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Simulation of the redistribution and fate of contaminants from soil-injected animal slurry

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ABSTRACT

Spreading of contaminants from land-applied animal slurry may create hazard for both soil and water environments. Both the leaching and persistence of the contaminants is controlled by the redistribution of the contaminants immediately after application, while the redistribution is influenced by site conditions (here different slurry dry matter content and soil texture). HYDRUS-2D was used to simulate the redistribution of water, chloride, mineral N, *Salmonella* Typhimurium Bacteriophage 28B (phage), *Escherichia coli*, and steroid hormone estrogens near the slurry injection slit over a 50-day period after slurry injection at two field sites (Silstrup and Estrup) in Denmark to estimate the controlling transport and reaction parameters based on field measurements of the contaminants. The calibrated model was thereafter used to predict the leaching potential into the subsoil. The simulations confirmed that the higher water contents measured in the slurry application slit were due to a change in the hydraulic parameters. Chloride was redistributed considerably beyond the sampled soil profile at Estrup, but not at Silstrup, which had lower hydraulic conductivities than Estrup. Average size of the microorganisms affected their mobility; the bigger the size, the higher was the effect of the site conditions. The sorption coefficient of estrogens for slurry-amended soil was remarkably lower than that for unamended soil. The study suggests that dissolved organic carbon retained in slurry can facilitate the transport of contaminants. *E. coli*, phage, and estrogens were vulnerable to leaching from the very first precipitation event after the slurry application, whereas mineral N started to leach when NO_3-N accumulated. Model predictions suggest that there are potential risks of leaching of these contaminants from the top soil to the subsoil associated with the land-injected slurry.

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1. Introduction

The spreading of pathogens, steroid hormones, and nutrients from land-applied animal slurry is a hazard for the aquatic environment (Doltra and Munoz, 2010; Guber et al., 2005; Jenkins et al., 2009; Laegdsmand et al., 2009; Lee et al., 2007). Pathogenic contamination of ready-to-eat types of crops or drinking water can cause various diseases in humans (van Overbeek et al., 2010). Estrogenic hormones are endocrine disrupters and can affect the reproductive systems of aquatic life even at a very low concentration (1–2 ng/L) (Lahnsteiner et al., 2006). Release of nutrients from agricultural land into surface water can contribute to eutrophication and have impact on aquatic ecology. Heavy rainfall after a slurry application is the most frequent cause for the release of slurry-borne contaminants to water bodies (Jenkins et al., 2008; Kjaer et al., 2007). Pathogens from the top soil can move with both surface runoff and infiltrating water through preferential pathways, avoiding the normal filtering capacity of soils (Coffey et al., 2010; Guber et al., 2007; Jenkins et al., 2006; Lee et al., 2003). Although estrogenic hormones readily sorb to soils, they have nevertheless been found in subsurface water draining from manure-amended soils (Kjaer et al., 2007; Laegdsmand et al., 2009).

The redistribution process of contaminants depends on their chemical characteristics that can influence their leaching and persistence in soils. The redistribution and transport processes under field conditions are complex, particularly when the contaminants are reactive and degradable such as steroid hormones and pathogens. The redistribution process of water and solutes depends on the gradients of the soil water potential and solute concentrations, respectively, and attachment–detachment processes. In field conditions one frequently encounters temporal and spatial variations in water contents, flow velocities, dispersion, and dilution

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(Schijven and Šimůnek, 2002). A small change in bulk density and porosity caused by the traffic of agricultural equipment can lead to considerable differences in soil hydraulic conductivities (Coquet et al., 2005). Soil column experiments with disturbed and homogeneous soils under steady-state water flow conditions may not represent field conditions properly (Kjaer et al., 2007). Furthermore, the redistribution process for contaminants applied with liquid manure can be different than when they enter the soil environment with irrigation water (Guber et al., 2005). The immobile organic matter originating from slurry can change the hydraulic properties of the soil in and around the slits through which slurry is injected (Hoorman and Shipitalo, 2006; Petersen et al., 1996; Petersen and Andersen, 1996). Presence of slurry may also alter the sorption capacity of both organic and inorganic particles of soil with alkaline pH and high carbon and salt content (Lucas and Jones, 2009). Additionally, slurry enriched with dissolved organic carbon (DOC) can enhance DOC-mediated transport of contaminants (Stumpe and Marschner, 2007). The combined effects of the chemical, physical, and microbiological changes following slurry application on the fate of contaminants are therefore important to investigate at a slurry-injected field site.

Calibration of transport parameters through simulation of the field observation data helps to understand the effect of the properties of slurry and soil on the fate of different slurry-borne contaminants. Various models are used to simulate and assess the transport and fate of contaminants in soils. A numerical model is a tool to investigate various processes intensively and elaborately in an inexpensive way. HYDRUS (2D/3D) (Šimůnek et al., 2006) is a physically based mechanistic model that solves the Richards equation for water flow and a convection–dispersion equation for solute transport (Šimůnek et al., 2008). The model has been used during the last few years to simulate the transport of soil water (Hassan et al., 2010; Kandelous and Šimůnek, 2010; Ma et al., 2010), salts (Roberts et al., 2009), nitrates (Crevoisier et al., 2008; Doltra and Munoz, 2010; Wang et al., 2010), microorganisms (Jiang et al., 2010; Schijven and Šimůnek, 2002), and organic contaminants (Cheviron and Coquet, 2009; Pang et al., 2000) in variably-saturated soil formations in a variety of soil geometries and irrigation systems. The model was chosen, as it is capable of simulating reactive and colloidal transport in two dimensions. It was hypothesized that the parameters obtained in simulating the redistribution and transport of constituents in the slurry-injected soil would be different compared to unamended soil or those observed in laboratory because of the presence of slurry organic matter, salts and altered soil hydraulic properties. The objective of the study was (a) to investigate how effectively the redistribution process of different contaminants injected into soils with animal slurry follows the general transport theory incorporated in simulation models, (b) to compare the parameters obtained in this study with those available in literature, and (c) to understand the details of the redistribution process beyond the boundary of our field experiment.

2. Materials and methods

2.1. Field experiment

This study was conducted at two experimental sites, Silstrup (56° 56′ N, 8° 39′ E) and Estrup (55° 30′ N, 11° 45′ E), of the Danish Pesticide Leaching Assessment Program. Soil properties for both sites are given in Table 1. Different types of slurry (at Silstrup: 6.38% dry matter content, 2.8% C, 2.95 g NH_4-N/L; at Estrup: 0.8% dry matter content, 0.4% C, 2.34 g NH_4-N/L) were injected at two field sites directly into pre-ploughed soil at a 25-cm spacing with an average injection depth of 9 (Silstrup) or 10 cm (Estrup). While slurry was applied at different rates, a similar N application (125 kg N/ha) was used at both sites. All constituents used in the study were slurry-borne, except for spiked phages. In April 2009, slurry was applied during the first week, and spring barley sown in the second week, at both sites. Three slurry injection slits and five sampling positions per injection slit were randomly selected and marked with labelled flexible sticks immediately after slurry injection. Three intact soil profiles, one for each slit, with a 20 cm × 4 cm surface area, having the slurry slit in the middle and a total depth of 15 cm (Silstrup) or 17 cm (Estrup) were sampled on days 0, 1, 6, 18, and 46/49 after the application (Fig. 1). Each profile was subdivided into a top layer (a slurry injection depth) and a bottom layer (the rest of the profile depth). The top layer was again subdivided horizontally into four sections (A–D): section A (a 4 cm wide slurry slit) in the middle, and sequentially sections B (2 cm wide), C (3 cm), and D (3 cm) at both sides of section A. The bottom layer was subdivided into sections E and F. Only one side of the slurry slit is shown in Fig. 1. Samples taken from sections B at both sides of the slit were thoroughly mixed to prepare one sample. Similar mixing was done for samples from sections C, D, E, and F, assuming symmetrical distribution of all contaminants. The gravimetric soil water content in each thoroughly mixed fresh subsample was analyzed by drying (105 °C for 24 h), chloride concentrations by ion chromatography (Metrohm AG, Switzerland), NH_4-N and NO_3-N by an Auto-analyzer III Digital Colorimeter (Bran & Luebbe, Germany), viable *E. coli* by plate counting *on E. coli* Petrifilms (3 M a/s, Denmark), and phages by a double-agar layer method as described by Amin et al. (2013). Estrogens (estradiol and estrone) concentrations were determined by GC–MS/MS technique described in detail by Hansen et al. (2011). Hydrometeorological data were collected using the micrometeorological and hydrological instruments installed at both field sites. The meteorological data at two field sites during the field experiment is shown in Fig. 2.

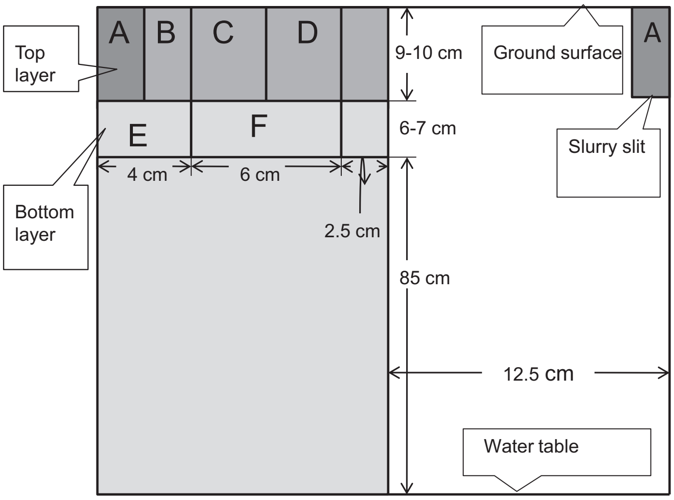

Fig. 1. Cross sectional view of the area between two neighbouring slurry slits (A). The shaded area is the modelled area and areas denoted A–F are the sampling sections.

2.2. Simulation studies

HYDRUS (2D/3D) (Šimůnek et al., 2006, 2008) was used to simulate the redistribution and persistence of slurry-borne contaminants in soils during a 50-day period following a direct injection of slurry. Only one half of the symmetrical soil profile between two adjacent slurry-injected slits (Fig. 1) was simulated to reduce calculation time. The simulated area included the entire vadose zone from the soil surface to the groundwater table situated in 1 m depth.

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