). The plastic in microplastics: A review. Marine Pollution Bulletin, 119, 12–22. https://doi.org/10.1016/j.marpolbul.2017.01.082

Aquino, T., Aubeneau, A., & Bolster, D. (2015). Peak and tail scaling of breakthrough curves in hydrologic tracer tests. Advances in Water Resources, 78, 1–8. https://doi.org/10.1016/j.advwatres.2015.01.016

Benhabib, K., Simonnot, M. O., Faure, P., & Sardin, M. (2017). Evidence of colloidal transport of PAHs during column experiments run with contaminated soil samples. Environmental Science and Pollution Research, 24, 9220–9228. https://doi.org/10.1007/s11356-017-8586-4

Bero, N. J., Ruark, M. D., & Lowery, B. (2016). Bromide and chloride tracer analysis to determine sufficiency of plot size and well depth placement to capture preferential flow and solute leaching. Geoderma, 262, 94–100. https://doi.org/10.1016/j.geoderma.2015.08.001

Bläsing, M., & Amelung, W. (2018). Plastics in soil: Analytical methods and possible sources. Science of the Total Environment, 612, 422–435. https://doi.org/10.1016/j.scitotenv.2017.08.086

Bradford, S. A., Yates, S. R., Bettahar, M., & Simunek, J. (2017). Physical factors affecting the transport and fate of colloids in saturated porous media. Water Resources Research, 38. https://doi.org/10.1029/2002wr001340

Burt, K. R., & Lowe, C. N. (2011). Controlled cultivation of endogeic and anecic earthworms. In A. Karaca (Ed.), Biology of earthworms (pp. 107–121), Berlin, Heidelberg: Springer. https://doi.org/10.1007/978-3-642-14636-7_7

Capowiez, Y., Sammartino, S., & Michel, E. (2014). Burrow systems of endogeic earthworms: Effects of earthworm abundance and consequences for soil water infiltration. Pedobiologia, 57, 303–309. https://doi.org/10.1007/s11562-014-0001-2

Chatelain, M., & Mathieu, J. (2017). How good are epigeic earthworms at dispersing? An investigation to compare epigeic to endogeic and anecic groups. Soil Biology and Biochemistry, 115, 123–128. https://doi.org/10.1016/j.soilbiobioch.2017.04.004

Crawford, C. B., & Quinn, B. (2017a). Microplastics, standardisation and spatial distribution. In Microplastic pollutants (pp. 101–130). Amsterdam: Elsevier. https://doi.org/10.1016/B978-0-12-809406-8.00005-0

Crawford, C. B., & Quinn, B. (2017b). The biological impacts and effects of contaminated microplastics. In Microplastic pollutants (pp. 159–178). Amsterdam: Elsevier. https://doi.org/10.1016/B978-0-12-809406-8.00007-4

Crawford, C. B., & Quinn, B. (2017c). The interactions of microplastics and chemical pollutants. In Microplastic pollutants (pp. 131–157). Amsterdam: Elsevier. https://doi.org/10.1016/B978-0-12-809406-8.00006-2

de Souza Machado, A. A., Klaos, W., Zarfl, C., Hempel, S., & Rillig, M. C. (2018). Microplastics as an emerging threat to terrestrial ecosystems. Global Change Biology, 24, 1405–1416. https://doi.org/10.1111/gcb.14020

Ellerbrock, R. H., & Gerke, H. I. (2004). Characterizing organic matter of soil aggregate coatings and biopores by Fourier transform infrared spectroscopy. European Journal of Soil Science, 55, 219–228. https://doi.org/10.1046/j.1365-2389.2004.00593.x

Francis, G. S., & Fraser, P. M. (1998). The effects of three earthworm species on soil macroporosity and hydraulic conductivity. Applied Soil Ecology, 10, 11–19. https://doi.org/10.1016/S0929-1393(98)00045-6

Gao, H., Yan, C., Liu, Q., Ding, W., Chen, B., & Li, Z. (2019). Effects of plastic mulching and plastic residue on agricultural production: A meta-analysis. Science of the Total Environment, 651, 484–492. https://doi.org/10.1016/j.scitotenv.2018.09.105

Geyer, R., Jambeck, J. R., & Law, K. L. (2017). Production, use, and fate of all plastics ever made. Science, 357, 1452–1457. https://doi.org/10.1126/sciadv.1700782

Hendrickx, J., & Flury, M. (2001). Uniform and preferential flow mechanisms in the vadose zone. In Conceptual models of flow and transport in the fractured vadose zone (pp. 149–187). Washington, DC: The National Academies Press.

Huerta Lwanga, E., Gertsen, H., Gooren, H., Peters, P., Salanki, T., van der Ploeg, M., ... & Geisen, V. (2017). Incorporation of microplastics from litter into burrows of Lumbricus terrestris. Environmental Pollution, 220, 523–531. https://doi.org/10.1016/j.envpol.2016.09.096

Huerta Lwanga, E., Mendoza Vega, J., Ku Quej, V., Chi, J. L. A., Sanchez Del Cid, L., Chi, C., ... & Geissen, V. (2017). Field evidence for transfer of plastic debris along a terrestrial food chain. Scientific Reports, 7. https://doi.org/10.1038/s41598-017-14588-2

Jarvis, N., Koestel, J., & Larsbo, M. (2016). Understanding preferential flow in the vadose zone: Recent advances and future prospects. Vadose Zone Journal, 15(12). https://doi.org/10.2136/vzj2016.09.0075

Jarvis, N. J. (2007). A review of non-equilibrium water flow and solute transport in soil macropores: Principles, controlling factors and consequences for water quality. European Journal of Soil Science, 58, 523–546. https://doi.org/10.1111/j.1365-2389.2007.00915.x

Jarvis, N. J., Moeyns, J., Koestel, J., & Hollis, J. M. (2012). Preferential flow in a pedological perspective. In H. Lin (Ed.), Hydropedology (pp. 75–120). Waltham, MA: Academic Press. https://doi.org/10.1016/B978-0-12-386941-8.00003-4

Jégou, D., Cluzeau, D., Hallaire, V., Balesdent, J., & Tréhen, P. (2000). Breakthrough curves in hydrologic tracer tests. In J. Tréhen (Ed.), Hydrology of soil aggregates and biopores by Fourier transform infrared spectroscopy. European Journal of Soil Science, 36, 27–34. https://doi.org/10.1016/S0011-5134(99)00045-6

Jiang, J.-Q. (2018). Occurrence of microplastics and its pollution in the environment: A review. Sustainable Production and Consumption, 13, 16–23. https://doi.org/10.1016/j.spc.2017.11.003

Karup, D., Moldrup, P., Paradello, M., Katuwal, S., Norgaard, T., Greve, M. H., & de Jonge, L. W. (2016). Water and solute transport
in agricultural soils predicted by volumetric clay and silt contents. *Journal of Contaminant Hydrology*, 192, 194–202. https://doi.org/10.1016/j.jconhyd.2016.08.001

Kavdir, Y., & Ilay, R. (2011). Earthworms and soil structure. In A. Karaca (Ed.), *Biology of earthworms* (pp. 39–50). Berlin, Heidelberg: Springer. https://doi.org/10.1007/978-3-642-14636-7_3

Keesstra, S. D., Geissen, V., Mosse, K., Piiranen, S., Scudiero, E., Leistra, M., & van Schaik, L. (2012). Soil as a filter for groundwater quality. *Current Opinion in Environmental Sustainability*, 4, 507–516. https://doi.org/10.1016/j.cosust.2012.10.007

Koestel, J., Dathe, A., Skaggs, T. H., Klakegg, O., Ahmad, M. A., Babko, M., … Jarvis, N. (2018). Estimating the permeability of naturally structured soil from percolation theory and pore space characteristics imaged by X-ray. *Water Resources Research*, 54, 9255–9263. https://doi.org/10.1002/2018WR023609

Koestel, J., & Larsbo, M. (2014). Imaging and quantification of preferential solute transport in soil macropores. *Water Resources Research*, 50, 4357–4378. https://doi.org/10.1002/2014WR015351

Koestel, J. K., Moeys, J., & Jarvis, N. J. (2011). Evaluation of nonparametric shape measures for solute breakthrough curves. *Vadose Zone Journal*, 10, 1261–1275. https://doi.org/10.2136/vzj2011.0010

Koestel, J. K., Moeys, J., & Jarvis, N. J. (2012). Meta-analysis of the effects of soil properties, site factors and experimental conditions on solute transport. *Hydrology and Earth System Sciences*, 16, 1647–1665. https://doi.org/10.5194/hess-16-1647-2012

Lamandé, M., Labouriau, R., Holmstrup, M., Torp, S. B., Greve, M. H., Heckrath, G., … Jacobsen, O. H. (2011). Density of macropores as related to soil and earthworm community parameters in cultivated grasslands. *Geoderma*, 162, 319–326. https://doi.org/10.1016/j.geoderma.2011.03.004

Lei, K., Qiao, F., Liu, Q., Wei, Z., Qi, H., Cui, S., … An, L. (2017). Microplastics releasing from personal care and cosmetic products in China. *Marine Pollution Bulletin*, 123, 122–126. https://doi.org/10.1016/j.marpolbul.2017.09.016

Leue, M., Ellerbrock, R. H., & Gerke, H. H. (2010). DRIFT mapping of organic matter composition at intact soil aggregate surfaces. *Vadose Zone Journal*, 9, 317–324. https://doi.org/10.2136/vzj2009.0101

Li, X., Chen, L., Mei, Q., Dong, B., Dai, X., Ding, G., & Zeng, E. Y. (2018). Microplastics in sewage sludge from the wastewater treatment plants in China. *Water Research*, 142, 75–85. https://doi.org/10.1016/j.watres.2018.05.034

Lots, F. A. E., Behrens, P., Vijver, M. G., Horton, A. A., & Bosker, T. (2017). A large-scale investigation of microplastic contamination: Abundance and characteristics of microplastics in European beach sediment. *Marine Pollution Bulletin*, 123, 219–226. https://doi.org/10.1016/j.marpolbul.2017.08.057

Luo, L., Lin, H., & Halleck, P. (2008). Quantifying soil structure and preferential flow in intact soil using X-ray computed tomography. *Soil Science Society of America Journal*, 72, 1058–1069. https://doi.org/10.2136/ssaaj2007.0179

Lusher, A. L., Welden, N. A., Sobral, P., & Cole, M. (2017). Sampling, isolating and identifying microplastics ingested by fish and invertebrates. *Analytical Methods*, 9, 1346–1360. https://doi.org/10.1039/c6ay02415g

Mahon, A. M., O’Connell, B., Healy, M. G., O’Connor, I., Officer, R., Nash, R., & Morrison, L. (2017). Microplastics in sewage sludge: Effects of treatment. *Environmental Science & Technology*, 51, 810–818. https://doi.org/10.1021/acs.est.6b04048

Masipan, T., Chotpanratar, S., & Boonkaewwan, S. (2016). Experimental and modelling investigations of tracer transport in variably saturated agricultural soil of Thailand: Column study. *Sustainable Environment Research*, 26, 97–101. https://doi.org/10.1016/j.serj.2016.04.005

Nizzetto, L., Butterfield, D., Futter, M., Lin, Y., Allan, I., & Larssen, T. (2016). Assessment of contaminant fate in catchments using a novel integrated hydrobiogeochemical-multimedia fate model. *Science of the Total Environment*, 544, 553–563. https://doi.org/10.1016/j.scitotenv.2015.11.087

Pagenkemper, S. K., Athmann, M., Uteau, D., Kautz, T., Peth, S., & Horn, R. (2015). The effect of earthworm activity on soil bioporosity: Investigated with X-ray computed tomography and endoscopy. *Soil and Tillage Research*, 146, 79–88. https://doi.org/10.1016/j.still.2014.05.007

Piaas, E., Meyer-Wolfarth, F., Banse, M., Bengtsson, J., Bergmann, H., Faber, J., … Taylor, A. (2019). Towards valuation of biodiversity in agricultural soils: A case for earthworms. *Ecological Economics*, 159, 291–300. https://doi.org/10.1016/j.ecolecon.2019.02.003

Rillig, M. C., Ziersch, L., & Hempel, S. (2017). Microplastic transport in soil by earthworms. *Scientific Reports*, 7. https://doi.org/10.1038/s41598-017-01594-7

Rogasik, H., Schrader, S., Onasch, I., Kiesel, J., & Gerke, H. H. (2014). Micro-scale dry bulk density variation around earthworm (*Lumbricus terrestris*) burrows based on X-ray computed tomography. *Geoderma*, 213, 471–477. https://doi.org/10.1016/j.geoderma.2013.08.034

Sammartino, S., Lissy, A.-S., Bogner, C., Bogaert, R., Capowiez, Y., Ruy, S., & Cornu, S. (2015). Identifying the functional macropore network related to preferential flow in structured soils. *Vadose Zone Journal*, 14(10). https://doi.org/10.2136/vzj2015.05.0070

Sammartino, S., Michel, E., & Capowiez, Y. (2012). A novel method to visualize and characterize preferential flow in undisturbed soil cores by using multislice helical CT. *Vadose Zone Journal*, 11(1). https://doi.org/10.2136/vzj2011.0100

Sander, T., & Gerke, H. H. (2009). Modelling field-data of preferential flow in paddy soil induced by earthworm burrows. *Journal of Contaminant Hydrology*, 104, 126–136. https://doi.org/10.1016/j.jconhyd.2008.11.003

Schneider, A.-K., Hohenbrink, T. L., Reck, A., Zangerlé, A., Schröder, B., Zehe, E., & van Schaik, L. (2018). Variability of earthworm-induced biopores and their hydrological effectiveness in space and time. *Pedobiologia*, 71, 8–19. https://doi.org/10.1007/jpedobi.2018.09.001

Siegfried, M., Koelmans, A. A., Besseling, E., & Kroeze, C. (2017). Export of microplastics from land to sea. A modelling approach. *Water Research*, 127, 249–257. https://doi.org/10.1016/j.watres.2017.10.011

Soto-Gómez, D., Pérez-Rodriguez, P., Vázquez-Juiz, L., López-Periago, J. E., & Paradela, M. (2018). Linking pore network characteristics extracted from CT images to the transport of solute and colloid tracers in soils under different tillage managements. *Soil and Tillage Research*, 177, 145–154. https://doi.org/10.1016/j.still.2017.12.007

Van Cauwenberghle, L., Devriese, L., Galgani, F., Robbens, J., & Janssens, C. R. (2015). Microplastics in sediments: A review of techniques, occurrence and effects. *Marine Environmental Research*, III, 5–17. https://doi.org/10.1016/j.marenvres.2015.06.007
van der Heijden, G., Legout, A., Pollier, B., Bréchet, C., Ranger, J., & Dambrine, E. (2013). Tracing and modeling preferential flow in a forest soil: Potential impact on nutrient leaching. Geoderma, 195–196, 12–22. https://doi.org/10.1016/j.geoderma.2012.11.004

Vos, H. M. J., Ros, M. B. H., Koopmans, G. F., & van Groenigen, J. W. (2014). Do earthworms affect phosphorus availability to grass? A pot experiment. Soil Biology and Biochemistry, 79, 34–42. https://doi.org/10.1016/j.soilbio.2014.08.018

Yu, M., van der Ploeg, M., Lwanga, E. H., Yang, X., Zhang, S., Ma, X., … Geissen, V. (2019). Leaching of microplastics by preferential flow in earthworm (Lumbricus terrestris) burrows. Environmental Chemistry, 16, 31–40. https://doi.org/10.1071/en18161

Zhang, S., Yang, X., Gertsen, H., Peters, P., Salanki, T., & Geissen, V. (2017). A simple method for the extraction and identification of light density microplastics from soil. Science of the Total Environment, 616–617, 1056–1065. https://doi.org/10.1016/j.scitotenv.2017.10.213

Zhang, Y., Zhang, M., Niu, J., & Zheng, H. (2016). The preferential flow of soil: A widespread phenomenon in pedological perspectives. Eurasian Soil Science, 49, 661–672. https://doi.org/10.1134/s1064229316060120

Zhang, Z. B., Peng, X., Zhou, H., Lin, H., & Sun, H. (2015). Characterizing preferential flow in cracked paddy soils using computed tomography and breakthrough curve. Soil and Tillage Research, 146, 53–65. https://doi.org/10.1016/j.still.2014.05.016

**How to cite this article:** Yu M, van der Ploeg M, Ma X, Ritsema CJ, Geissen V. Effects of microplastics and earthworm burrows on soil macropore water flow within a laboratory soil column setup. *Vadose Zone J*. 2020;19:e20059. https://doi.org/10.1002/vzj2.20059