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Soil properties and susceptibility to preferential solute transport in tilled topsoil at the catchment scale

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SUMMARY

Preferential water flow and solute transport can have dramatic effects on the leaching of contaminants to groundwater and surface waters (via subsurface drainage) and is therefore of major concern to policy and decision-makers in the realm of water resources management. Unfortunately, we cannot measure these processes at the landscape scales that are relevant for management (farms, catchments, regions), which implies that an approach based on pedotransfer functions is needed to support model predictions. However, the extent to which susceptibility to preferential solute transport can be predicted from proxy site and soil attributes that can be observed and mapped at the landscape scale is still largely unknown. We therefore carried out non-reactive solute breakthrough experiments on 45 topsoil columns sampled from the contrasting soil types found in a 13 km^2 agricultural catchment in Sweden. Non-parametric indicators of preferential solute transport were derived from the shapes of the solute breakthrough curves and related to soil physical and hydraulic properties measured in the same columns. The results showed that preferential transport was weakly (and negatively) correlated with the saturated macropore hydraulic conductivity. In contrast, it was much more strongly controlled by the size of the largest water-filled pore, which in turn was significantly correlated to the saturated hydraulic conductivity of the soil matrix and soil textural classes. Preferential transport was also weakly expressed in three fine-textured soils of large organic carbon content. We conclude that the spatial pattern of preferential transport across the studied catchment should show a clear deterministic component since it depended on soil properties (e.g. clay content) that are expressed relatively uniformly across larger areas of land.

1. Introduction

Water and dissolved solutes may move rapidly along certain high-conductance pathways in soils bypassing a large fraction of the porous matrix. This preferential transport can occur at the pore-scale in structural macropores (i.e. biopores, fissures and voids created by tillage implements; Jarvis, 2007) and in matrix-sized pores at the Darcy scale due to differences in hydraulic properties resulting from spatial variation in texture, bulk density or water repellency (e.g. Kung, 1990; Ritsema et al., 1993). The fact that preferential flow and transport can have dramatic effects on contaminant leaching (Jarvis, 2007) has prompted the development of many models that can deal with these processes (e.g. Šimůnek et al., 2003; Gerke, 2006). Model applications have mostly been restricted to column and small plot experiments at well-investigated sites, where input parameters can be derived by a combination of direct measurements and calibration (Köhne et al., 2009a,b; Jarvis and Larsbo, 2012). However, public authorities need models and decision-support tools that can account for the effects of macropore flow on leaching at the much larger scales (e.g. farms, catchments or even regions) that are relevant for management (Vanclooster et al., 2004). Models must then be used to make predictions without direct measurements of input parameters or site data for calibration. An important unresolved question is whether this can be done with acceptable uncertainty. Evidence from measurements of saturated hydraulic conductivity suggests that macropore networks are often highly variable and spatially uncorrelated at short distances (e.g. Lauren et al., 1988; Mallants et al., 1996). Indeed, it has been speculated as to whether macropore flow must be considered as an essentially unpredictable process (Beven, 1991).

Despite the complexity of soil pore networks, application of modern non-invasive X-ray imaging techniques (Wildenschild et al., 2002) has enabled some significant progress towards prediction of solute transport at the column scale. For example, various metrics of soil macropore geometry and topology have been compared statistically with transport characteristics measured in the same columns (e.g. Luo et al., 2010a), while pore network models re-constructed from 3D X-ray images can support direct predictions of solute transport (e.g. Köhne et al., 2011). However, from a pragmatic management point of view, the geometry and topol-

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ogy of pore networks will not be known in practice at scales larger than the column, so it is also important to know the extent to which the susceptibility of soils to a pore-scale process like macropore flow can be predicted from soil properties (e.g. texture, organic matter) and site attributes (e.g. land use and management, topography) that are measurable or observable with available technologies at the much larger scales relevant for management (fields, farms, catchments and regions). Within the framework of the emerging discipline of hydropedology (Lin et al., 2006; Pachepsky et al., 2008), some attempts have been made to develop landscape-scale vulnerability and risk assessment schemes that account for macropore flow. Quisenberry et al. (1993) were the first to propose a system to classify the potential of mapped soil types for preferential flow. However, the classification system was rather limited in scope, covering the dominant soils of South Carolina. More recently, Iversen et al. (2011) derived a groundwater vulnerability map for the whole of Denmark based on soil survey data (clay content) and pedotransfer functions for near-saturated hydraulic conductivity, assuming that the saturated macropore hydraulic conductivity is a good proxy variable for the risk of preferential solute leaching. Dadfar et al. (2010) and Allaire et al. (2011) also proposed preferential flow indicators for national-scale mapping of leaching risks in Canada. Common to these schemes is that they appear not to have been validated. McLeod et al. (2008) developed vulnerability maps for microbial leaching in New Zealand by linking the national 1:50,000 soil map to a risk classification system that considers macropore flow as the dominant transport mechanism. The system was developed from data obtained from lysimeter breakthrough experiments carried out on twelve dominant soil types in the country (e.g. McLeod et al., 2001, 2004). A conceptual model to classify the susceptibility of soil pedons to preferential transport resulting from both biopores and soil aggregation was proposed and tested by Jarvis et al. (2009) and Jarvis et al. (2012). This classification scheme was later linked to a complete parameter inference system comprising 'class' and continous pedotransfer functions for the dual-permeability model MACRO and tested against lysimeter experiments collated from the literature (Moeys et al., 2012). Studies that have demonstrated correlations between basic soil properties (texture, organic matter) and parameters of dual-porosity or dual-permeability models provide additional support for the idea that predictions of preferential flow at the landscape scale may be possible (Vervoort et al., 1999; Shaw et al., 2000; Jarvis et al., 2002; Børgesen et al., 2006; Jarvis et al., 2007; Jarvis, 2008). However, these studies were carried out on rather small datasets with limited soil diversity. Koestel et al. (2012) carried out a literature meta-analysis for a much larger dataset that suggested that clay content exerts a key control on soil susceptibility to macropore flow. They also concluded that variations in experimental conditions and cross-correlations between potential predictor variables probably obscured other more subtle effects of soil properties and site attributes on preferential transport.

Thus, although some significant progress has been made in recent years, there is clearly an urgent need for further studies to investigate the extent to which the susceptibility to macropore flow can be predicted from proxy site and soil attributes that can be observed and mapped at large scales. In particular, we know of only a few studies that have experimentally characterized preferential solute transport in soil at the field scale (e.g. Lennartz et al., 1997; Poulsen et al., 2006; Koestel et al., 2013) and none at catchment scales. We therefore measured non-reactive solute breakthrough curves on 45 topsoil columns sampled from the contrasting soil types found in a small agricultural catchment in Sweden. Non-parametric indicators of preferential solute transport are derived from the shapes of the breakthrough curves and related to soil physical and hydraulic properties measured in the same columns. We test the hypothesis that the strength of preferential solute transport in regularly-tilled soil is largely a function of soil texture and organic matter content, since these variables determine the nature of aggregation (Tisdall and Oades, 1982; Dexter, 1988; Six et al., 2004).

2. Materials and methods

2.1. Study site and basic soil properties

The study was carried out in the E21 catchment in Östergötland, east-central Sweden (58.4°N, 15.0°E), one of the nutrient and pesticide monitoring catchments run by SLU on behalf of the Swedish Environmental Protection Agency (see Fig. 1). Information on land use practices (cropping, tillage, fertilization, etc.) is gathered by annual farmer interviews. The total catchment area of 13 km^2 consists of 95% agricultural land (conventionally cultivated), with main crops of winter and spring sown cereals, rape, potatoes and peas. The soils are derived from glacial and post-glacial fluvial sediments and glacial till and have a wide range of organic matter and texture (U.S.D.A. texture classes ranging from loamy sand to clay loam).

The experimental effort required to support a rigorous geostatistical analysis of the variation in preferential solute transport at the landscape scale was beyond the resources available to this study. We therefore decided on a simpler approach. In late August 2010, 56 undisturbed soil columns (20 cm long and 20 cm in diameter) were collected from the topsoil at 14 locations (i.e. four replicate columns per location, sampled within 0.5 m of each other) using a hydraulic press mounted on the back-end of a tractor. The sites were selected to cover the variations in measured texture and organic matter content found in a previous grid survey of the catchment at 60 locations (see Fig. 1; Ghafoor et al., 2011). The median distance from one sampling location to the nearest neighbor location was 0.69 km, with minimum and maximum values of 0.19 and 1.5 km, respectively. The columns were stored at 4 °C until the experiments started. The columns were prepared by carefully removing excess soil from the bottom with a knife. A thin (<1 mm) polyamide porous cloth (pore size 50 μm) was placed at the bottom of each column to prevent the loss of large soil particles along with leachates.

Bulk soil samples were taken in the field from the walls of the holes created by the removal of each column. Total organic carbon was measured on these samples using a Leco CN 2000 (LECO Corp., St. Joseph, MI, USA). Soil texture was measured on the fine earth fraction (<2 mm) using the standard pipette method (Day, 1965) for the three USDA texture classes (% clay, silt and sand) after sieving to measure the gravel content (>2 and <20 mm).

2.2. Column breakthrough curve (BTC) experiments

The columns were placed in an irrigation chamber with hydraulic atomizing fine spray nozzles fixed at a height of 80 cm from the surface of the columns. A detailed description of the irrigation system was given by Liu et al. (2012). The irrigation system was calibrated before use to achieve an irrigation intensity of 0.5 cm h^{-1}. In the Swedish rainfall climate, this intensity has a return period of ca. 0.4, 4 and 30 years for rainfall durations of 2, 6 and 12 h respectively (Hernebring, 2006). The soil columns were first irrigated from a tank filled with tap water with an electrical conductivity (EC) of ca. 0.45 mS cm^{-1} for 2–4 days to leach excess salts and reach a constant background EC. The effluent was conducted through a small plastic vessel with a water-filled volume of approximately 25 cm^3 in which the electrical conductivity of the effluent was logged with WTW EC meters (Wissenschaftlich-Tech-