


ORIGINAL ARTICLE

A new method to trace colloid transport pathways in macroporous soils using X-ray computed tomography and fluorescence macrophotography

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The fast and deep percolation of particles through soil is attributed to preferential flow pathways, and their extent can be critical in the filtering of particulate pollutants in soil. Particle deposition on the pore walls and transport between the pores and matrix modulate the preferential flow of particulate pollutants. In the present research, we developed a novel method of combining fluorescence macrophotography and X-ray computed tomography (CT) to track preferential pathways of colloidal fluorescent microspheres (MS) in breakthrough experiments. We located accumulations of MS by fluorescence imaging and used them to delimit the deposition structures along the preferential colloid pathways by superimposing these images on the 3-D pore network obtained from CT. Advection–diffusion with transport parameters from the dual-porosity equation correlated with preferential pathway features across different soil management techniques. However, management did not influence the morphology of the MS preferential pathways. Preferential flow occurred in only a small fraction of the total pore network and was controlled by pores connected to the soil surface and by matrix density.

Highlights:

- X-ray tomography and epifluorescence images were combined to identify preferential pathways in soil.
- Preferential pathways constituted approximately 1% of the soil bulk volume.
- Correlations between descriptors of preferential pathways and colloid transport were found.
- Tillage influenced the morphology of pores, but not the shape of preferential pathways.

KEYWORDS

particulate tracer, pore connectivity, pore descriptors, preferential pathways, tillage

1 | INTRODUCTION

Macropores are generally recognized to facilitate rapid long-range transport of particulate matter through the soil profile (Beven & Germann, 2013), causing agronomic, environmental, health and engineering issues. For example, deep

percolation of particulate contaminants and nutrients results in groundwater contamination and reduces crop yields (de Jonge, Kjaergaard, & Moldrup, 2004). Application of manures and urban wastes to soil can lead to contamination of groundwater with pathogenic microorganisms, which occurred in Ontario in 2000 when thousands of people

became seriously ill (Hrudey, Payment, Huck, Gillham, & Hrudey, 2003). In recent years, there has been an increase in the domestic use of engineered nanoparticles (Babakhani, Bridge, Doong, & Phenrat, 2017), which has coincided with their release into sewage (Benn, Cavanagh, Hristovski, Posner, & Westerhoff, 2010) and the environment (Hoppe et al., 2015). The presence of these harmful colloids in treated wastewater for irrigation (Russo, Alfredo, & Fisher, 2014) is a risk to human health and the environment (Molnar, Johnson, Gerhard, Willson, & O'Carroll, 2015). In environmental engineering, the performance of novel remediation techniques for soil contaminated with organic materials, metals or halogenated organic compounds using nano- and micro-particles (Mueller & Nowack, 2010) depends on accessibility to the contaminated soil sites (Pan & Xing, 2012).

The theory of colloidal transport in granular collectors is well developed (see Elimelech, Gregory, Jia, and Williams (1995) and references therein). However, transport in structured soils is still being studied. Linking the soil structure to transport is a large challenge that started three decades ago and continues because of the complex relations among spatial heterogeneity, variable chemical properties and scale (Bejat, Perfect, Quisenberry, Coyne, & Haszler, 2000). Advances in this field need to collect detailed information on the soil structure and porosity together with transport information from breakthrough experiments with dyes, unreactive tracers and microspheres. For example, the results of the experiments performed by Burkhardt, Kasteel, Vanderborght, and Vereecken (2007) and Flury and Wai (2003) are controversial: Burkhardt et al. found that transport properties depend on the pore-space geometry, whereas Flury and Wai gave more importance to the water content or the pore-water velocity. Köhne, Köhne, and Šimůnek (2009) reviewed the state of the art for modelling preferential flow and physical non-equilibrium transport under transient conditions. The above authors concluded that structure-related information, namely, macroporosity, connectivity, tortuosity and surface area of the matrix, among other descriptors, is relevant to describe colloid transport. Moreover, the spatial arrangement of the soil pores has a strong influence on the transport of solutes and colloids (Vogel, Weller, & Ippisch, 2010), as well as the fraction of macropores that transmit particles (Burkhardt et al., 2007; Passmore, Rudolph, Mesquita, Cey, & Emelko, 2010). Nielsen, Styczen, Ernstsén, Petersen, and Hansen (2011) showed that biopores promoted deep transport. Koch, Kahle, and Lennartz (2016) found that titanium (IV) oxide (TiO₂) colloids, with an average size of 0.3 μm, were transported exclusively by macropores using both root and earthworm channels. In the same research, a soluble dye tracer travelled through the matrix but reached greater depth via macropores, where the dye percolated to a depth similar to that of TiO₂. These findings support the notion that pore network connectivity and biopores should be considered to describe particle transport in structured soil.

In addition to the above, soil structure is not static; agricultural practices can dramatically modify the soil pores with further influence on transport (Bronick & Lal, 2005). Tillage breaks the aggregates and disrupts the continuity of large biopores and replaces them with cracks and repacked pores or with massive structures without macropores. In addition, soil compaction by machinery traffic and tillage instantly modify the organization of pores (Horn, 2004). However, porosity reorganizes after a few years with no-tillage or minimum tillage practices (Zurmühl & Durner, 1996).

Several techniques, such as water or air percolation and tracer leaching (Shipitalo, Dick, & Edwards, 2000), are used to study the effects of tillage on physical soil properties. However, in recent decades X-ray computed tomography (CT) techniques have been successfully applied to examine the effect of soil management on the pore architecture (Ambert-Sanchez, Mickelson, Ahmed, Gray, & Webber, 2016) and to study tracer transport in different types of soil (Paradelo et al., 2016). Descriptors of morphological, statistical and fractal properties can be studied together with other physical properties to describe soil functions (Naveed et al., 2013).

Following this approach, in a previous article (Soto-Gómez, Pérez-Rodríguez, Vázquez-Juiz, López-Periago, & Paradelo, 2018) we reported significant correlations among macroscopic descriptors of CT porosity, soil physical properties and some parameters of the advection–diffusion equation with dual porosity. These correlations suggested the importance of particle trapping on the macropore walls. Therefore, we hypothesized that information on an individual macropore basis obtained from the location of preferential pathways and deposition sites in transport experiments can provide details about colloid transport in structured soil-pore networks.

In the present research, we aimed to be more precise and to study only the pores that can transmit microspheres. Therefore, our main objective was to develop a method for the identification of preferential pathways for microsphere transport in soils with different pore networks, using macro-photography of fluorescent particles and CT. These techniques have not been combined in any previous research as far as we know. We also studied the pores connecting the top of the soil to the bottom (potential preferential pathways) and examined the effect of agricultural management on the characteristics of the particle transport pathways extracted with the method proposed.

2 | MATERIALS AND METHODS

2.1 | Soil sampling and breakthrough experiments

The general procedures for soil sampling, CT scanning and breakthrough experiments were described in Soto-Gómez et al. (2018); therefore, they are only briefly explained here.

In the present study, 16 undisturbed soil columns (100-mm height \times 84-mm diameter) were sampled from two adjacent experimental plots (Centro de Desenvolvimento Agrogaudeiro, Ourense, NW Spain, coordinates 42.099 N–7.726 W WGS84): eight columns from a plot devoted to organic agriculture with more and less earthworm activity deduced in the field from the signs of surface alteration (named Org. A and Org. B, respectively), four columns from a plot of spring cereal with no-till after sowing and with the roots of the crop preserved (Conv. NT) and four columns from a shallow-tilled plot (Conv. ST). We had two types of sampling: probability sampling performed randomly over the plots to obtain the Conv. NT, Conv. ST and Org. B samples, and non-probability sampling in the case of Org. A. In this last case, the samples were chosen deliberately in parts of the plot

where we observed more earthworm activity, to test the most favourable scenario for particle transport. Our experimental design involved pseudoreplication rather than true replication. Nevertheless, we consider that statistical analysis is justified because our three plots were large and adjacent, so they shared most of their characteristics.

The samples were taken vertically, discarding the vegetation cover (2–12-cm depth). The chemical properties of the soils from the different plots were very similar, with coefficients of variation in general less than 5%, with a pH of 5.9 (with an SE of 0.05) in a 1:10 soil:water mixture. Moreover, all soils had the same sandy loam texture.

After sampling, the columns were stored at 4°C before analysis. Samples were scanned by X-ray CT with a dental scanner, 3-D Cone-beam i-CAT (Imaging Sciences

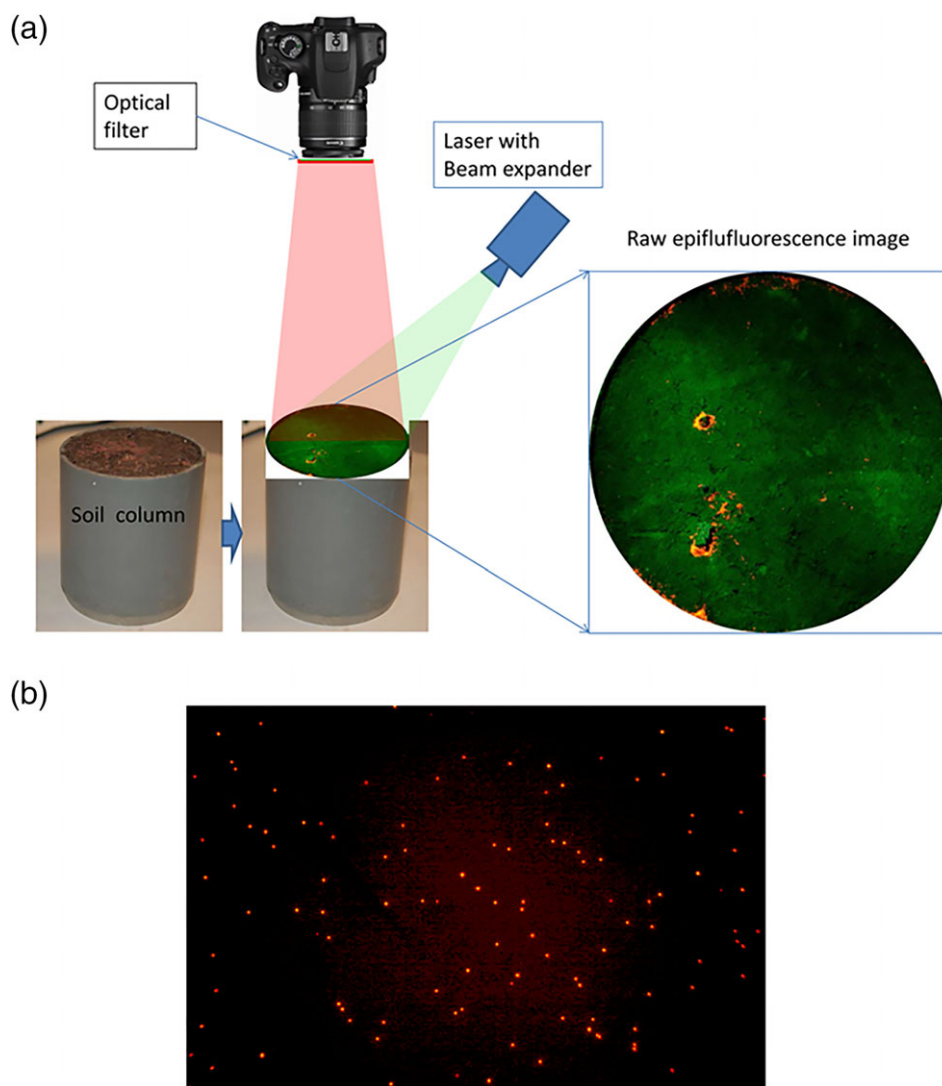


FIGURE 1 (a) Schematic diagram of the system used to make fluorescence photographs of the cross-sections of the soil column. The photographs were used to identify the deposition sites of fluorescent microspheres (MS) after the breakthrough experiments. Excitation light was a green laser module 532 nm coupled to a beam expander and a 24° diffusion angle speckle reducer. The camera objective was attached to an optical passband filter between 592 and 635 nm, 43 nm bandwidth. Accumulations of microspheres appear as orange fluorescence stains around the pore walls in the raw image. Background green colour is shown intentionally as a reference only in this photograph; this was obtained with a less selective long-pass optical filter (>590 nm) that allowed some of the laser light reflected by soil to reach the camera sensor. (b) Example of fluorescence microphotography used for quantification of MS retained in the filter (red dots)

International LLC, Hatfield, PA, USA), using 120 kV, 5 mA current and a voxel size of 0.24 mm. The software Image-J version 1.52a (Rasband, 2012) was used to analyse the raw data and extract properties such as the CT porosity (i.e., the percentage of pores larger than 0.24 mm extracted from the computed tomography images), the connectivity (calculated through the Euler characteristic) (Toriwaki & Yonekura, 2002) and the surface and volume of the pores (Soto-Gómez et al., 2018). We considered that pores below the CT resolution (240 μm) are the micro- and meso-pores that constitute the porosity of the matrix. The CT pores that connected from top to bottom through the soil column were separated using the 3-D object counter (Bolte & Cordelières, 2006). The bounding box features (smallest box encompassing the object) allowed identification and characterization of the connecting pores.

For the breakthrough experiments, red fluorescent polystyrene latex microspheres (MS) of $1 \pm 0.11 \mu\text{m}$ (Magsphere Inc., Pasadena, CA, USA) were used as

colloidal tracers. We used a suspension of 2.28×10^8 microspheres mL^{-1} in a solution of 0.025 M Br^- (KBr). The water content of columns during breakthrough was close to saturation with an effective saturation of 0.92 ± 0.03 , and the flow boundary conditions were a constant flux at the upper boundary with a flow rate of $\sim 10 \text{ mL/hr}$ (5.1 mm/hr) and a seepage face at the bottom. The flow rate was reduced in some columns (nos 9, 10, 15 and 19) to avoid surface ponding resulting from the decrease in infiltration at late stages of the breakthrough (for further information, see Soto-Gómez et al. (2018)). Water and microsphere suspensions were distributed dropwise at random points across the topsoil surface by a robotic arm attached to a dripper connected to a peristaltic pump (Minipuls III pump, Gilson Inc., Middleton, WI, USA).

Before the breakthrough experiments, drip irrigation with deionized water (DW) was applied to the columns until the flow rate at the seepage face and turbidity of the outflow were undetectable. After reaching stable conditions, a pulse

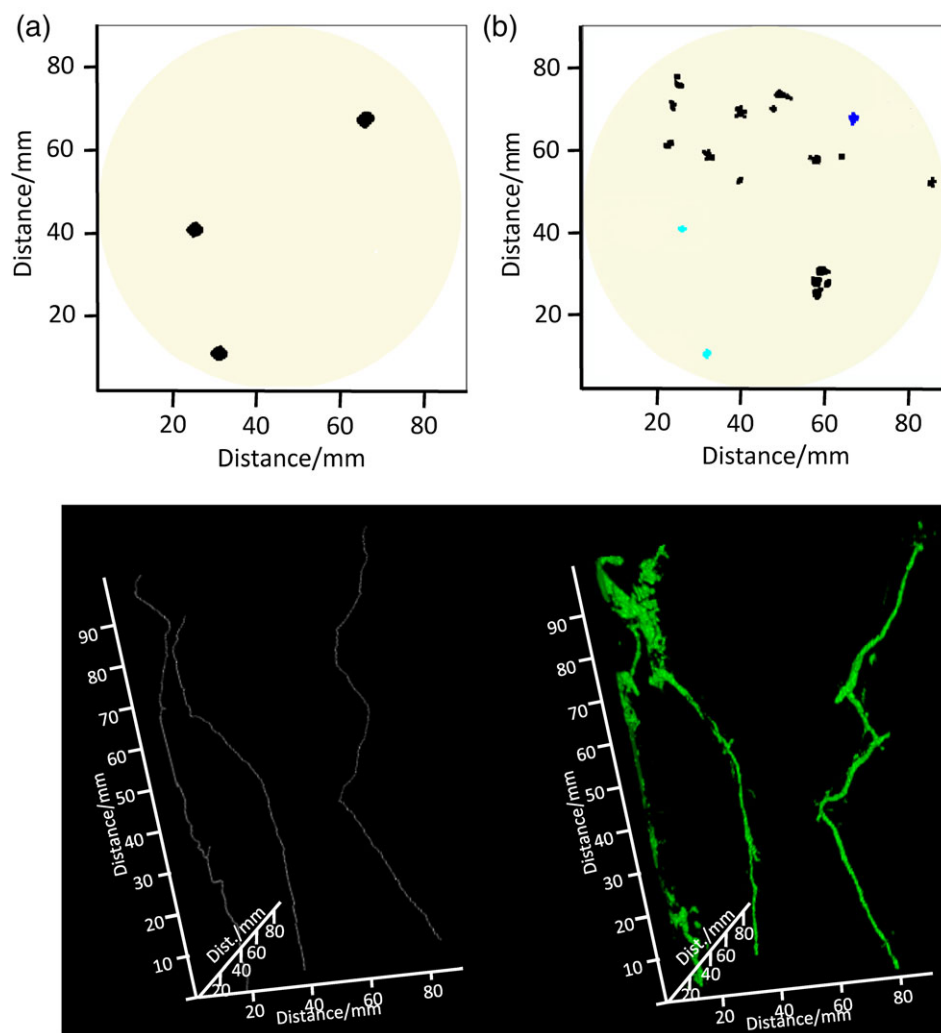


FIGURE 2 Sample images of the microspheres (MS) pathway identification procedure: (a) detail of a slice of the pathway skeleton dilated (black), (b) cross-section of combined computed tomography (CT) pores and the fluorescent paths showing the pores not used by the MS (in black), the CT pore paths used by the MS connecting from top to bottom (in light blue) and paths used by MS, but not connecting the top to the bottom (in dark blue), (c) 3-D view of the MS pathway skeleton and (d) 3-D representation of the entire volume of the MS pathways

of the MS suspension was applied ($\approx 2\text{--}3$ pore volumes, PV), followed by 10 PV of MS-free DW. The volume of effluent collected ($\approx 4\text{--}6$ mL per tube) was determined by weighing, Br^- was measured by automated colorimetry (van Staden, Mulaudzi, & Stefan, 2003) and the particle concentration was determined by fluorescence spectroscopy (Jasco Fluorescence Spectrometer, Jasco FP-750, Tsukuba, Japan). The porosity and bulk density used in the flow calculations were determined from the soil columns after drying, and after microsphere counting and pathway identification.

2.2 | Microsphere counting and pathway identification

Once the breakthrough experiments had been performed, the columns were sliced into 5-mm sections with a nylon string and a spatula. A piston jack and a precision Vernier caliper were used to extrude the soil from the PVC casing in 5-mm steps. Fluorescence macrophotographs from the upper end of each soil slice were taken in a dark room (Figure 1a). The light excitation source was a green laser module (10 mW and 532 nm; Edmund Optics Inc., stock No #84-929, Barrington, NJ, USA) coupled to a cone beam expander (Edmund Optics Inc., stock No #58-272) and a 24° diffusion angle speckle reducer (Edmund Optics Inc., stock No #88-393). Fluorescence images were taken with a digital camera (Canon EOS 400D, Tokyo, Japan) with an exposure of 5 s and a sensitivity of ISO-200. The camera objective (55 mm) was coupled to a dichroic filter passband between 592 and 635 nm with a 43-nm bandwidth (Edmund Optics Inc., serial No #67-048) (Figure 1a). Thus, the stained zones where the microspheres accumulated were identified. No microsphere counting was performed in the images because of the self-quenching effect: the tendency of the fluorescent dyes to reabsorb the emitted fluorescence when the concentration of fluorophores is large (Klaath et al., 2007). The images were taken at 16 Mpixel resolution, which allowed the detection of microsphere aggregates larger than 30 μm . The fluorescence images were segmented using the Otsu threshold (Otsu, 1979) in Image-J to obtain the proportion of stained surface in each image. The Otsu method assumes that the images have two types of pixels (black and white) and it separates them by considering the minimum intraclass variance and the maximum interclass variance.

Once the images had been taken, the slices were transported in Petri dishes to identify microsphere accumulations under a fluorescence laboratory magnifier. In each slice, the soil pore walls stained by microspheres (see Figure 1a) were collected with perforating punches and stored in centrifuge vials. The rest of the soil slice was stored separately in a bottle. The contents of the tubes and bottles were weighed. Then, the microspheres retained both in the contour of the macropores and in the soil matrix were quantified separately as follows: 10 mL (pore walls) or 20 mL (matrix) of a non-ionic surfactant solution (Tween 20 in distilled water, 0.02%) was added to their

respective vials or bottles to increase the dispersion and stability of the suspensions and to avoid aggregation of the MS. The suspensions were shaken and homogenized for 10 s by ultrasonication. Aliquots (0.5 mL each, three replicates) were immediately pipetted and diluted in appropriate volumes of 0.02% Tween 20 and filtered through nitrocellulose membranes (pore size 0.45 μm , diameter 47 mm). The particles were counted in the filter using digital images obtained with a fluorescence laboratory magnifier and a digital camera (Figure 1b). With this method, we calculated the percentages of MS retained in the matrix (% MS matrix) and in the pore walls (% MS pores) of the total MS. Image processing was performed with Image-J, using supervised thresholding to identify the microspheres and the Bone-J Particle Analyzer plugin for counting the individual microspheres (Doube et al., 2010).

A fraction of the microspheres that passed through soil pores was attached to the pore walls. This feature was used to track the MS pathways along the CT pore network. The 3-D reconstruction of the pathways from fluorescence images cannot provide the precise geometry required for

TABLE 1 Summary and description of the variables studied

Property	Description
CT porosity/%	[†] Percentage of the volume occupied by the ^a CT pores.
Connected CT porosity/%	[†] Percentage of CT pores connecting the top surface of the soil column to its bottom.
Connectivity	The number of connected structures in the pore network, determined by calculating the Euler characteristic of the CT pore skeleton.
Bulk density/g cm ⁻³	Mass of air-dried soil per unit of bulk volume.
MS and Br retained/%	[‡] Percentage mass of microspheres and bromide retained in the soil column at the end of a breakthrough experiment.
MS matrix/%	[‡] Percentage of microsphere mass retained in the soil matrix with respect to the total concentration.
MS pores/%	[‡] Percentage of microsphere mass retained in the CT pore walls with respect to the total concentration.
Average stained surface/%	Percentage of soil slice covered by fluorescent stains calculated as the average percentage of all slices per soil column.
MS paths/%	[†] Percentage of pore volume with walls coated with microspheres (see Section 2.2).
MS connected paths/%	[†] Stained pores connecting the top surface of the soil column to its bottom.
MS disconnected paths/%	[†] Stained pores not connecting the soil column from top to bottom.
MS disconnected/MS paths	Ratio of not-connecting stained CT pores to the total stained pores expressed as a volume ratio.
MS paths skeleton properties	Properties of the skeleton of the microsphere pathways, including the number of branches, junctions, tortuosity and total, average and maximum branch length.

^a CT pores are those pores bigger than 0.24 mm extracted from the computed tomography (CT) images.

[†]Volume of CT pores is related to the bulk soil volume expressed in percentage.

[‡]Percentage is related to the mass of microspheres (MS) or Br^- injected into the column during the breakthrough experiments.

further analyses. Moreover, with CT images only it is not possible to identify the actual preferential flow paths. Therefore, fluorescence stains and CT images were combined to increase the quality of the reconstructed microsphere pathways; this is a novel procedure that involves merging the stacks of binary images of macropores (from CT) and MS fluorescence stains (from macrophotographs). First, the two stacks were scaled and aligned using the reference marking notches in the column casing. We used the Simple Neurite Tracer plugin, implemented in ImageJ (Longair, Baker, & Armstrong, 2011), to trace the microsphere pathways. The tracing started by locating the centre of a fluorescent spot in the bottom image of the MS stack. Then, the same point in the CT stack (at the same depth) was selected, and the path started only if the point belonged to a macropore. The next step was to move to the slice of the MS fluorescence stack immediately above and repeat the operation. If the new microsphere spot was located in the same pore identified previously in the CT stack, the software drew the trajectory of the MS pathway by choosing the voxels with a similar shade (dark = pore) across the images in the CT stack. The process continued to the upper end of the sample until a skeleton of the MS pathways was obtained.

The Bone-J software collected information on junctions, branches and lengths (Euclidean distances and real length) of the macropore skeletons, which were stored as vectors. The vector information on the microsphere paths across the CT stack described the 'skeleton' of the colloidal transport pathways, which is the thin version of the path shape. Sequences of 3-D dilations over the skeleton (Figure 2a)

were performed and then overlapped with the binary CT images to define the shape of the conducting MS pores (% MS paths) (Figure 2b). With this technique, we calculated the proportion of connected CT pores used by the particles to travel across the column (% MS connected paths), the disconnected pores used (% MS disconnected paths) and their ratio (MS disconnected/MS Paths). Figure 2c and d show examples of the 3-D representation of the skeleton and the filled pores of the MS pathways, respectively.

2.3 | Statistical analysis

The normality of the variables was tested using the Kolmogorov–Smirnov test. Four variables had non-normal distributions: % MS paths, % MS connected paths, % MS disconnected paths and the ratio of MS disconnected/MS paths. Differences in soil characteristics regarding management were evaluated by a one-factor analysis of variance (ANOVA) (Ståhle & Wold, 1989). We checked that all residuals were normally distributed with the Kolmogorov–Smirnov test. The correlations between the variables studied were calculated by Pearson's method. The % MS path values were transformed to the natural logarithm of the value +1, and the MS disconnected/MS paths values were transformed to square roots. To simplify the interpretation the transformed values of the properties were not included in the tables, but the correlations were calculated with the transformed values where necessary. All analyses were performed using the software R (R Development Core Team, 2011).

TABLE 2 Average of the properties studied and the parameters obtained from the analysis of variance

Soil management	CT porosity/%	Connected CT porosity/%	Bulk density/g cm ⁻³	MS retained/%	Br retained/%	MS pores/%	MS matrix/%
Conv. ST	7.56	6.70	1.44	37.53	12.42	5.15	32.38
Conv. NT	4.65	4.06	1.49	40.99	14.58	5.59	36.30
Org. A	9.52	8.38	1.44	47.41	13.50	11.48	35.93
Org. B	4.34	3.31	1.47	31.47	7.45	7.71	23.76
SE	1.26	1.17	0.02	9.50	3.06	2.20	8.41
<i>F</i>	3.83	4.06	1.44	0.49	1.06	1.73	0.48
<i>p</i>	0.04	0.03	0.28	0.69	0.40	0.21	0.70
LSD	3.90	3.59	—	—	—	—	—
Soil management	Average stained surface/%	MS paths/%	MS disconnected paths/%	MS connected paths/%	MS disconnected/MS paths	MS paths: maximum branch length/mm	
Conv. ST	14.00	1.97	0.07	1.90	0.04	46.30	
Conv. NT	12.76	0.92	0.02	0.90	0.05	77.78	
Org. A	14.93	1.53	0.02	1.51	0.01	58.64	
Org. B	9.52	0.58	0.08	0.50	0.15	36.19	
SE	0.70	0.40	0.03	0.40	0.03	8.19	
<i>F</i>	11.32	2.32	0.93	2.45	2.25	4.77	
<i>p</i>	0	0.12	0.47	0.11	0.16	0.02	
LSD	2.16	—	—	—	—	25.25	

Conv. ST, conventional agriculture shallow tilled; Conv. NT, conventional agriculture with no-till after sowing; Org. A, organic agriculture with more earthworm alteration; Org. B, organic agriculture with less earthworm alteration; CT, computed tomography; MS, microspheres; SE, standard error; LSD, least significant difference (calculated for a Student's $t_p = 0.05$).

3 | RESULTS AND DISCUSSION

3.1 | Connected CT porosity

Features of the pore networks and skeletons extracted from the CT images are summarized and explained in Table 1. We considered some of these features, but we focus on the connection of CT pores and pathway properties. The values obtained for each property describing these features are given in Table 2.

Figure 3 shows representative examples of the pore network, one for each tillage treatment. We found that the total

CT porosity and the CT porosity considering only the pores connecting the top of the soil column to the bottom were strongly correlated (Pearson's $r = 0.99$). This strong correlation shows that the structure of the macropore network is arranged in such a way that it contributes mostly to the vertical connectivity along the entire column. The CT porosities showed significant differences between the tillage treatments. The number of connected pores in the Conv. ST plot (Figure 3b) were not significantly different from the other plots, but there was more intragroup variability, 6.7%

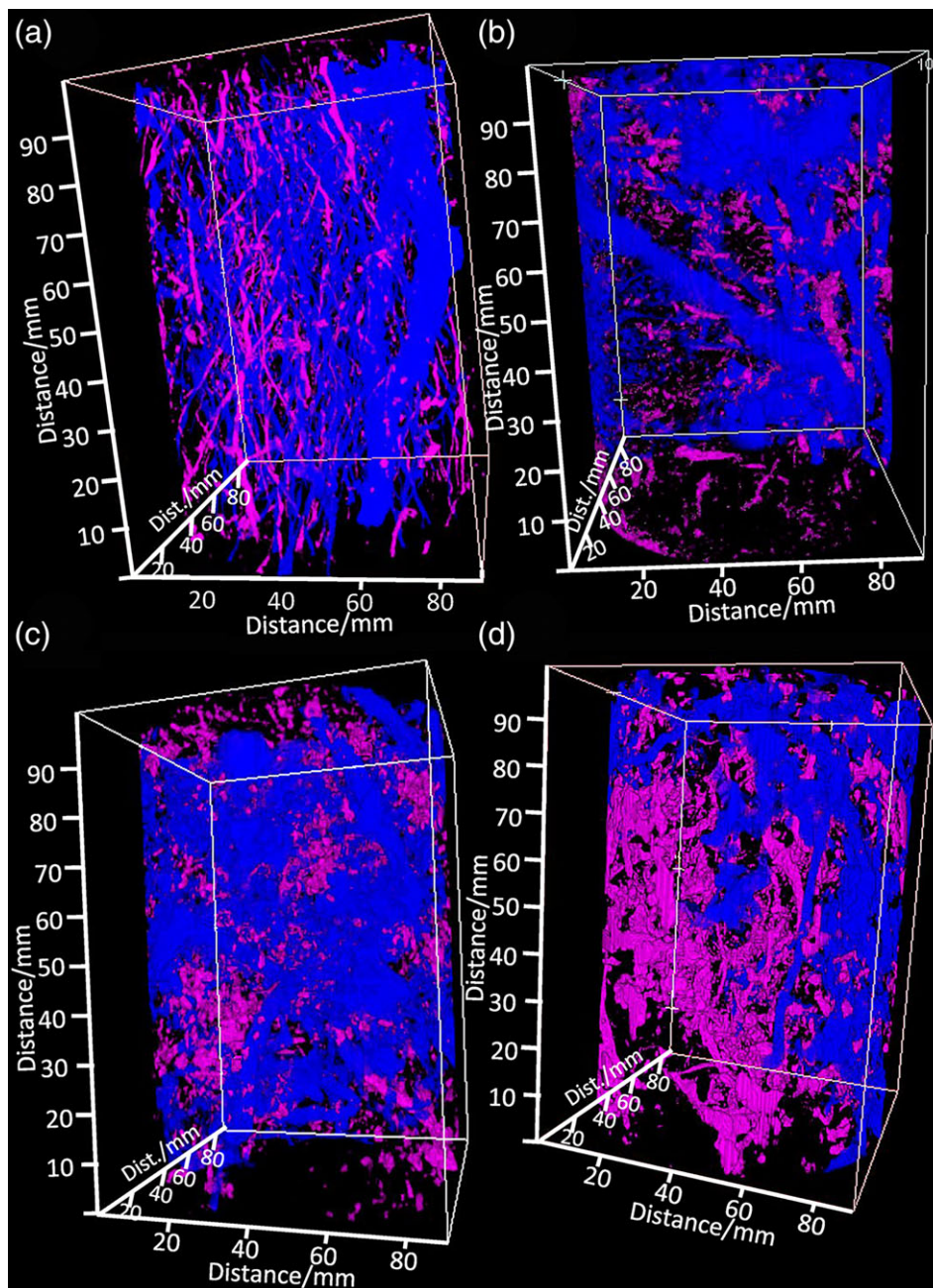


FIGURE 3 Three-dimensional representation of the computed tomography (CT) pores of four columns representing each of the four macropore structures: (a) conventional with no-till after sowing (Conv. NT), (b) conventional shallow till (Conv. ST), (c) organic agriculture with more earthworm alteration (Org. A) and (d) organic agriculture with less earthworm alteration (Org. B). The full-connecting pores from top to bottom are shown in blue and the disconnected ones in pink. The box frame in white indicates the scale in the three dimensions; perspectives were optimized for viewing so that axis lengths in the image differ from their actual sizes

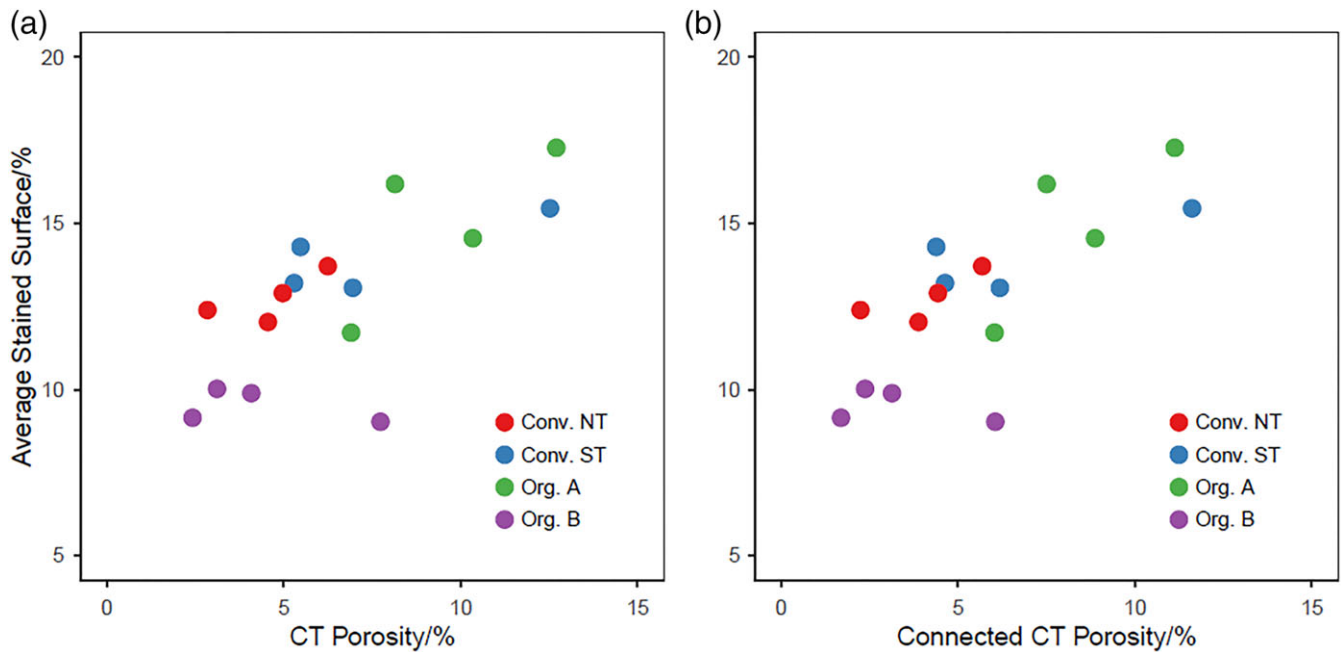


FIGURE 4 Correlation between the average of the percentage area stained by microspheres in the fluorescence macrophotographs, (a) the total computed tomography (CT)-porosity and (Pearson's $r = 0.71$) and (b) the CT porosity connected from top to bottom ($r = 0.75$) (both percentages are referred to the pore volume regarding the bulk soil volume)

TABLE 3 Summary of the correlation coefficients

	CT porosity/%	Connected CT pores/%	MS retained/%	Br retained/%	Average stained surface/%	MS paths/%	MS disconnected/MS paths
CT porosity/%	1.000						
Connected CT pores/%	0.995	1.000					
MS retained/%	n.s.	n.s.	1.000				
Br retained/%	n.s.	n.s.	<i>0.772</i>	1.000			
Average stained surface/%	<i>0.711</i>	0.748	n.s.	n.s.	1.000		
MS paths/%	0.745	0.772	n.s.	n.s.	0.599	1.000	
MS disconnected/MS paths	n.s.	-0.511	-0.525	-0.660	-0.635	n.s.	1.000

Bold face indicates correlations are significant at 0.1% level.

Italic face indicates correlations are significant at 1% level.

n.s., not significant, >0.5% level.

The MS paths/% values were transformed to the natural logarithm, and the MS disconnected/MS paths values were transformed to square roots.

CT, computed tomography; MS, microspheres.

(3.4%), and a denser zone (without CT pores) in the lower part of the core, which corresponded to the maximum depth of the shallow tillage. The Org. A plot (Figure 3c), with more earthworm activity, had a significantly larger percentage of connecting pores, 8.4% (2.2%), than the other two plots: NT, 4.1% (1.4%); Org. B, 3.3% (1.9%). The Conv. NT plot (Figure 3a) had many root pores and some isolated earthworm pores, whereas the Org. B plot had the fewest connecting paths.

Computed tomography connectivity did not show significant differences between zones but was slightly greater in the conventional plots and values were smallest in the Org. B columns. This feature was directly related to the retention of bromide ($r = 0.61$) and indicated that the number of connections increased the storage of bromide. In general, the

number of connections indicates the existence of more paths, more branches and, in the majority of cases, more dead-end properties that can enhance the exchange of solutes between the macropores and the matrix.

3.2 | Fluorescence macrophotographs

The analysis of the fluorescence macrophotographs showed no correlation between the stained area and the retention of microspheres in the column after the breakthrough experiments ($r = 0.08$). In the Org. B samples, most of the retention occurred in the pore walls (concentration was six times larger than that in the matrix); at the same time, the stained area in the matrix decreased. The average percentages of the stained areas were significantly different ($p < 0.05$) between

treatments: Org. B columns had the smallest stained area ($9.5 \pm 0.5\%$), followed by NT ($12.7 \pm 0.7\%$), ST ($14 \pm 1.1\%$) and Org. A ($14.9 \pm 2.4\%$) zones.

Figure 4a shows a strong correlation ($r = 0.71$) between the stained area and the CT porosity. It results from the penetration of microspheres in the matrix through the pore walls. Moreover, microspheres penetrate a few tenths of millimeters into the matrix surrounding the pores. This penetration has already been reported for dyes (Cey & Rudolph, 2009). The correlation improved slightly when only the proportion of CT pores connecting from the top to the bottom of the soil was considered (Figure 4b). Table 3 gives a summary of the correlation coefficients. Excluding the root pores from the above analysis decreased the correlation between CT porosity and the stained area to Pearson's $r = 0.42$. This

difference supports the interpretation that root channels contribute to the transport of microspheres and is consistent with other research that showed that roots increased dye transport with water content close to saturation (Liu, Janssen, & Lenartz, 2016).

3.3 | Microsphere pathways

Examples of the 3-D reconstruction of MS pathways that connect the tops with the bottoms of the soil columns are displayed in Figure 5a–d. It is noteworthy that the MS were encountered in both connected and disconnected pores. In the second case, the MS enter into the disconnected pores through the micro- and meso-pores of the soil matrix. The volume of stained pores represents only a small fraction of

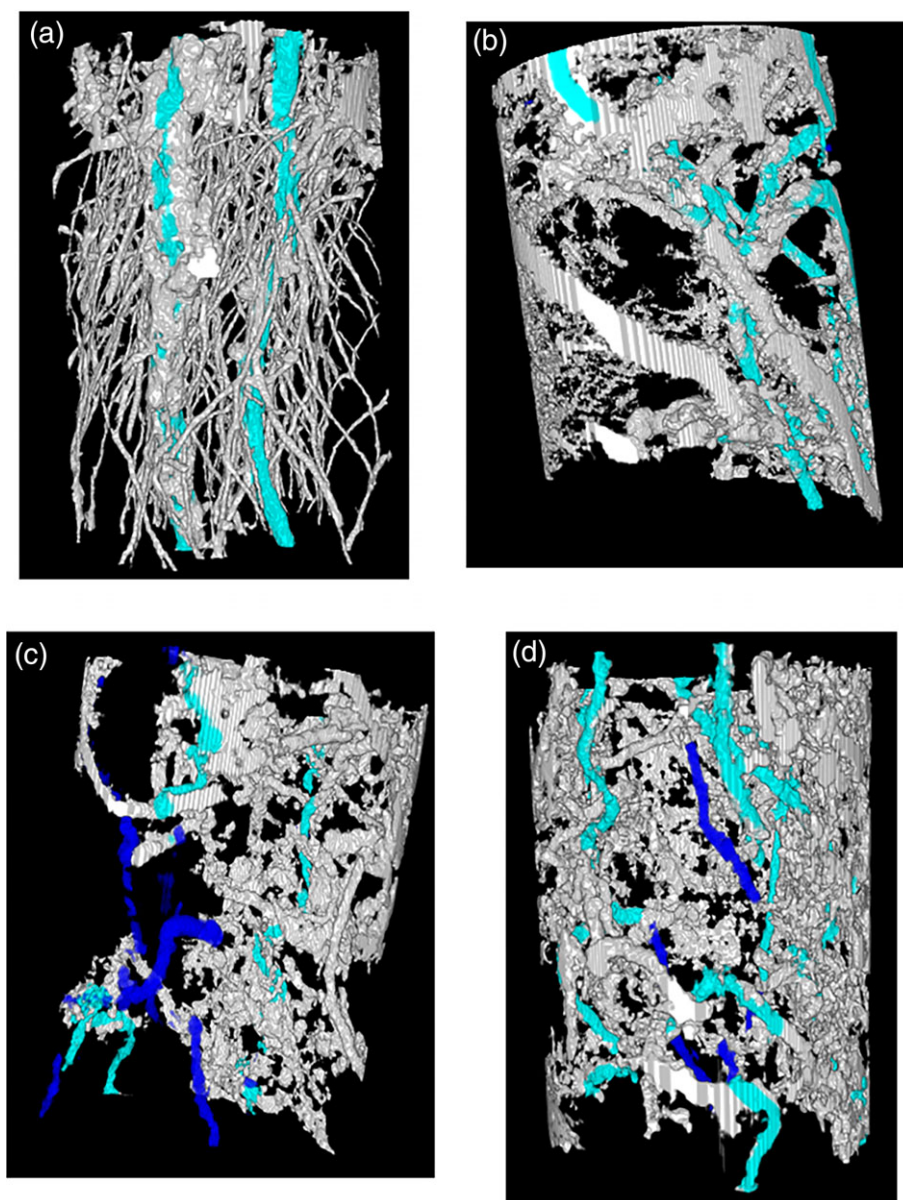


FIGURE 5 Three-dimensional representations of the colloid pathways in four soil columns: (a) Conv. NT, (b) Conv. ST, (c) Org. A and (d) Org. B. The connecting pores from top to bottom are in white (connected computed tomography (CT) pores). The microsphere (MS)-connecting paths from top to bottom are light blue and the MS paths that do not connect are in dark blue. Conv. NT, conventional with no-till after sowing; Conv. ST, conventional shallow till; Org. A, organic agriculture with more earthworm alteration; Org. B, organic agriculture with less earthworm alteration

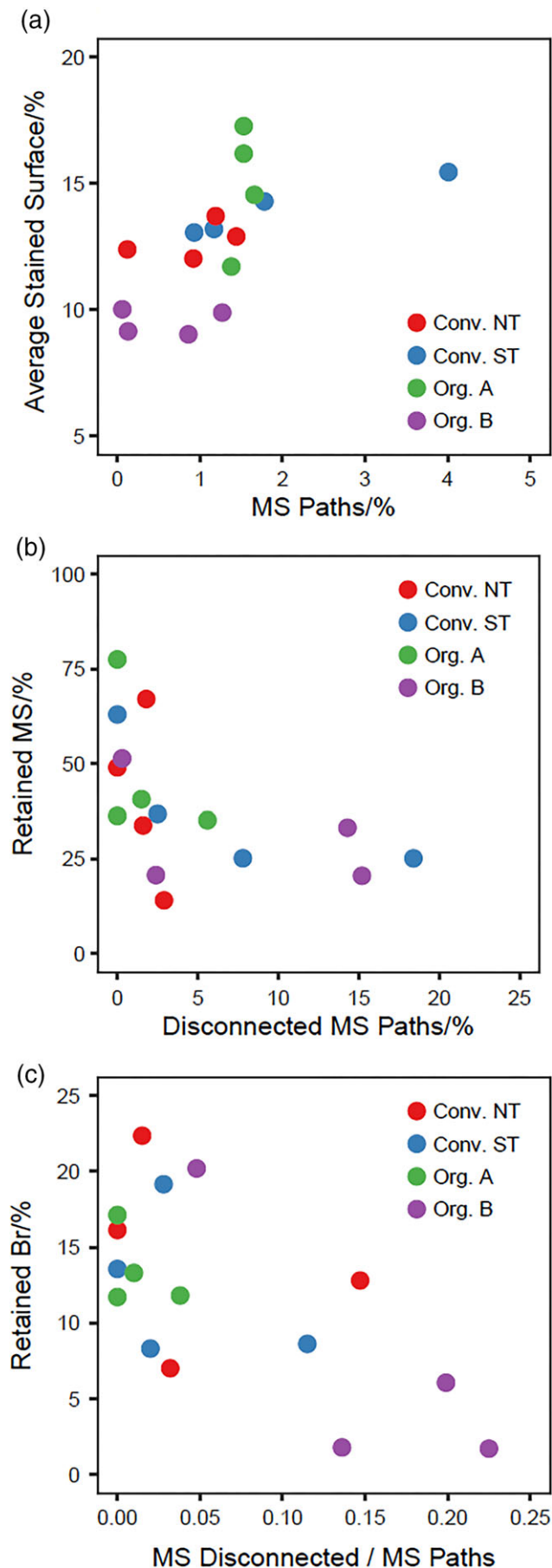


FIGURE 6 Legend on next column.

soil volume ($1.25 \pm 0.9\%$) and one-fifth of the CT-porosity volume.

For all the pathway characteristics studied (see Tables 1 and 2 for descriptions and summary), only the maximum branch length showed significant differences regarding soil management. Soils from NT plots had longer paths (77.8 ± 19.1 -mm length) because of the high density of root channels. In the Org. A soil, paths had an intermediate length (58.6 ± 12 mm), mostly consisting of earthworm burrows. However, the maximum branch lengths of MS paths were shorter in Org. B (36.2 ± 22.5 mm) and ST (46.3 ± 7.7 mm) soils because of less earthworm activity in the former and the greater disruption of paths by tillage in the latter. The other pathway descriptors and the mass balance of transport of MS did not differ between the types of soil tillage, which suggests that preferential flow occurred in macropores with similar morphology. Moreover, some of the pores that connected from top to bottom appeared to start or end in the wall of the column (between the soil and the carcass), a problem that arises from sampling in soil with a large biopore density. This effect could account for the similar mass balance between the types of soil tillage. However, the shape of MS preferential pathways and the mean surface stained were reasonably independent of that effect.

The correlation between the percentage volume of stained CT pores (% MS Paths) and the percentage of stained area in the soil slices (Figure 6a) suggests that fluorescence macrophotography provided good estimates of the CT pores acting as preferential MS pathways. Figure 6b and c show strong inverse relations between retention (MS and Br^-) and the ratio MS disconnected/MS connected described in Table 1. Figure 6b suggests that increasing the ratio of connecting pores decreased colloid retention in soil, and indicates that deposition of MS in the matrix occurred mainly in the columns with the smallest CT porosity (Org. B and Conv. ST). Conversely, in the Org. A and Conv. soils, which had the smallest matrix density, the microspheres were transported through the matrix, but in this case, deposition of MS on the disconnected macropores was less. We hypothesized that in these soils the matrix flow transporting MS did not pass through the disconnected macropores. Evidence for the transport of particles through the matrix has been reported in similar experiments in artificial soils with poorly connected macroporosity (Lehmann et al., 2018) and with repacked soils (Darnault et al., 2017). The authors of this last study noted that *Cryptosporidium parvum* oocysts (with diameters three to five times larger than the microspheres used here)

FIGURE 6 Relations between (a) percentage of pore volume forming microsphere (MS) paths and percentage of the average stained surface in fluorescence photographs ($r = 0.60$), (b) percentage of MS particles retained in the column and percentage of disconnected computed tomography (CT) pores forming MS paths ($r = 0.54$) and (c) percentage of bromide retention and proportion of disconnected MS paths (in relation to the total MS paths) ($r = 0.66$)

moved through the matrix of sandy loam soil in small numbers. Because the soil used in our study had textural and chemical properties similar to those of the above reference, the movement of smaller particles through the matrix is feasible.

4 | CONCLUSIONS

We have presented a novel method to trace the preferential transport pathways of microspheres in soils with different types of macropores that were identified by computed tomography. The soil management techniques produced CT pores with different morphologies. However, the differences were not significant when we analysed the morphologies of preferential microsphere pathways using the same descriptors; that is, these preferential pathways were independent of soil management. Earthworm pores, cracks and root pores led to different spatial distributions of particle deposition sites, but their occurrence did not influence the mass balance of microspheres. Soil bulk density and pore continuity affected the spatial distribution of microspheres trapped in the soil matrix.

The first results obtained with the method presented, based on the combination of X-ray computed tomography and fluorescence macrophotography, outline the importance of transport across macropore walls. They reinforce current knowledge about links between soil structure and colloid transport. Further development of this method will contribute to a better understanding of the transport of colloids in structured soils, and will help in several fields, such as the assessment of bacterial transport and colloidal pollution, remediation with reactive engineered particles and development of soil management strategies to control deep percolation of particulate nutrients and contaminants.

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