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Experimental approach of lessivage: Quantification and mechanisms

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ABSTRACT

Lessivage, also called argilluviation, consists of a substantial vertical transfer of particles less than 2 μm from a superficial departure horizon to a deeper horizon. This process is common in many soil types and responsible for the development of a textural differentiation in soil profiles in the subsurface. However, the mechanisms of lessivage are still poorly understood, and to our knowledge, lessivage has rarely been quantified.

We propose here two original experiments of in vitro pedogenesis on soil columns to analyse the mechanisms acting in eluviation and illuviation, the two phases of lessivage, and to quantify these two phases in terms of particle export and fixation. We paid special attention to the experimental conditions, so that the conditions were favourable for lessivage and as close as possible to field conditions.

The eluviation experiment showed that the release of particles was not the determining process for lessivage. We also showed that the smectite selectivity of eluviation was not continuous over time. Both physical and chemical processes were identified as acting on both eluviation and illuviation.

Concerning illuviation, experiments showed that from 25 to 90% of the eluviated particles were retained in the deeper horizon. Although large, to our knowledge this range represents the first quantification of illuviation.

1. Introduction

Lessivage, also called argilluviation, consists of a substantial vertical transfer of particles less than 2 μm from a superficial departure horizon, called the eluviated horizon or the E-horizon, to a deeper horizon, called the illuviated or the Bt-horizon (WRB, 2006). This process is thus responsible for the development of a textural differentiation in soil profiles in the subsurface.

Lessivage has been described in many soil types (WRB, 2006). However, other processes may also be responsible for a textural differentiation as stated by Presley et al. (2004), Krull et al. (2006), or Phillips (2007). Therefore, the existence of lessivage has been questioned by Legros (2007). Quénard et al. (2011) demonstrated by a mass balance approach that lessivage is responsible for the profile texture differentiation in only 1 to 12% of the soil profiles identified as Luvisol and Albeluvisol in the French Soil database DONESOL (Grolleau et al., 2004; www.gissol.fr).

Quénard et al. (2011) also reanalysed literature data on particle transfer in soils measured in laboratory experiments. This re-analysis of the literature showed that few of the existing data were obtained for the soil conditions favourable for lessivage. The lessivage process occurs in filtering unconsolidated material, generally of loamy or sandy loamy texture, as aeolian, alluvial and colluvial deposits or glacial till. More precisely, in a non-sodic environment, horizons rich in smectite, with pH ranging from 4 or 5 to 6.5, are sensitive to eluviation, while horizons with pH higher than 6.5 favour illuviation (Quénard et al., 2011). In addition, published experiments were generally performed on small columns (<10 cm in height) that enhance particle losses at the column base or with free drainage boundary conditions that change the shape of the particle breakthrough curve (Sharma et al., 2008). Such an experimental design prevents quantification of eluviation. In addition, these experiments generally simulate one rain event or a few rain events (Jacobsen et al., 1997; Kjaergaard et al., 2004a,b; Laegdsmand et al., 2005; Schelde et al., 2002) and may therefore not be as representative of a long-term process such as lessivage. In addition, according to Quénard et al. (2011), none of the published experiments allowed for the measurement of illuviation. The only experiments on particle fixation in soils were performed by adding dispersed particles to the input water (Saiers and Lenhart, 2003; Seta and Karathanasis, 1997). These illuviation experiments are too far from the field conditions in terms of particle input (quantity, nature and dynamics) to allow for conclusions on the intensity and on the dynamics of the process to be made. Illuviation was thus mainly indicated to date by the observation of clay coatings and cutanes along soil profiles or on thin soil sections using micromorphological analysis (Gunal and Ransom, 2006; Jamagne, 1973). Some attempts at quantification of lessivage do exist in the literature and are based on the clay coating quantification (Gutiérrez-Castorena et al., 2007; McKeague et al., 1980; Thompson et al., 1990). However, coatings have different origins — lessivage, wetting–drying cycles, and new formation (Boixadera et al., 2003; Gutiérrez-Castorena et al., 2007), which

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makes the nonambiguous attribution of individual coatings to a particular process difficult, and therefore the quantification of illuviation is also difficult.

Nevertheless, the published experiments identified some of the mechanisms responsible for particle release and fixation (DeNovio et al., 2004; Gamerdinger and Kaplan, 2001; Jacobsen et al., 1997; Kaplan et al., 1993; Laegdsmand et al., 1999; Michel et al., 2010; Ryan et al., 1998; Saiers and Lenhart, 2003; Schelde et al., 2002; Seta and Karathanasis, 1997). While some of the mechanisms described are physicochemical (particle surface–solution interactions entering into dispersion and flocculation processes), others are physical (splash effect, wetting–drying cycles, filtration, shear stress among others, see Quénard et al., 2011, for more details). The relative contributions of these two types of mechanisms to particle release and fixation have rarely been reported, to our knowledge.

In that context, we propose here two original experiments consisting of in vitro pedogenesis on soil columns, to follow eluviation and illuviation over time. We paid special attention to the experimental conditions, so that the experimental conditions were favourable for lessivage and as close as possible to field conditions. The objectives of these experiments were i) the quantification of eluviation and illuviation, ii) the analysis of the mechanisms acting in these processes, and iii) the impact of the rain intensity on these processes and their associated mechanisms.

2. Materials and methods

2.1. Choice of the soil and sampling methodology

On the basis of the analysis performed by Quénard et al. (2011), we chose, for our laboratory experiments, two E-horizons of Luvisols developed in loess with contrasting pH and clay mineralogy. For eluviation, an E-horizon, called L1, containing smectites and with a pH of 6.2 was chosen, while for illuviation, an E-horizon, called L2, containing no smectite and with a pH of 7 was chosen (Table 1).

For the column experiments, undisturbed cylinders (with height and diameter of 15 cm) were sampled in two different Luvisols at a depth between 35 and 50 cm. As earthworms were observed in the field, they were killed by electricity to avoid disturbance of the soil structure. The cylinders were then kept in a cool chamber at 4 °C before the experiments. Additional cylinders were collected for the determination of the bulk density and bulk samples were collected for classical pedological and clay mineral determination (Table 1). The fractions of the soils supposedly mobilised by lessivage (namely <0.2 μm, 0–2 μm and 0–5 μm) were analysed by X-ray diffraction (XRD) (Bruker-AXS, D8 Advance) for both the L1- and L2-horizons. Their particle-size distributions were also measured by a laser particle sizer (Malvern S).

Table 1
Characteristics of the E-horizons sampled for the column experiments.

Characteristics	L1	L2
Sampling depth (cm)	35–50	35–50
<2 μm (g kg^{-1})[1]	307	156
2–20 μm (g kg^{-1})[1]	285	319
20–50 μm (g kg^{-1})[1]	302	380
50–200 μm (g kg^{-1})[1]	80	109
200–2000 μm (g kg^{-1})[1]	26	36
pH	6.2	7.0
Organic carbon (g kg^{-1})	3.5	2.8
Bulk density (g cm^{-3})	1.6	1.5
Porosity	0.39	0.44
Smectite[2]	Abundant	Absent

[1] Particle size fractionation was determined by sieving and Robinson's pipette methods at Laboratoire d'Analyses des Sols of l'INRA Arras following the AFNORX31-107 methodology.
[2] Clay mineralogy was determined by X-ray diffraction on oriented slides according to Robert and Tessier's (1974) methodology.

2.2. Experimental design

On basis of the analysis performed by Quénard et al. (2011), we designed column experiments using undisturbed decimetric soil cylinders, and we decided to apply suction at the base of the columns using a vacuum pump.

To monitor eluviation, eight soil columns consisting of undisturbed soil cylinders sampled in the L1-horizon were built up, four replicates for each rain intensity. This experiment is referred to as L1-experiment in the following text, and the corresponding columns are referred to as LX–Y where X represents the rain intensity modality and Y the number of the column (ranging from 1 to 4).

To monitor illuviation (particle deposition), complex columns were built consisting of two soil cylinders that were overlaid. The top cylinder consisted of an undisturbed L1-cylinder, while the bottom cylinder consisted of an undisturbed L2-cylinder. To ensure good contact between the two cylinders, some L1-material was added to the top of the L2-cylinder. Six columns were then built up for each rain intensity. This experiment is referred to as the L1/L2-experiment in the following text, and the corresponding columns are referred to as LLX–Y, where X represents the rain intensity modality and Y is the number of the column (ranging from 1 to 6).

The base of the column consisted of a Büchner funnel connected to an Erlenmeyer flask. The flask contained 2 mL of Na_3PO_3 (150 g L^{-1}) to prevent particle aggregation in the drained water (Fig. 1). A 110-μm nylon mesh filter was located at the base of the soil column. The Erlenmeyer flask was connected to a vacuum pump.

One L1 column and one L1/L2 column were equipped with two and four porous cups located at different depths (5, 12, 20 and 27 cm) to monitor the chemistry of the soil water. One L1 column and one L1/L2 column were equipped with three and six tensiometers located at different depths (5, 10, 14, 16, 20 and 25 cm) and connected to a Campbell station to monitor the pressure head variations within the columns.

Table 2 summarises the number of columns available for each experiment, their equipment and the experiment in which they were used.

2.3. Experimental conditions

2.3.1. Upper boundary conditions

Twenty-eight rain events were applied to the soil columns using a rain simulator. Two rain intensities were applied: 20 mm h^{-1} and 6 mm h^{-1}. These rain intensities were chosen to represent a storm event and a fine winter rain. The lowest intensity feasible with our rain simulator was 6 mm h^{-1}. The water used as rainwater was osmosed water that had a pH and ionic charge close to natural rainwater. Thirty millimetres of water were applied for each rain event regardless of the intensity that was considered. Pluviometers were located

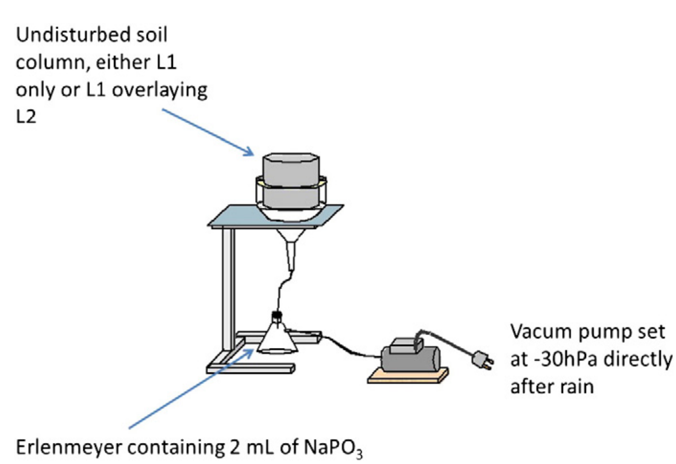

Fig. 1. Experimental design (not to scale).