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# Linking pore network characteristics extracted from CT images to the transport of solute and colloid tracers in soils under different tillage managements

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## ABSTRACT

The understanding of relations between quantitative information of soil structure from X-ray computed tomography (CT) and soil functions is an important topic in agronomy and soil science. The influence of tillage on macroporosity (i.e., pores measured by CT $> 240\,\mu m$ in all directions) could be manifested in their effects on solute and colloid transport properties. Tillage will also have crucial importance on preferential flow; i.e., a direct flow through root and earthworm channels. Increasing knowledge of the relationships between soil tillage, structure, and transport contributes to a deeper insight into the key factors of soil management influencing productivity, environmental quality and crop health. The aim of this work is the identification of relationships between soil management of the pore network and the influence of the characteristics of the paths identified by CT on the transport of solute and colloidal tracers. In this work, we used CT to characterize the macropore network ( $> 0.24$ mm) of sixteen columns (100 height × 84 diameter, mm) of adjacent plots under different soil management as follows: conventional management with shallow tillage after sowing (4 samples), conventional management with no tillage after sowing (4 samples), and organic vegetables (8 samples). The soil samples were installed in columns under a dripper, and the transport behavior was examined during breakthrough of $Br^-$ and 1-μm latex microspheres in samples near saturation. Transport of $Br^-$ and latex microspheres was modeled using a two-region physical non-equilibrium model (dual porosity). Preferential flow was higher under organic management, although the pore water velocities were, in general, lower. The preferential flow of $Br^-$ was correlated with the total volume of macropores extracted from each tomography, and the local increase in the Hounsfield value (i.e., CT matrix density, $CT_{Matrix}$) surrounding the macropores. The denser lining, produced by the earthworms in the inner walls of the pores, was inversely correlated with the kinetic exchange coefficient between mobile and immobile zones of the dual-porosity model. The macropore roughness indicated by the CT-macropore surface area was correlated with the solute dispersion coefficient and with the solute travel time. Finally, we found that the overall $CT_{Matrix}$ density is inversely related to the preferential flow. The importance of this work lies in the improvement of the accuracy of predictions related to flow and transport through soils, especially those processes that include particles traveling through the soil.

## 1. Introduction

Tillage modifies the natural soil structure by changing the bulk density, the size of the aggregates, the soil penetration resistance and the water holding capacity. The objective of tillage is to eliminate weeds and mix the soil, thus temporarily increasing the oxygenation and the soil water holding capacity (Coolman and Hoyt, 1993). However, repeated tillage activities for several years have led to less aggregated and easily erodible soils (Hevia et al., 2007). No-tillage or other soil conservation methods aim to decrease the biopore disruption and to preserve the natural soil pore network.

The pore network has strong effects on the ability of soil to allow the movement of water downwards and to transport soluble and particulate substances. Furthermore, the water availability and flow are of great

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importance for the crops, i.e., in the seedling emergence, in the size and number of roots, and in the plant density (Rashidi and Keshavarzpour, 2007).

Conventional and conservation tillage may produce differences in the number, shape, size, and continuity of the soil pores. No-tillage and minimum tillage techniques allow the soil to develop a complex and well-connected pore network because they do not disrupt earthworm activity, root channels and cracks (Cannell, 1985). The macropores and cracks represent only a small percentage of the soil pores, but they have a huge influence on the transport of water, solutes and suspended colloids. These pores can be used by the water to bypass the upper layers of the soil. Moreover, colloidal particles with attached substances (facilitated transport) can travel faster through these channels, increasing the nutrient loss by leaching (de Jonge et al., 2004). Particulate organic matter, labile colloidal nutrients, viruses, bacteria, and protozoa have limited mobility through the soil matrix but can travel several meters in the soil by using preferential pathways (macropores), such as earthworm and root pores (McDowell-Boyer et al., 1986).

Usually, the role of macropores in solute and colloidal transport is studied by tracer experiments in soil columns or in the field, using soluble substances or colloids (Paradelo et al., 2013; Soto-Gómez et al., 2016), or measuring some of the macroscopic soil characteristics such as the hydraulic conductivity and the air permeability (Kjaergaard et al., 2004). However, in the last years, X-ray CT has proved to offer important information on structural parameters of the soil pore network system, such as pore topology and morphology, without altering the sample (Katuwal et al., 2015a). This method has been successfully used to study the effects of soil management (conventional tillage and no-tillage) on the soil pore structure and analyze the changes in the macroporosity with depth and pore size distributions (Pires et al., 2017). Other works used CT images to analyze the compaction consequences and their effects on the soil atmosphere and to determine the bulk density without altering the sample (Lipiec and Hatano, 2003). CT can be used for visualization and description of the root distribution (Perret et al., 2007). In this case, there are some discrepancies between this method and a destructive one; the CT underestimates the length of the roots due to the spatial resolution of the scan.

Furthermore, CT techniques have been used successfully to estimate solute transport parameters (Anderson et al., 2015, 2014). Solute breakthrough studies with a continuous CT monitoring showed that most of the solute transport occurred throughout the highly continuous biogenetic pores (Luo et al., 2008). Naveed et al. (2013) found good correlations between soil air permeability and the equivalent pore diameter divided by the tortuosity (both calculated from CT images).

In this work, we hypothesized that differences in soil structure created by different soil tillage managements, inferred from the X-ray CT derived characteristics, would influence the transport of solutes and colloids.

The objectives of the present study are as follows: (i) to characterize the structure of soil under different tillage managements and with different degrees of earthworm activity (deducted from the signs of surface alterations observed); (ii) to model the transport of $Br^-$ and fluorescence microspheres; and (iii) to relate transport characteristics to CT-derived characteristics to estimate the dynamic behavior of colloidal particles in the soil.

## 2. Material & methods

### 2.1. Soil sampling

Sixteen undisturbed columns (100 mm in height × 84 mm in diameter) were collected using PVC cases in January 2013 from two adjacent experimental parcels (Centro de Desenvolvemento Agrogandeiro, Ourense, northwestern Spain, coordinates 42.099N, −7.726W WGS84). Eight undisturbed soil columns were sampled from a plot under organic management (Org) with a long historical use devoted to root crops and vegetables, with the removal of the stubble. Two subzones with different earthworm activity were identified, namely, high (Org. A) and low (Org. B) activity (we took 4 samples of each subzone). We consider that in these two subzones, the type of pores is similar, whereas the difference lies in their number and shape. This consideration was deducted in the field from signs of surface alteration. In a conventional zone, four columns were taken from a plot devoted to spring cereal with no-till (Conv. NT) after sowing, so the roots were preserved, and the other four columns were from a plot that was shallow-tilled (Conv. ST) after sowing.

The columns were extracted vertically (2–12 cm depth). They were sealed immediately and refrigerated at 4 °C to prevent structure alteration before CT scanning and transport experiments. Chemical properties and texture were almost identical in bulk samples adjacent to each soil column with a pH, in a 1:10 soil:water ratio, of 5.9 ± 0.05. The soil texture class was sandy loam according to the USDA soil classification (Table 1).

The soil columns were mounted with a mesh in the bottom and the weight was recorded. Then, columns were slowly saturated upwards from the bottom by applying suction to the upper part of the flow cell with a peristaltic pump. Saturated water content ($\theta_s$) was calculated as the difference of weight of the saturated soil minus the weight of the dry soil. After saturation, we let the columns drain for 1 h. After that, moisture ($\theta$) was measured as above. Since we tried to perform the transport experiments close to saturation (flow rate $\approx 10\,\mathrm{mL\,h^{-1}}$), we considered this value as the lower limit of the actual water content during the transport experiments (Table 2).

### 2.2. Macropore characterization with CT

The CT images were acquired with a dental 3D Cone-beam i-CAT scanner (Imaging Sciences International LLC, PA, Hatfield, USA), using 120 kV, 5 mA current and a voxel size of 0.24 mm.

The raw data were processed with the free software ImageJ version 1.52a (Schindelin et al., 2012). Images were cropped to fit the soil enclosed into the column and then converted to binary values using Sauvola's auto local thresholding analysis (Sauvola and Pietikäinen, 2000) to segment the soil matrix and macropores (samples of this segmentation appear in Fig. 1). To apply this method, the following settings were used: radius of 50 pixels, parameter 1 ($k$ value) of 0.3 and parameter 2 ($r$ value) of 128 (default value). The value of each pixel was:

$$\text{Pixel} = (\text{pixel} > \text{mean} * (1 + k + (\text{standard deviation}/r - 1))) \quad (1)$$

The CT-macroporosity was defined as the soil volume fraction

**Table 1**
Soil texture results for the three plots with standard deviations.

| Management | % Coarse Sand (> 0.5 mm) | % Fine Sand (0.5 − 0.05 mm) | % Silt (0.05 − 0.002 mm) | % Clay (< 0.002 mm) | % Organic Matter |
|---|---|---|---|---|---|
| Conv. NT (n = 4) | 46.2 ± 0.5 | 26.1 ± 0.9 | 5.7 ± 2.9 | 10.9 ± 1.2 | 11.1 ± 2.6 |
| Conv. ST (n = 4) | 42.9 ± 2.4 | 28.3 ± 1.7 | 5.3 ± 4.1 | 11 ± 0.6 | 12.5 ± 4.6 |
| Org. (n = 8) | 44.5 ± 0.2 | 29 ± 0.4 | 8.1 ± 0.3 | 9.2 ± 0.7 | 8.5 ± 0.5 |