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Geochimica et Cosmochimica Acta 189 (2016) 37–57

Geochimica et Cosmochimica Acta

www.elsevier.com/locate/gca

Factors controlling the chemical composition of colloidal and dissolved fractions in soil solutions and the mobility of trace elements in soils

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Received 3 June 2015; accepted in revised form 4 June 2016; available online 11 June 2016

Abstract

The objectives of this study were to determine the processes and physico-chemical conditions that affect the composition of the soil solutions of a forest soil and to elucidate their impact on the transport of major and trace elements through the colloidal (0.2 μm to 5 kDa) and dissolved (<5 kDa) fractions in the first meter of soil. All experiments were performed with soil solutions obtained using lysimeter plates situated on an experimental spruce parcel of the Strengbach catchment (Northeastern France). The surface samples filtered at 0.2 μm facilitated the examination of the influence of litter decomposition on the chemical composition of the upper soil solutions. The impact of the soils biogeochemical conditions (pH, moisture, temperature, oxic or anoxic conditions) on litter decomposition was also examined. More particularly, the increase in NH_4^+ and NO_2^- compounds in some of the soil solutions points to denitrification processes in an anoxic environment. Thus, under anoxic conditions, the soil solution is enriched in Ca, P, Mn and Zn, whereas under oxic conditions it is enriched in Al and Fe. The physico-chemical conditions are more seasonally dependent in the upper soil horizons than in the deeper ones and have an impact on the variability of the chemical composition of the soil solutions. The colloidal and dissolved fractions of the soil solutions were obtained by tangential flow ultra-filtration. The experimental results reveal that nutrients, such as NO_3^- and P, are primarily in the dissolved fraction and consequently bioavailable; secondary minerals may be dissolved and/or precipitate in the colloidal fraction, such as pyromorphite ($Pb_5(PO_4)_3(OH, Cl, F)$). The results further indicate that microbial activity influences the composition of the colloidal and dissolved fractions, and possibly enriches the colloidal fraction in Ca, Mn and P, diminishes the concentrations of Pb, V, Cr and Fe in the dissolved fraction, and changes the structure of organic carbon (OC). These results are important for a better understanding of the role of the colloidal and dissolved (<5 kDa) fractions in the transport of the major and trace elements in soil solutions and, more particularly, the mobility of pollutants and the bioavailability of nutrients for forested ecosystems.
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Keywords: Organic carbon; Colloidal fraction; Soil solutions; Litterfall degradation; Tangential ultra-filtration (TFF)

1. INTRODUCTION

The mobilization of major and trace elements in soils begins with the leaching of the soil surface by rain and/or throughfall. The resulting soil solution transports elements originating from litterfall decomposition, soil alteration

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http://dx.doi.org/10.1016/j.gca.2016.06.009
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and atmospheric deposition. It migrates through the soil and facilitates the transport of metals, nutrients or pollutants into deeper soil horizons. Therefore, the transport processes of these different components in soil solutions control nutrient availability for vegetation and the nutrient composition of surface waters (Aiuppa et al., 2000; Gustafsson et al., 2000; Bauer et al., 2008; Egli et al., 2010; Fraysse et al., 2010; Clarholm and Skyllberg, 2013).

The composition of soil solutions can be affected by various processes such as adsorption of metals on soil organic matter or clays, which delays migration until desorption (Bradl, 2004; Sipos et al., 2005; Meng et al., 2009; Wu et al., 2011; Filella and Williams, 2012). The seasonal alternation of wet and dry cycles changes the redox conditions of soil and soil solutions, affecting the mobility of their components due to differing solubilities of, e.g., Fe, Cu, Cr, and Mn (Fuss et al., 2011; Miller et al., 2012; Fulda et al., 2013; Shaheen et al., 2014). These cycles of oxic and anoxic periods also govern microbial activities influencing the composition of soil solutions by, e.g., the dissolution of soil particles in a selective manner to obtain specific nutrient elements required for their growth (Blum et al., 2002; Aouad et al., 2006; Gabor et al., 2014; Gangloff et al., 2014a; Kleber et al., 2015). The vegetation also influences the soil solution composition through absorption or adsorption of nutrients (Clarholm and Skyllberg, 2013) or through litter degradation (Stille et al., 2006). Thus, the biochemical processes influence the soil solution composition and, in particular, the concentrations of dissolved and particulate organic carbon (OC). Organic carbon reacts with cations as a function of molecular size, organic functional groups (Gangloff et al., 2014b) and structural evolution with depth (Lorenz et al., 2000; Kaiser et al., 2002; Ussiri and Johnson, 2003; Don and Kalbitz, 2005; Ussiri and Johnson, 2007). These parameters influence the colloidal and dissolved phases present in the soil solution and, consequently, the transport at the soil/soil solution interface.

Numerous ultra-filtration experiments have been performed with sea-water or surface waters to better understand the transport mechanisms of major and trace elements (Ingri et al., 2000; Dahlqvist et al., 2004; Andersson et al., 2006; Singhal et al., 2006; Waeles et al., 2008; Liu et al., 2013), but only a few studies have been performed on soil solutions (van Hees et al., 2001; Pokrovsky et al., 2005; Pédrot et al., 2009). The current study increases the understanding of the transport of major and trace elements by the colloidal and dissolved phases in the first meter of the soil, as well as their spatial and temporal displacement in the soil of a forested ecosystem. It was performed on soil solutions obtained by zero tension lysimeter plates installed in the forested Strengbach catchment (Riotte and Chabaux, 1999; Tricca et al., 1999; Schmitt et al., 2003; Stille et al., 2006; Cenki-Tok et al., 2009; Stille et al., 2009; Lemarchand et al., 2010; Rihs et al., 2011; Stille et al., 2011; Lemarchand et al., 2012; Viville et al., 2012; Pierret et al., 2014; Gangloff et al., 2014a; Gangloff et al., 2014b). The samples were collected during two periods (2009–2010 and 2012–2013) at different depths in the soil profile and ultra-filtered for the determination of the chemical composition of the colloidal and dissolved phases and, thus, leading to a better understanding of the spatial and temporal displacement of major and trace elements in the soil of a forested ecosystem.

2. MATERIALS AND METHODS

2.1. Sampling site

The forested Strengbach catchment, with area surface of 80 ha, is located in the eastern Vosges Mountains (northeastern France) at altitudes ranging from 883 m at the outlet to 1146 m at the peak (Fig. 1). The forest is dominated by conifers (80%) and beeches (20%). The climate of the Strengbach catchment is oceanic mountainous. Rainfall occurs throughout the year, with an annual average of 1400 mm, and 20–25% of the precipitation is snow, which falls between December and April. The average annual temperature is 6 °C. The weather conditions recorded during the sampling periods are provided in Electronic Annex E.A.T1. The catchment has been investigated since 1986 and has become a completely equipped environmental observatory with permanent sampling and measuring stations (http://ohge.unistra.fr).

The bedrock of the catchment is a hydrothermally altered Hercynian leucogranite. In addition, small microgranite and gneiss bodies occur. The soils of the experimental parcel VP2 situated under spruces on the northern slope of the catchment are brown acidic (acid dystrochrept type). The acidification of soils is caused to natural acidification (podzolization process) and to the introduction of anthropogenic acidic atmospheric deposition in the 1990s.

The pH range is between 3.7 and 5. This acidity decreases the buffering capacity of the soil and, thus, accelerates weathering and podzolization, including leaching and illuviation processes in the soil (Lundström et al., 2000). The O horizon (humus) consists of spruce needles in varying stages of decomposition with a thickness of 1–3 cm. The A horizon (10–15 cm thick) is dark brown and has an organic matter (OM) content of approximately 100 g kg^{-1}. The B horizon (50 cm thick) is reddish brown with an OM content of 10 g kg^{-1} less. The BC horizon reaches a depth of approximately 105 cm. It is greyish to reddish brown. The soil profile has been described previously, including its mineralogical composition (Fichter et al., 1998; Probst et al., 2000; Stille et al., 2009; Stille et al., 2011; Pierret et al., 2014; Gangloff et al., 2014b). This study focuses more particularly on the soil solution of this parcel, collected using zero tension lysimeter plates situated at depths of 5, 10, 30 and 60 cm. Sixteen soil solution samples were collected between 09/09/2009 and 09/09/2010 and 10 between 09/25/2012 and 08/06/2013 (Electronic Annex E.A.T2).

2.2. Preparation of the samples of spruce needles

Needles collected from spruces on the experimental VP2 parcel were washed with ultra-high purity (UHP) water (18.2 MΩ cm) and dried in an oven at 60 °C. The dried material was reduced to powder using an agate mortar. One hundred to 150 mg were weighed and poured in a

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