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Impact of preferential flow on soil chemistry of a podzol

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ABSTRACT

Preferential flow paths are thought to affect the patterns of chemical properties of forest soils. However, little is known about their influence on podzols in coniferous forests. In our study we examined how soil chemical properties of a podzol in a Norway spruce stand are affected by preferential flow. We did three tracer experiments with Brilliant Blue FCF and analyzed soil chemical parameters (exchangeable cations, pH, total C, total N and C:N ratio) of preferential flow paths and soil matrix. For statistical analysis, we used mixed-effects models to account for a hierarchical sampling of our data. We found 5.0 g kg^{-1} more C, 0.24 g kg^{-1} more N, a C:N ratio larger by 2, smaller pH values (0.16 pH units), 32% more Ca and 57% more Mg in preferential flow paths than in soil matrix. Compared to the adjacent soil matrix, the content of Al did not differ significantly. However, 67% more Fe were found in preferential flow paths. These distinct chemical properties are probably due to root exudates, transport of solutes and dissolved organic carbon and percolation of acid soil solution from organic horizons along preferential paths. We attribute the increase of Ca and Mg to their transport via preferential flow paths after the application of lime some years ago. We conclude that a lower pH might enhance the release of Fe (and possibly Al) and thus increase podzolisation. In addition, our results show that soil liming could affect both the topsoil and the subsoil via transport of basic cations along preferential flow paths.

1. Introduction

Podzols are soils that develop on sandy to loamy textured materials and occur in boreal, temperate and tropic regions (Driessen et al., 2001; McKeague et al., 1983). In temperate climates podzols are found at high altitudes, in mid-mountain ranges under coniferous vegetation or in heathlands ((Sauer et al., 2007), and the references therein). Typically, four main horizons can be distinguished: "[…] *a dark-colored organic surface horizon; a bleached eluvial horizon; a reddish, brownish or black illuvial horizon enriched in amorphous materials; and a sandy C horizon*" (McKeague et al., 1983).

In a review article (Lundström et al. (2000)) summarized the basic ideas of podzolisation: *mobilization–downward transport–immobilization* of Al and Fe. They outlined that Al and Fe can be removed from the eluvation horizon E by (a) complexation by organic acids and downward transport as soluble organo-metal-complexes or by (b) silicate weathering and downward transport as inorganic colloids, wherease mechanism (a) dominates in most soils. If Al and Fe are transported downwards as organo-metal-complexes, their immobilization in the illuvial B horizon is explained either by (a) precipitation/adsorption due to an increased C to metal ratio or by (b) microbial degradation of the organic ligand (Lundström et al., 2000). Buurman and Jongmans (2005) identified discrepancies between the existing podsolisation theories and field observation concerning the nature of organic matter and proposed a modification. Indeed, the above mentioned mechanisms suggest an immobilization of organic matter (OM) together with Al and Fe. However, according to Buurman and Jongmans (2005), in well-drained podzols with an intensely rooted B horizon, the accumulation of OM is mainly due to root debris and not to illuvation.

In our study we focus on the relationship between the podzolisation process and preferential flow of water in a podzol forest soil under Norway spruce. Preferential flow describes all phenomena where water flows through localized pathways bypassing a portion of the soil matrix (Hendrickx and Flury, 2001). Main transport mechanisms of preferential flow are inhomogeneous matrix flow and macropore flow. Hendrickx and Flury (2001) explained in their work that inhomogeneous matrix flow usually occurred in coarse-textured soils induced by textural differences or water repellency, for example. According to these authors, macropore flow was typical for highly structured soils or soils containing biopores like root channels or earthworm burrows.

Several studies showed that predominant flow paths could be stable for decades. Ritsema and Dekker (2000), for instance, observed that preferential flow paths reoccurred at the same locations during successive rain events in a water repellent sandy soil. They concluded that in soils without anthropogenic disturbance (e.g. untilled agricultural or forest soils) preferential flow paths might remain stable for an unlimited period of time. These findings accord well with results by Hagedorn and Bundt (2002). They estimated an age of about 40 years for

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preferential flow paths in a forest soil by measuring the distribution of radionuclides.

Due to temporal stability and reoccurrence of preferential flow at the same location, biological and chemical conditions in preferential flow paths and soil matrix are likely to differ. Bundt et al. (2001b), for example, found higher cation exchange capacity, base saturation, organic C and organic N concentrations in preferential flow paths of a forest soil. In addition, there were indications that soil organic matter in preferential flow paths was younger and N cycling faster than in the soil matrix (Bundt et al., 2001a). This is in accordance with Hagedorn et al. (1999) who reported an increased N transformation in preferential flow paths compared with the soil matrix. These authors mentioned that along flow paths nitrate concentrations were higher, denitrification activity after rainfalls increased and net nitrification started earlier after drying and was enhanced.

Previous studies on differences between preferential flow and soil matrix focused on microbial biomass (Vinther et al., 1999), included treatments like wood ash application (Bundt et al., 2001b) or considered agricultural soil (Wuest, 2009). In contrast, the aim of this work is to determine how soil chemical properties (concentration of exchangeable cations, pH, total C, total and C:N ratio) are affected by preferential flow in a podzol under natural conditions. Podzols have been studied for many years and a vast amount of literature on their occurrence and development exist. However, to our knowledge, the abundant studies on the chemistry of podzols do not distinguish between regions of preferential flow and the soil matrix.

The present work is part of a larger study on flow processes in a forest soil. In an earlier paper Bogner et al. (2010) analyzed the main flow mechanisms at the same study site by mixed-effects modeling. We identify preferential flow paths by dye tracer application and define them as dye stained areas. We hypothesize that preferential flow paths are locations of enhanced podzolisation compared to the adjacent soil matrix.

Most studies that investigated differences between preferential flow paths and soil matrix used the paired *t*-test or its non-parametric equivalent and analyzed different depths separately (e.g. (Bundt et al., 2001b; Vinther et al., 1999)). In contrast, we propose to employ mixed-effects models to account for the hierarchical nature of sampled data and spatial heterogeneities. This method allows us to consider all plots and all depths in one single analysis and model the covariance structure of the sampled data explicitly.

2. Materials and methods

2.1. Site description

The study site Coulissenhieb II is situated in the Lehstenbach catchment in southeast Germany (50°08′N, 11°52′E, 770 m above see level). This catchment is part of the Fichtelgebirge — a mountain ridge dominated by the Norway spruce (*Picea abies L.*) with wavy hair-grass (*Deschampsia flexuosa L.*) as main understorey vegetation (Gerstberger et al., 2004). The mean annual precipitation is about 1160 mm, with a maximum in December and a second maximum in July; and the mean annual air temperature equals approximately 5°C (Foken, 2003). This region has a continental temperate climate with a maritime character because of high precipitation (Gerstberger et al., 2004).

At Coulissenhieb II the soil is classified as Haplic Podzol (IUSS Working Group WRB, 2007) with five mineral soil horizons (AE, Bsh, Bs, Bw and Bw/C) with a sandy to loamy texture and a up to 15-cm thick mor-type organic layer consisting of Oi, Oe and Oa. Fig. 1 summarizes the distribution of the soil fine fraction. The AE and the Bsh horizons are often discontinuous and have irregularly shaped boundaries (Bogner et al., 2010).

Schulze et al. (2009) reported extremely acidic pH_{CaCl_2} values ranging from 3.3 in Oa to 4.2 in the subsoil. They measured an organic C and total N contents in the Oa horizon of about 21% and 1% respectively that decreased with depth to 1% C and 0.2% N in Bw. Furthermore, according to Hentschel et al. (2007) the base saturation decreases with depth from 52% in Oa to 16% in Bw/C. They attributed this large value in the topsoil to an accidental diffuse application of dolomite ($CaMgCO_3$) between 1994 and 1999 by loss from a flying helicopter supposed to lime adjacent forest stands.

Stones play an important role at Coulissenhieb II site. Their content varies strongly within the site and with soil depth and ranges between few percent in the topsoil and up to 75% in the subsoil (Gerstberger et al., 2004). During our study at Coulissenhieb II we worked on three different experimental plots situated approximately 50 m apart that differed strongly in the content of large stones. While on plots 1 and 2 their content did not exceed 5%, a continuous layer of stones was present in the Bw (10–50%) and partly in the EA and Bsh horizons on plot 3.

2.2. Field and laboratory work

We did three tracer experiments with Brilliant Blue FCF (a sodium salt) and potassium iodide. Brilliant Blue is an organic dye that is often used for tracer studies in vadose zone hydrology (Flury et al., 1994; Forrer et al., 2000). It is well seen against most soil colors and according to Flury and Flühler (1994) its use in field studies is toxicologically acceptable. However, due to a non-linear interaction with the soil matrix, the dye might be retarded so that its patterns are different from those of infiltrating water (Kasteel et al., 2002; Ketelsen and Meyer-Windel, 1999). To assure that Brilliant Blue stained patterns were similar to infiltration patterns of water we used iodide as a reference tracer. Iodide patterns were visualized on two profiles per plot by sprinkling an iron(III) nitrate and starch solution on the soil (Lu and Wu, 2003).

The tracer solution was applied on a surface of about 2 m^2 with a rate of 64 mm h^{-1} using an automated sprinkler (e.g. (Ghodrati et al.,

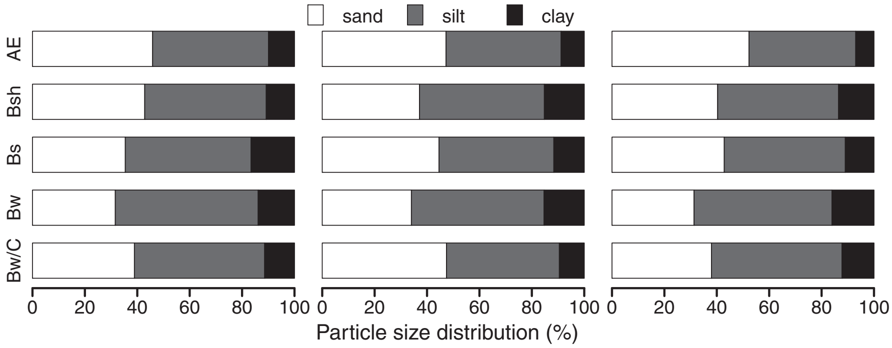

Fig. 1. Distribution of the soil fine fraction (median of 1 to 7 samples per horizon and plot). Sand fraction corresponds to 2000–63 μm, silt to 63–2 μm and clay to <2 μm. Plots 1 to 3 are shown from left to right.