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Characterizing land use impact on multi-tracer displacement and soil structure

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SUMMARY

Leaching of solutes below the root zone has been identified as a main source of potential groundwater pollution. The occurrence of preferential flow paths in structured soils can enhance rapid leaching of solutes below the root zone. There is evidence that the actual land use can affect solute displacement by altering soil structure and the abundance of preferential flow paths. In the present study, a field experiment was conducted to assess the impacts of land use (grassland vs. no-till cropland) on profile-scale displacement of bromine (Br) and Brilliant Blue FCF. The objectives were (i) to study both solutes displacement patterns, (ii) to analyze the spatial variation and anisotropic variance structures of the solutes and controlling physical soil properties, and (iii) to analyze soil structure development as a result of the land use system and possible implications for solute displacement. Two ponding infiltration experiments with Potassiumbromide (KBr) and Brilliant Blue FCF were performed on a silt loam soil in Lexington, KY. A total of 30 mm multi-tracer solution was infiltrated on an area of 1.20 × 0.70 m. Eleven vertical profile sections (width: 1.10 m, depth: 0.80 m) were excavated in steps of 0.05 m and sampled. Dye stained areas were mapped based on digital image analysis. Small soil samples were taken for Br concentrations, soil texture, and volumetric soil water content at regular intervals along a vertical 0.10 × 0.10 m raster. Vane shear resistance was measured as a proxy for mechanical soil strength. X-ray fluorescence analysis was used to determine total Br contents and the relative SiO_2 signal intensity, the latter being used as proxy for soil particle size distribution. Although both experimental sites were under the same land use until some 10 years ago before the current land uses were established, solutes displacement differed between both land uses. The dye-stained patterns revealed a high proportion of non-equilibrium flow through vertically orientated macropores and a less permeable soil matrix at the grassland site. Continuous biological activity since transversion into grassland resulted in these macropores and the absence of any compaction in the subsoil. Large proportions of Br also infiltrated directly into the loose, densely rooted soil matrix close to the surface. Soil structure development at the no-till cropland site was mainly controlled by agricultural operations. The homogeneous Br distribution in the topsoil reflected a less dense soil matrix with a network of well-connected inter-aggregate pores. A residual plough pan restricted solute displacement to deeper soil layers or to groundwater bodies. Although ponding infiltration was applied in this study, the leaching risk for both applied solutes – Br and Brilliant Blue FCF – was rather small.

1. Introduction

1.1. Solute transport in structured soil

Transport of solutes through agriculturally used soils has received increasing attention in recent years as solute displacement below the root zone has been identified as a main source of potential groundwater pollution (Beven and Germann, 1982; Öhrström et al., 2004). Especially in structured soils, preferential flow paths and macropores can enhance rapid leaching of water and solutes below the root zone through bypassing the soil matrix under certain surface boundary conditions (Bouma and Dekker, 1978). Many experimental studies give evidence of these non-equilibrium water flow and solute transport phenomena (Gerke, 2006; Jarvis, 2007; Kodešová et al., 2011; Sander and Gerke, 2007; Wang and Zhang, 2011; Weiler and Naef, 2003). As small pores in the soil matrix are mainly predefined by soil texture, the

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occurrence and formation of structural pores are a result of complex interactions of climatic conditions – e.g., by formation of shrinking cracks – (Sander and Gerke, 2007), the activity of burrowing fauna such as earthworms (Cey and Rudolph, 2009), plant root growth and decay (Bodner et al., 2014; Nobles et al., 2010), soil type (Kodešová et al., 2011), and the actual land use (Bachmair et al., 2009). Based on these factors, Jarvis (2007) and Bormann and Klaassen (2008) stressed the need to better understand the impact of different land uses on soil structure and resulting pore geometry. As pointed out by Huisman et al. (2004), understanding land use impacts on water flow and solute transport is a prerequisite for better simulating possible impacts of land use change with respect to water resources management.

Numerous studies have investigated water flow at sites under one specific land use type (Bachmair et al., 2009). Moreover, most of the existing studies focussed on either differences in the hydraulic properties of the soil matrix or in the macropore system. For instance, Bormann and Klaassen (2008) compared physical and hydraulic soil properties under forest, grassland, and cropland. The study revealed considerable differences in bulk density, water retention, and hydraulic conductivity between the analyzed land uses. Bachmair et al. (2009) reported considerable differences in flow patterns of Brilliant Blue FCF dye under different land uses. The authors found a higher proportion of vertically oriented, continuous macropores at grassland sites compared to cropland. Schwen et al. (2012) analyzed Br^- leaching in a silt loam soil under grassland and cropland and different irrigation characteristics. They reported that solute leaching was mainly controlled by the land use with a larger Br^- displacement depth on the cropland. However, their experimental design permitted to assess the land use impact on soil structure and preferential flow pathways. Thus, there is a demand for comprehensive studies on the effects of land use on water flow and solute transport in the entire flow domain.

1.2. Tracers used to follow different flow domains

To observe flow processes of water and solutes in the field, different tracers have been used. Many studies used dyes such as Brilliant Blue FCF to study soil structure and identify preferential flow pathways (Kodešová et al., 2011; Nobles et al., 2010; Sander and Gerke, 2007; Wang and Zhang, 2011; Weiler and Naef, 2003). Brilliant Blue FCF is a food dye that is cheap, non-poisonous, and can be easily detected visually or by digital image analysis (Weiler, 2001). It is known to dissociate to a mono- or bivalent anion (depending on pH) and can also form ionic pairs with Ca^{2+} (Flury and Flühler, 1995) or adsorb to clay particles (Ketelsen and Meyer-Windel, 1999; Wang and Zhang, 2011). Thus, it has a restricted mobility in the soil pore system and can be used as proxy for the movement of larger organic molecules (e.g., pesticides) or to stain macropores and other preferential flow paths.

Contrarily, conservative inorganic tracers such as bromide (Br^-) or iodine (I^-) can be used for tracing water flow through the entire pore domain. These tracers have been mainly used to analyze solute flow and displacement processes in soil columns and at larger spatial scales (plot to field scale) (Flury and Flühler, 1995; Nobles et al., 2010; Öhrström et al., 2004; Schwen et al., 2012, 2013; Wang and Zhang, 2011). Due to its high solubility, small molecular size and low reactivity, these tracers can be used as proxy to observe the displacement of salts and nutrients (fertilizers) that are applied to agriculturally-used soils.

As outlined above, the tracers Brilliant Blue FCF and Br^- are subject to different flow mechanisms (macropore-restricted flow vs. flow across the entire flow domain). Thus, the combination of both tracers in field solute experiments would allow a comprehensive description of solute displacement processes that are subject to treatments of interest (e.g., soil management or land use). However, only few studies used tracer combinations to date (e.g., Bogner et al., 2008; Hangen et al., 2004; Nobles et al., 2010; Öhrström et al., 2004; Wang and Zhang, 2011). Nobles et al. (2010) analyzed solute leaching in caliche soils by using Br^- and Brilliant Blue FCF. They found that Br^- moved through the soil matrix in piston flow patterns, while Brilliant Blue FCF followed preferential flow paths. Moreover, Br^- was less retarded and moved to greater vertical and horizontal distances. This was also reported by Bogner et al. (2008) for a sandy loam soil. Öhrström et al. (2004) found a retardation of Brilliant Blue FCF compared to Br^- of 1.5 in a sandy loam soil. Wang and Zhang used a combination of I^- and Brilliant Blue FCF to assess the influence of the ponding head and measurement scale on heterogeneous water flow in a structured clay soil. The authors concluded that water flow as indicated by the I^- tracer contained more information on flow heterogeneity than the dye-stained macropores alone.

Another aspect that needs to be considered is the way how tracer solutions are applied to the soil. In some studies, tracers were applied by sprayers or sprinkling devices to the soil surface (e.g., Bachmair et al., 2009; Gerke and Köhne, 2004; Öhrström et al., 2004; Schwen et al., 2012; Weiler, 2001; Wendroth et al., 2011). Subsequently, the tracer was subject to irrigation treatments with different amounts or intensities to enhance infiltration into the soil. This application method simulates solute displacement as a result of natural rainfall mostly under unsaturated soil conditions. Other authors used ponding head infiltration of tracer solution within a framed area (e.g., Kodešová et al., 2011; Nobles et al., 2010; Sander and Gerke, 2007; Wang and Zhang, 2011). This application method represents rather extreme infiltration conditions. These may occur as a result of severe precipitation events that exceed the infiltration capacity of the soil. Ponding infiltration conditions can be used as a worst case scenario when leaching of nutrients or contaminants below the root zone is studied. Ponding infiltration of dye can also ensure a maximum staining degree of preferential flow paths and macropores that are open to the soil surface. The connection to the soil surface is required when dye tracers are used as a proxy to study soil structure and the macropore system (Kodešová et al., 2011). Wang and Zhang (2011) found that the distribution of small amounts of tracer solution (20–40 mm) was mainly restricted to the macropore network, while larger amounts (60–80 mm) inhibited a larger degree of matrix flow.

1.3. Detection methods for Br and major elements

The most common method to quantify total Bromine (Br) contents or Bromide (Br^-) concentrations in soil samples is by using distilled water extracts and ion chromatography. However, this method comes along with a considerable sample preparation effort. To analyze a large sample number for Br contents, new methods are required. Lu and Wu (2003) presented an in-situ method, where Br^- becomes visible in soil profile sections by a chemical reaction with silver ferrocyanide. Subsequently, the authors analyzed the profile sections by digital image analysis as applied for dye staining patterns. The method allows a detailed documentation of tracer distributions for 2-dimensional profile sections. However, the method also requires to analyze calibration samples by standard methods such as ion chromatography. Another disadvantage is that silver ferrocyanide is poisonous and its application may harm humans and the environment.

Abderrahim et al. (2011) detected total Br contents of dried soil samples by wavelength dispersive X-ray fluorescence (WD-XRF). The authors showed that the XRF method performs well for predicting Br contents that agree with Br^- concentrations in water extracts. As solid samples are analyzed directly, this method requires a reduced sample preparation effort compared to ion