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Selective transport and retention of organic matter and bacteria shapes initial pedogenesis in artificial soil - A two-layer column study

Katharina Lehmann[a,*], Sabine Schaefer[a], Doreen Babin[b], John Maximilian Köhne[c], Steffen Schlüter[c], Kornelia Smalla[b], Hans-Jörg Vogel[c], Kai Uwe Totsche[a]

[a] *Friedrich Schiller University Jena, Institute of Geosciences, Department of Hydrogeology, Burgweg 11, D-07749 Jena, Germany*
[b] *Julius Kühn-Institut - Federal Research Centre for Cultivated Plants (JKI), Institute for Epidemiology and Pathogen Diagnostics, Messeweg 11-12, D-38104 Braunschweig, Germany*
[c] *Helmholtz Centre for Environmental Research - UFZ Halle, Department of Soil System Sciences, Theodor-Lieser-Strasse 4, D-06120 Halle, Germany*

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ABSTRACT

Organic particles including microorganisms are a significant fraction of the mobile organic matter (MOM) pool that contributes to initial pedogenesis. Still, the dynamics and the interplay of the multitude of processes that control the mobilization, transport, and retention of MOM are vastly unclear. We studied this interplay using an ‘artificial soil’ as model for a young, unstructured soil with defined initial composition employing a novel two-layer column experiment. The upstream layer was composed of a mixture of well-defined mineral phases, a sterile organic matter source and a diverse, natural microbial inoculant mimicking an organic-rich topsoil. The downstream layer, mimicking the subsoil, was composed of the mineral phases, only. Columns were run under water-unsaturated flow conditions with multiple flow interruptions to reflect natural flow regimes and to detect possible non-equilibrium processes. Pore system changes caused by flow were inspected by scanning electron microscopy and computed micro-tomography. MOM-related physicochemical effluent parameters and bacterial community diversity and abundance were assessed by molecular analysis of the effluent and the solid phase obtained after the long-term irrigation experiment (75 d). Tomographic data showed homogeneous packing of the fine-grained media (sandy loam). During flow, the initially single-grain structured artificial soil showed no connected macropores. In total, 6% of the initial top layer organic matter was mobile. The release and transport of particulate (1.2%) and dissolved organic matter (4.8%) including bacteria were controlled by non-equilibrium conditions. Bacterial cells were released and selectively transported to downstream layer resulting in a depth-dependent and selective establishment of bacterial communities in the previously sterile artificial soil. This study underlines the importance of bacterial transport from the surface or topsoil for colonization and maturation of downstream compartments. This initial colonization of pristine surfaces is the major step in forming biogeochemical interfaces - the prominent locations of intensive biological activity and element turnover that seem to play a major role for the functioning of soil.

1. Introduction

The release and transport of organic matter (OM) and its interaction with mineral surfaces may be considered as the crucial and first step for the initial colonization and maturation of subsurface environments. The association of organic substances and microorganisms with minerals control aggregate formation and stability (cf. Six et al., 2004; Young and Ritz, 2000). This results in a frequently hierarchical organized aggregate system of increasing structural and functional complexity (cf. Totsche et al., 2018), and affects structural stability, hydraulic and transport properties of soils, and the biogeochemical cycling of carbon, nitrogen (Franzluebbers, 2002; von Lützow et al., 2008), and other elements. Organic substances that reside in the fluid phases in natural porous media are referred to as mobile organic matter (MOM). MOM exhibits a wide range of sizes from nanometers to several micrometers and is composed of a vast variety of compounds, encompassing low molecular weight organic substances (Kalbitz and Knappe, 1997; Münch et al., 2002), (macro-)molecules including bio-polymers (cf.

Abbreviations: MOM, mobile organic matter; AS, artificial soil; SL, source layer; RL, reception layer; IL, interface layer; ARW, artificial rainwater

* Corresponding author.
E-mail addresses: katharina.lehmann@uni-jena.de (K. Lehmann), Sabine.Schaefer@uni-jena.de (S. Schaefer), doreen.babin@julius-kuehn.de (D. Babin), max.koehne@ufz.de (J.M. Köhne), steffen.schlueter@ufz.de (S. Schlüter), kornelia.smalla@julius-kuehn.de (K. Smalla), hans-joerg.vogel@ufz.de (H.-J. Vogel), kai.totsche@uni-jena.de (K.U. Totsche).

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Kögel-Knabner, 2002) of colloidal size (de Jonge et al., 2004; McCarthy and Zachara, 1989; Rousseau et al., 2004), bioparticles, such as microorganisms (bacteria, archaea, fungi), viruses, spores, as well as cell and tissue fragments and debris (Keller and Auset, 2007; Sen, 2011). A large amount of MOM is recycled in topsoil food webs (Kramer et al., 2012; Kramer and Gleixner, 2006). So far, only a minor portion of soil OM is regarded to be exported from the topsoil to subsoil environments (cf. Rumpel and Kögel-Knabner, 2011).

Release, transport and retention of MOM in soil are highly “complex phenomena” (Unc and Goss, 2004), due to the multitude of incompletely understood physical, chemical, and biological processes (Bradford et al., 2015). Release of MOM may be controlled by dissolution, desorption, peptization, solubilization and hydrodynamic detachment (Bradford and Torkzaban, 2008) or combinations of these. Pore size distribution, pore space geometry and hydraulic connectivity are structural controls of the transport of MOM (de Jonge et al., 2004). In mature soils, macropores favor preferential and pronounced translocation of MOM (Jacobsen et al., 1997; Kjaergaard et al., 2004; Lægdsmand et al., 1999) and microorganisms (Bundt et al., 2001; Dibbern et al., 2014). Macropores, as structural, non-capillary pores with an equivalent diameter larger than 300–500 µm (Jarvis, 2007) develop in response to shrinking/swelling cycles and bioturbation (e.g. earth worm burrows, root channels). Fresh sediments as well as very young soils that develop from sediments frequently have a single grain texture but lack a secondary pore system. Field studies in pedogenetically young environments like glacier forefields showed that the initial soil formation and microbial colonization mainly depends on bedrock mineral composition as well as structural properties that govern hydrological processes (Dümig et al., 2011). Subsequently, initial carbon input, microbial communities and plant colonization (Schulz et al., 2013) shape further soil development.

Yet, studies with the full-size spectrum and chemical variety of organic and biotic matter are lacking. Related laboratory experiments that applied water-unsaturated flow conditions either aimed at the understanding of dissolved OM-affected transport of contaminants (de Jonge et al., 2004; Totsche et al., 1997) or microbial transport (e.g. Chen, 2008). Besides, in these column experiments OM and/or microorganisms were mostly fed with the influent solution to ‘simple’ porous media (Chen, 2008; Schäfer et al., 1998) like coarse-grained quartz sand or glass beads (Brusseau et al., 1997b). In a more complex and rather pioneering approach, van Elsas et al. (1991) investigated the unsaturated movement of *Pseudomonas fluorescens* from a top layer mixture through loamy-sand-packed columns. They showed increased cell transport with decreased bulk density, higher initial soil moisture and root penetration. Huysman and Verstraete (1993) spiked the top of soil columns with a solution containing different bacterial strains. For their migration experiment, they reported a strongly reduced translocation of bacteria with increased clay content due to higher retention.

Bacterial retention seems to be the primary step in the initial colonization and biofilm formation (Hori and Matsumoto, 2010). Retention is controlled by numerous processes which include straining, various attachment mechanisms to immobile interfaces, sedimentation, mechanical filtration and capture in low- to no-flow regions (Bradford and Torkzaban, 2008; Bradford et al., 2013; Engström et al., 2015; Ginn et al., 2002). Other factors that affect the (bio)colloid and particle retention are spatiotemporal hydraulic variations (water content, flow velocity), solution chemistry (e.g. pH, ionic strength, dissolved organic carbon), as well as the surface properties and size/shape of (bio)colloids (e.g. hydrophobicity, charge), surface properties of the solid phase (e.g. composition, roughness) and pore structure (Bolster et al., 2001; Li and Logan, 2004; Bradford and Torkzaban, 2008; Bradford et al., 2013; Hori and Matsumoto, 2010). In view of this, it is not surprising that our mechanistic understanding of the interplay of processes that control the mobilization and retention of organic and biotic matter, including particularly indigenous soil microorganisms during early pedogenesis, is still in its infancy.

In our experimental-pedogenesis study, we investigated the simultaneous release, transport and redistribution of MOM including a viable natural-soil microbial community in a column experiment under water-unsaturated flow conditions. We used a novel two-layer approach and designed an ‘artificial soil’ model system of known composition. We aim for to elucidate the role of MOM, including microorganisms, for the initial colonization of pristine mineral surfaces in unconsolidated porous media. To do so, we mimic the natural situation of an organic rich, microbially active topsoil horizon (“source layer”) that rests on a pristine, unstructured subsoil-layer (“reception layer”). As ‘artificial soil’, we mixed soil minerals typical for temperate climates: quartz, illite and goethite. The top layer additionally contained a sterilized organic matter source and a microbial inoculum obtained from a Luvisol.

Our key questions are: (i) How is MOM released and translocated within the two-layer system? (ii) What are the mobile fractions of the organic matter? (iii) How does composition and relative abundance of the mobile bacterial community relate to the indigenous consortium? (iv) To what extent is MOM retained at the mineral surfaces in the downstream compartment? To answer these questions, we conducted time-resolved hydrochemical and microbiological effluent analysis and a depth-resolved sampling for solid-phase parameters at the end of the transport experiment. Computed microtomography (µCT) before and after the transport experiments was done to assess changes in the porous system due to the water flow. Batch experiments were used to assess the like liquid phase composition presumed at equilibrium, yet, at a wider solid/liquid ratio.

2. Materials and methods

2.1. Artificial soil components and percolation solution

2.1.1. Minerals

We prepared artificial soil (AS) mixtures (Table 1) in sandy loam texture (USDA soil classification). Sand-sized (Haltern H33, Quarzwerke GmbH, Frechen, Germany) and silt-sized (W11 Millisil, Quarzwerke GmbH, Frechen, Germany) quartz were mixed with illite (INTER-ILI Mérnöki Iroda Kft., Hungary) and goethite (Bayferrox 920, LANXESS GmbH, Cologne, Germany). Quartz sand (< 0.5 mm) was washed with ultrapure water (Milli-Q®) and dried before mixing. Quartz silt was wet-sieved (> 36 µm; Milli-Q®). The finest quartz fraction was removed to prevent clogging of column system components (porous plate, tubes). Illite aggregates were ground by mortar and dry-sieved to aggregate sizes between 36 and 90 µm. Goethite aggregates were dry-sieved (< 36 µm). After mixing, the initial pH (H_2O) of the homogenized mineral mixture (reception layer, see Section 2.3) was 6.5.

2.1.2. Organic matter source

Farmyard manure (FYM) was used as additional OM source as this material is one major OM source in agricultural soils. As reported by Pronk et al. (2012), manure represents already partly decomposed OM which makes it more related to soil OM than fresh plant litter. The more recent studies on OM turnover in soil point to the fact, that a large portion of the “active” OM pool derives from plant roots and microbes (debris, lysis, excretions), being rich in substances that are rather easily degradable, like low-molecular weight organic acids, sugars, polysaccharides and proteins (Kögel-Knabner, 2002; Kramer and Gleixner, 2006; Marschner and Kalbitz, 2003). Such substances are also more enriched in FYM. Based on these findings, manure seems to be a good surrogate of the active OM pool in agricultural soil and thus suited best for “experimental soil science”. The farmyard manure originates from a long-term fertilization experiment in Bad Lauchstädt, Germany (Merbach and Schulz, 2012), was used as a natural carbon and OM source. It was air-dried, sieved (< 2 mm) and autoclaved twice. Manure was homogenized and added to the mineral mixture of the top layer (source layer, see Section 2.3).

Within joint studies of the priority program SPP1315 (Totsche et al.,

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