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Agricultural drainage-induced Albeluvisol evolution: A source of deterministic chaos

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ABSTRACT

It is currently widely accepted that soil formation is not only deterministic, obeying the well-known soil-forming factor theory, but also chaotic, being highly sensitive to small variations in the initial conditions that persist and grow over time. However, the origins as well as the specific time-scales of such chaotic evolutions still need to be explored. In this paper, the morphological degradation in Albeluvisols after 18 years of agricultural subsurface drainage was quantified using image analysis in combination with mass balance calculations on a high-spatial-resolution soil sequence sampled perpendicularly to a drain line. Soil changes were found to i) vary as a result of complex interactions between the human-induced perturbations of the soil system and the prevailing environmental factors such as local topography and ii) result from a positive feedback loop between the soil moisture, soil water flows and mass transport. Human-induced perturbations of soil system are highly sensitive to the initial conditions and induce divergent soil changes over time and may be a non-negligible source of deterministic chaos. Finally, the significant material losses quantified on time scales as short as two decades suggested that human-induced perturbations of the soil system may be an interesting way to study the time-scales for such chaotic evolutions.

1. Introduction

It is currently widely accepted that soil formation is, on the one hand, deterministic, as it obeys the well-known soil-forming factor theory (Jenny, 1941) but, on the other hand, non-linear and highly sensitive to small perturbations and variations of initial conditions that persist and grow over time through local positive feedbacks (Webster, 2000). These characteristics have led to the whole process being labelled as deterministic chaos or deterministic uncertainty (Phillips, 1993; Phillips et al., 1996). The concept of deterministic chaos arose from the classical soil processes and mechanisms that include thresholds, storage effects, saturation and depletion, self-activating and self-limiting soil processes, competitive feedbacks, multiple modes of adjustment, self-organisation and hysteresis (Phillips, 2003), which amplified the local lithological or topographical variations (Toomanian et al., 2006; Webster, 2000) and disturbances (Phillips and Marion, 2005). Such dynamical instabilities occur at different spatio-temporal scales (Phillips, 2001, 2005). For a local spatial scale and for time scales ranging from that of a hydrological event to a season, deterministic chaos was underlined by the development of an unstable wetting front, fingered flow or other preferential flows (Faybishenko, 2004; Ritsema et al., 1997, 1998). For broader spatial scales and for mature and often old soils, deterministic chaos induced divergence in the soil thickness (Minasny and McBratney, 1999; Phillips, 2010) or in the soil diversity (Phillips, 2001; Phillips et al., 1996; Toomanian et al., 2006). However little is known regarding the propagation of the deterministic chaos with time, that is, from the scale of a hydrological event to that of mature soils. Human perturbations of a soil system, which in some cases can be easily dated, might be a powerful tool to explore the deterministic chaos propagation in time for time scales that range from a few tens of years to a century.

Albeluvisols are characterised by the formation of albeluvic tongues that involves dispersion and eluviation of clay minerals after the reduction and the removal of iron-oxide bonding in the clay particles (Pedro et al., 1978; Van Ranst and De Coninck, 2002). These soils are likely to be prone to deterministic chaos because of the eluviation-induced feedbacks between the soil moisture and mass flux (Phillips et al., 1996; Ritsema et al., 1997, 1998) and because these soils exhibit a complex geometry of preferential flow in the tongues (Diab et al., 1988). Moreover, for cropping purposes, Albeluvisols are frequently artificially drained which gives rise to graded changes along the drain line in the direction of the water flow (Montagne et al., 2009) as well as changes in the intensity of eluviation (Kapilevich et al., 1991; Montagne et al., 2008; Yli-Halla et al., 2009). Consequently, drainage of the Albeluvisols may result in its chaotic divergence. In that case, slight differences in the distance to the drain line and/or in the slope would result in a divergent evolution. Therefore, drained Albeluvisols are a model case to

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demonstrate the possibility of human-perturbation of the soil-system to initiate a chaotic soil evolution and to observe how such chaotic evolution propagates with time.

The computation of material fluxes with a mass balance approach (Brimhall et al., 1985, 1988, 1991; Egli and Fitze, 2000) for a soil positioned immediately adjacent to the drain line with respect to a soil positioned far away from the drain line and therefore considered as unchanged succeeded in the characterisation of the material fluxes related to the evolution of Albeluvisol in response to a subsurface agricultural drainage (Montagne et al., 2008). Such an approach was employed here on a high spatial-resolution soil sequence. The soil sequence was sampled across the drain line, and the sampling strategy involved incremental distances to the drain line and slight differences in slope, to capture the divergent soil evolution. Results were then interpreted as potential data to demonstrate the initiation of chaotic soil evolutions as a result of human-induced perturbations of the soil system.

2. Material and methods

2.1. Studied site and soil characteristics

The studied site is on the crest of the Yonne plateau (France, Fig. 1a and b), where the Albeluvisols developed in the Quaternary loamy deposits (Baize and Voilliot, 1988). These soils exhibited the classical Ap/E/Bt/C profile development (Driessen et al., 2001) of an Albeluvisol, with a silty and bleached E-horizon of grey colour that tongued into the underlying ochre coloured and clay illuviation Bt-horizon. Both contained black concretions and impregnations (Montagne et al., 2008). The complex juxtaposition of the bleached E-horizon with residual soil volumes of the clay illuviation, Bt-horizon, was labelled as follows:

- E&Bt-horizon, between 35 (40) to 55 (60) cm in depth, where the most abundant volumes are white (10YR8/2 to 10YR8/1) to light yellowish brown (10YR6/4) colour and thereby referred to as the white-grey and pale brown volume, respectively (Fig. 2);
- the degraded Bt-horizon, between 55 (60) to 65 (70) cm in depth, where the most abundant volumes, called ochre, are of yellowish brown colours (10YR5/6 to 10YR5/8). A small quantity of a clay-rich light brownish grey volume (10YR6/2), referred to as the brown-salmon, was also observed.

The main primary pedological characteristics at the solum scale, such as particle size distribution, pH or organic C contents are reported in Montagne et al. (2008).

The subsurface drainage network was installed in 1988 (16 years before sampling) by the subsoiling perpendicularly to the main slope and at one-metre depth (Fig. 1c). Drain lines were spaced 15 m apart. A 7 m long trench was dug perpendicularly to one of the drain lines, i.e., along the main slope (Fig. 1c). The selected drain line crossed the trench almost at the middle, 3 m from the left border and 4 m from the right border. The right side of the trench was on a very flat part of the crest whereas the left part showed a very gentle slope from the drain line (upstream position) to the left border (downstream position). The following macroscopic observations (schematised in Fig. 3) indicated that:

(i) the thicknesses of the different horizons varied within 5 cm along the trench, which was not considered significant;
(ii) within a distance of approximately 50 cm on both sides of the drain, the soil was disturbed by subsoiling operations during the drain installation;
(iii) as the distance to the drain decreased from 2 to 0.5 m, the quantities of the white-grey, pale-brown and black soil volumes increased, both in the E&Bt- and in the degraded Bt-horizons. In contrast, the quantity of the clayey ochre soil volume decreased and;
(iv) beyond 2 m from the drain, the amount of different soil volumes did not change significantly.

2.2. Soil sampling strategy

To quantify the Albeluvisol evolution in response to the agricultural drainage it was necessary to quantify the relative quantities of the different soil volumes and determine their composition as a function of the distance from either side of the drain line. The studied trench was sampled at six positions located at −300 and −60 cm for the left hand side and at 60, 110, 210, and 400 cm for the right hand side. The position of the drain was fixed at 0 (Fig. 3). At each position, a pair of two undisturbed soil monoliths, of 1 decimetre in size (approximately 27×15×12 cm), was sampled from the E&Bt-horizon and the degraded Bt-horizon (Fig. 3). One monolith was used for the quantification of the relative abundances of different soil volumes, and the other monolith was used for the chemical analysis. The monoliths sampled in the E&Bt-horizon were considered as representative of the whole 20 cm thick E&Bt-horizon, whereas those sampled in the degraded Bt-horizon were essentially representative of the upper ten centimetres of the Bt-horizon.

2.3. Quantification of the soil volumes by image analysis

From each pair of soil monoliths, one was gently air dried for two weeks, oven dried at 40 °C for another week and impregnated for

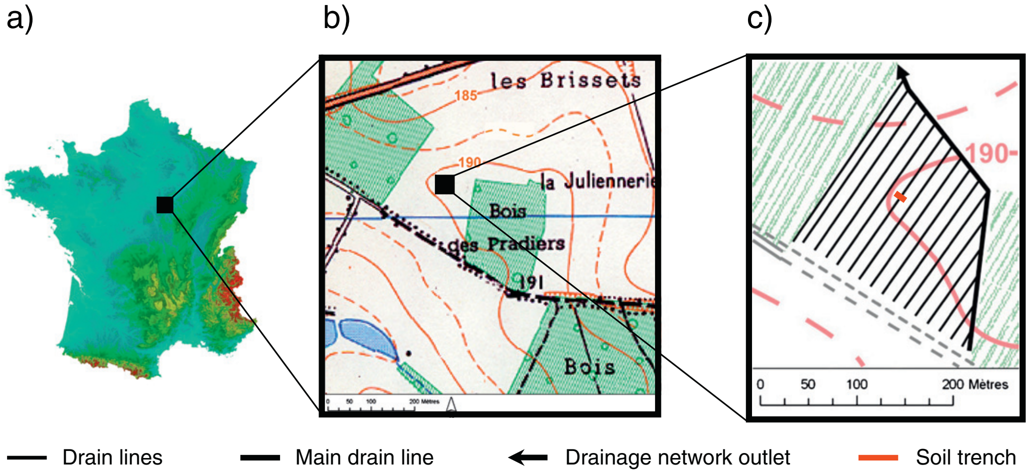

Fig. 1. Location of (a) the studied area in France; (b) the studied trench in the sampled plot with the topography; and (c) the drainage system at the plot scale.