Geoderma 207–208 (2013) 310–322

Contents lists available at SciVerse ScienceDirect

Geoderma

journal homepage: www.elsevier.com/locate/geoderma

Characterization of tillage effects on the spatial variation of soil properties using ground-penetrating radar and electromagnetic induction

François Jonard [a,*], Mohammad Mahmoudzadeh [b], Christian Roisin [c], Lutz Weihermüller [a], Frédéric André [b], Julien Minet [b], Harry Vereecken [a], Sébastien Lambot [b]

[a] Agrosphere (IBG-3), Institute of Bio- and Geosciences, Forschungszentrum Jülich GmbH, 52425 Jülich, Germany
[b] Earth and Life Institute, Université catholique de Louvain, Croix du Sud 2 Box L7.05.02, 1348 Louvain-la-Neuve, Belgium
[c] Agriculture and Natural Environment Department, Walloon Agricultural Research Centre, rue du Bordia 4, 5030 Gembloux, Belgium

ARTICLE INFO

Article history:
Received 16 March 2012
Received in revised form 14 May 2013
Accepted 27 May 2013
Available online 28 June 2013

Keywords:
Soil tillage
Ground-penetrating radar
Electromagnetic induction
Digital soil mapping
Soil water content
Soil resistance

ABSTRACT

Tillage practices influence physical, chemical, and biological soil properties, which also affect soil quality and consequently plant growth. In this study, the main objective was to evaluate the effects of different tillage practices on soil physical properties such as soil water content (SWC) by using geophysical methods, namely, ground-penetrating radar (GPR) and electromagnetic induction (EMI). Additional measurements such as soil sampling, capacitance probe, and soil penetrometer data were acquired as ground truths. The study was performed for three contrasting tillage practices, *i.e.*, conventional tillage (CT), deep loosening tillage (DL), and reduced tillage (RT), applied on different plots of an agricultural field. The data showed that tillage influences soil resistance in shallow soil layers (deeper tillage decreases soil resistance), which could be partly seen in on-ground GPR data. In addition, reference SWC measurements (capacitance probes and soil sampling) were in fairly good agreement with the water content estimates from off-ground GPR. We also observed a tillage effect on shallow surface SWC, while deeper SWC seems to be unaffected by tillage. Mean surface SWC was significantly lower for CT compared to DL and RT, which was partly explained by lower pore connectivity between the topsoil and the deeper layers after conventional tillage. Moreover, the variance of the SWC within the conventional tillage plots was larger than within the other plots. This larger SWC variability could be explained by a greater soil heterogeneity induced by the plowing process. Overall, this study confirms the potential of GPR and EMI for the determination of soil physical properties at the field scale and for the assessment of agricultural management practices.

1. Introduction

Agricultural management practices can affect soil physical, chemical, and biological properties with consequences for the movement of water, nutrients, and pollutants in the vadose zone, and for plant growth (Strudley et al., 2008). Alternative management practices such as conservation tillage or reduced tillage are encouraged to prevent environmental risks like soil erosion, flooding, and pesticide leaching in the groundwater. However, producers are reluctant to adopt these practices as their effects on soil and crop production are not yet well understood (Alletto et al., 2011). The impact of tillage practices on soil hydraulic properties (Ndiaye et al., 2007; Sauer et al., 1990; Schwen et al., 2011a,b; Strudley et al., 2008) and their consequences on preferential flow (Elliott et al., 2000; Kulasekera et al., 2011), soil state variables (soil water content and soil temperature) (Kovar et al., 1992; Tan et al., 2002), soil physical properties (soil penetration resistance, soil bulk density, soil porosity) (Jabro et al., 2009), and plant growth (Alletto et al., 2011; Zhang et al., 2011) have been subject to intensive research over the past decade. However, according to the recent review by Strudley et al. (2008), experimental results from field and laboratory studies do not show consistent effects of tillage practices on soil properties. Moreover, to obtain information about soil properties, most of these studies used invasive methods such as time-domain reflectometry, capacitance sensors, or soil sampling, which are time-consuming and offer only local information. Therefore, these techniques are limited to a small spatial extent. In addition, time-lapse measurements are not feasible within agricultural fields, although they would provide valuable insights into the changes of the state variables (*e.g.*, soil water content and soil temperature) or the processes involved.

* Corresponding author. Tel.: +49 2461 61 9518; fax: +49 2461 61 2518.
E-mail address: f.jonard@fz-juelich.de (F. Jonard).

0016-7061/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.geoderma.2013.05.024

In that respect, ground-penetrating radar (GPR) and electromagnetic induction (EMI) are non-invasive geophysical techniques which can be used to characterize the shallow subsurface properties at the field scale with high temporal and spatial resolutions (André et al., 2012; Cockx et al., 2007; Huisman et al., 2003; Jonard et al., 2011; Lambot et al., 2008; Slob et al., 2010). EMI is sensitive to soil electrical conductivity, which is mainly affected by soil water content (SWC), clay content, and salinity (Corwin and Lesch, 2005; Friedman, 2005), while GPR is sensitive to both soil electrical conductivity and dielectric permittivity, the latter primarily depending on SWC (Topp et al., 1980). Yet, until now, very few studies have used geophysical techniques to investigate the impact of tillage practices (*e.g.*, Basso et al., 2011; Oleschko et al., 2008; Richard et al., 2010). Recently, Müller et al. (2009) compared different geophysical techniques to characterize tillage effects on SWC and electrical resistivity. However, their sampling scheme was limited to two transects, which did not permit them to fully explain their observations. Basso et al. (2011) used electrical resistivity tomography applied to an entire field area, which enabled them to study the spatiotemporal dynamics of soil physical properties. Nevertheless, a high resolution could not be achieved, especially at the soil surface.

The general objective of this present study is to analyze the effects of tillage practices on the spatial variation of soil properties by using geophysical techniques. In particular, we focused on surface SWC, bulk soil electrical conductivity, and mechanical resistance. The study was conducted on an agricultural field in the loess belt of central Belgium (Gentinnes). GPR and EMI measurements were performed for three contrasting tillage practices, *i.e.*, conventional tillage (CT), deep loosening tillage (DL), and reduced tillage (RT). In this paper, we first present on-ground GPR images and soil strength maps to characterize the tillage effect on soil penetration resistance. Soil electrical conductivity and SWC maps from EMI and off-ground GPR data, respectively, are then presented and interpreted in the light of *in situ* observations. Finally, the tillage effect on SWC and its spatial distribution is discussed.

2. Materials and methods

2.1. Experimental site

The study was conducted on an agricultural field in Gentinnes, located in the loess belt of central Belgium (50°35′ N 4°35′ E). The soil is a silty loam soil classified as an Orthic Luvisol according to the FAO classification. Elevation varies between 137 and 145 m above sea level. The silt fraction dominates the clay and sand fractions (20.0, 74.5, and 5.5% for clay, silt, and sand, respectively) in the topsoil (0–25 cm), and the organic carbon content was 8.67 g kg^{-1}. The exact water table depth is unknown, but is in general deeper than 2 m. Since fall 2005, a soil tillage experiment has been implemented on the field to compare three contrasting tillage systems: (1) conventional tillage (CT) with moldboard plowing to ≈27 cm depth, (2) deep loosening tillage (DL) with a heavy tine cultivator to ≈30 cm depth, and (3) reduced tillage (RT) with a spring tine cultivator to ≈10 cm depth. The field was divided into 20 plots of 30 × 18 m^2 and each plot was characterized by one of the three tillage systems (Fig. 1). Only 12 plots were used for the geophysical measurements (4 replications per tillage system) and 3 other plots were used for the soil strength measurements. These 3 plots were located next to the 12 other plots, at a distance of about 15 m in the south-western part of the field (not shown in Fig. 1). The geophysical measurements were performed on April 13, 2010, while the soil strength measurements were performed on April 27, 2010. Average monthly rainfall recorded at a meteorological station located about 7 km away from the field was 75.3 mm in February, 36.0 mm in March, and 23.4 mm in April 2010. No rain was observed during the two measurement days and the daily reference evapotranspiration was close to 3 mm for both dates (Fig. 2).

2.2. Agricultural practices

Initially, the study site had been plowed in its entirety for several decades. Since 2005, it has been divided according to three tillage systems (CT, DL, and RT) and the same tillage treatment has been applied every year to the same plot, except in 2006 and 2008, where the DL tillage system was replaced by the RT tillage system. In 2006 and 2008, sugar beet was planted in April after seed bed preparation (with rotary harrow and drill), while winter wheat was sown in November (also with rotary harrow and drill). The wheat straw was chopped during the harvest and then mixed into the top soil layer by stubble harrowing. White mustard was used as a cover crop for all the plots during three fallow periods (2005–2006, 2007–2008, 2009–2010), *i.e.*, before sugar beet planting. White mustard was always sown in September using rotary harrow and drill. The three tillage treatments (CT, DL, and RT) were systematically applied before sowing white mustard or winter wheat. In April 2010, one day before the geophysical measurements, a minimum tillage was applied to all the plots with a disk harrow (to a depth of 5 cm) in order to reduce soil surface roughness for the radar measurements (Jonard et al., 2012). The day after the geophysical measurements, the whole field was prepared for seed bed with a disk harrow (to a depth of 3 cm) and flax was sown.

2.3. Reference soil water content measurements

Undisturbed soil samples (100 cm^3 Kopecky rings) were used as reference measurements for the volumetric SWC. Soil samples were collected between 0 and 5 cm depth on a regular grid in each plot (5 × 3 m spacing, *i.e.*, 35 samples per plot and 420 samples in total). Soil samples were also taken at two locations in each plot between 0 and 75 cm depth in 5 cm steps. The two locations were chosen arbitrarily around the middle of each plot. The volumetric water content of the soil samples was obtained by the weight loss after oven drying at 105 °C for at least 48 h. At each sampling point, soil dielectric permittivity was measured using two capacitance sensors, namely, the ThetaProbe ML2x sensor (Delta-T Devices Ltd, Cambridge, UK) and the 5TE sensor (Decagon Devices Inc., Pullman, Washington, USA), which were inserted vertically into the soil. The ThetaProbe sensor operates at 100 MHz and has four stainless steel rods of 6 cm length while the 5TE probe operates at a frequency of 70 MHz and has 3 prongs of 5.2 cm length. Three measurements with each probe were performed at a distance of less than 15 cm around each sampling point. The soil water content was then determined from the soil dielectric permittivity using Topp's model (Topp et al., 1980). It should be noted that using a site-specific relationship or a dielectric mixing model instead of Topp's model is likely to provide better absolute results. Nevertheless, Topp's model was chosen due to its simple application and because the present study is mainly focused on the comparison of SWC values with respect to different tillage treatments, which means that relative differences can be used.

2.4. Geophysical measurements

2.4.1. Ground-penetrating radars

Two different ground-penetrating radar (GPR) systems were used in this study: (1) off-ground radar for SWC retrieval and (2) common on-ground radar for soil stratigraphy imaging, whereby both radar systems were set up on an all-terrain vehicle (ATV) (Fig. 3).

2.4.1.1. Off-ground GPR. The radar system was set up using a ZVL vector network analyzer (VNA, Rohde & Schwarz, Munich, Germany),