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Identifying the characteristic scales of soil structural recovery after compaction from three in-field methods of monitoring

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ABSTRACT

The impact of compaction by traffic on agricultural soils is not strict and irreversible. After compaction by machine traffic, soil structure changes both spatially and temporally as different generative processes occur. These are generally well-described in the literature. However, the preferential periods of occurrence and the soil depths affected by changes – thus, the characteristic scales of soil structural recovery – remain hypothetical. Further investigation through precise spatial and temporal monitoring under real in-field soil conditions is needed.

In this paper, the structural changes of a locally trafficked silt–loam soil were assessed under both cropped and bare areas conventionally tilled from one-year soil monitoring. The monitoring was performed in-field by three methods at a low temporal resolution with the standard methods of visual description and soil coring in pits, and at a high temporal resolution with the non-destructive Electrical Resistivity Tomography (ERT) method. The specific use of ERT for this purpose is discussed.

Compaction by traffic affected the overall tilled soil layer and was shown to be time-persistent. This suggested a characteristic time-scale of a complete structural recovery longer than one year, regardless of soil management. At the finest temporal scale, the results also highlighted some seasonal processes that potentially affect the long-term recovery, such as bio-drilling and soil cracking. The processes were related to the soil management, the wetting/drying cycles and the freeze/thaw effect. They likewise induced the start of structure fragmentation in the first centimetres of the soil and acted abruptly in the dry period, preferentially under the area initially cropped, with persistent effects on the soil structure in the rainy and cool season.

1. Introduction

Soil compaction is regarded as one of the most serious environmental problems caused by conventional agriculture. For instance, it has been recorded to be affecting approximately 33 million ha in Europe regardless of soil management (Van Ouwerkerk and Soane, 1995). Indeed, traffic by wheeled and heavy farm machines is required for most agricultural operations even in no-till systems (Batey, 2009; Tullberg, 2010). Compaction modifies the spatial arrangement, size and shape of clods and aggregates (Defossez and Richard, 2002; Richard et al., 2001) and can severely disturb the soil functionality by reducing its permeability to air, water and heat and, consequently, crop production (Boizard et al., 2002; Keller et al., 2007; Lipiec and Hatano, 2003).

However, the impact of compaction on soil structure is not irreversible. Soils generally show subsequent structural recovery over time following the removal of the stress (Gregory et al., 2009). In addition to farming practices generally implemented to loosen the soil, including mechanical tillage, the incorporation of plant residues and manure to soil, and the selection of crop rotations with pasture plants, some natural regenerative processes related to biological activity and climate participate in soil structure recovery. The nature of regenerative processes is generally well described in the literature (Gregory et al., 2007). For instance, root growth, soil faunal activity and the swelling–shrinking and freeze–thaw cycles induce cracking and fragmentation of compacted zones, leading to an increase in porosity (Beylich et al., 2010; Seybold et al., 1999; Voorhees, 1983). However, no clear generalisation of the characteristic space- and time scales of the soil structure recovery, as defined by Blöschl and Sivapalan (1995), can be made in regard to 1) the wide variety of experimental conditions and soil managements analysed (Gregory et al., 2007) or 2) the general discrepancy between the processes and observational scales. For instance, the poor temporal resolution of standard and destructive, and thereby non-reproducible, methods implemented to monitor the soil structure (digging soil pits, soil sampling, penetrometry) (Håkansson, 1990) limit the identification of the soil

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zones that are most susceptible to structural recovery. The spatial extent, i.e., the soil areas and depths covered by the structural recovery, and the identification of the dominant periods of regenerative processes involved in recovery along with their duration remain hypothetical.

Further methods still need to be adopted for fine spatial and temporal soil structure monitoring. For instance, the non-destructive and rapid near-surface geophysical method of Electrical Resistivity Tomography could offer a practical solution. This method has already been used to analyse the soil water changes and the structural heterogeneity at high spatial and temporal resolutions (Besson et al., 2004; Samouëlian et al., 2005; Séger et al., 2009).

In this context, this study aims to describe the structural recovery of a silt–loam soil over one year following compaction from an experiment performed in real agricultural conditions, including cropping, bare soil and conventional tillage. The soil structure was monitored by three methods: 1) the Visual Description (VD) of the soil morphology, 2) soil coring that requires digging a trench and 3) the geophysical method of Electrical Resistivity Tomography (ERT). Methods 1 and 2 are standard methods with low temporal resolutions, and method 3 is rapid and non-destructive with a high temporal resolution. From these results, this study attempted to identify the main regenerative process and the characteristic scale of recovery. The use of ERT for this purpose was also discussed.

2. Material and methods

2.1. Experimental site and soil management

This experiment was performed in the Beauce region (region of mechanised crop production, Villebon, Eure-et-Loir, France), approximately 100 km southwest of Paris. The site was a small plot of 0.2 ha (25 m × 7.20 m) within a large conventionally tilled field, i.e., subjected to mouldboard ploughing (0–0.30 m) followed by disc harrowing (0–0.10 m). The soil was a well-drained Alfisol (USDA, 2010) and encompassed 1) a tilled silt–loam A horizon with high silt content (approximately 78%) susceptible to structure deterioration and 2) an argic Bt horizon (Table 1). This study was focused on the tilled A horizon.

In the central part of the plot (4 m in size) (Fig. 1), wheat was sown at the beginning of March 2009 for harvesting by hand reaping with sickle at the end of July 2009. The borders of the plot were non-cropped (1.50 m in size) (Fig. 1).

After seeding and in the wettest conditions, the plot was locally compacted by three crossings of a heavy tractor (85 kN with rear tyres 0.65 m width inflated at 200 kPa) along two single tracks parallel to the seeding direction. This operation created four compacted bands: two were located in the bare zones and the others were in the cropped zone as shown in Fig. 1.

2.2. Meteorological monitoring

Fig. 2 shows the rainfall, evapotranspiration and temperature per month for the entire experimental time, from March 2009 to March 2010. Rainfall and air temperature were monitored hourly in the field with a weather station (ARG100 rain gauge, CS215 temperature probe, and CR1000 data logger, Campbell Scientific, Inc., Utah, USA). Daily evapotranspiration (*ETo*) and the crop evapotranspiration (*ETc*) were obtained from a regional weather-based reference station (MétéoFrance, Chartres, France) and from the Regional Agriculture Chamber (Eure-et-Loir, France), respectively.

Table 1
Soil characteristics of A and Bt horizons of Eutric Luvisol. OM: organic matter; CEC: cation exchange capacity.

	Depth (m)	Clay ($\mathrm{g\ kg^{-1}}$)	Silt ($\mathrm{g\ kg^{-1}}$)	Sand ($\mathrm{g\ kg^{-1}}$)	OM ($\mathrm{g\ kg^{-1}}$)	CEC ($\mathrm{cmol\ kg^{-1}}$)
A horizon	0 to -0.35	17.5	78.2	4.3	9.73	10.3
Bt horizon	-0.35 to -1	25.4	70.9	3.7	3.82	10.6

Four seasonal periods I, II, III and IV are identified in Fig. 2 and correspond to the drying (March–July 2009), the dry (July–September 2009), the wetting (September–December 2009) and the wet and cool periods (the beginning of 2010), respectively.

2.3. Temporal monitoring of soil water content and soil temperature

The soil volumetric water content was measured by TDR (Time Domain Reflectometry) (Topp et al., 1980). TDR probes ($n = 16$) 0.30 m in length (TDR CS601, Campbell Scientific, Inc., Utah, USA) were inserted horizontally, i.e., parallel to the soil surface, at depths of −0.1, −0.20 and −0.25 m in the compacted and non-compacted zones and at a depth of −0.35 m in the plough pan. Additionally, four temperature probes (PT 100 sensor, Campbell Scientific, Inc., Utah, USA) were inserted into the soil at depths of −0.05, −0.10, −0.15, and −0.25 m.

The probes were all connected to an automatic data acquisition system (CR1000 data logger, Campbell Scientific, Inc., Utah, USA) (Fig. 1). The water content and temperature were recorded hourly from April 2009 to March 2010. We focused only on the dataset measured at the same times as the ERT measurements ($n = 23$ dates). For clarity, water contents estimated from TDR readings were denoted θ_{TDR}.

2.4. Soil structure monitoring

Three combined methods were used to monitor the soil structure changes: Visual Description (VD) from soil pits, soil coring and Electrical Resistivity Tomography (ERT). The monitoring started in April 2009, one month after wheat seeding, and ended in March 2010, 9 months after the wheat harvesting.

2.5. Visual Description (VD) of pits

The soil structure in soil pits dug perpendicularly to the traffic direction (Fig. 1) was monitored using Visual Description (VD). The features and locations of the structural zones were described within the soil profile. The intensity of compaction was assessed by analysing the sizes, shapes and hardness of clods (Gautronneau and Manichon, 1987). Soil pits ($n = 5$) crossed the compacted bands in both the bare and cropped areas. The first two pits were dug at the time of crop growth, on June 11 (line 1, period I) and July 7, 2009 (line 2, periods I–II). Three other pits were dug on August 20, 2009 (line 3, period II), November 10, 2009 (line 4, period III), and March 16, 2010 (line 5, period IV) after harvesting.

2.6. Soil coring

After the pits were dug, 96 undisturbed soil cores (0.05 m × 0.05 m; $0.98\ 10^{-4}\ \mathrm{m^3}$) were sampled at depths of −0.05, −0.10, −0.15 and −0.25 m in both the compacted zones ($n = 29$) and the non-compacted zones ($n = 57$). The cores were weighed and dried at 105 °C to estimate their dry bulk densities and water contents:

$$\rho_a = \theta_{cores}/w_{cores} \tag{1}$$

where w_{core} is the gravimetric water content ($\mathrm{kg\ kg^{-1}}$), θ_{cores} is the volumetric water content ($\mathrm{m^3\ m^{-3}}$), and ρ_a is the dry bulk density ($\mathrm{kg\ m^{-3}}$).