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Temporal variation in soil physical properties improves the water dynamics modeling in a conventionally-tilled soil

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ABSTRACT

Temporal variations in soil physical properties are rarely recorded in field experiments or considered when modeling water and solute dynamics in agricultural soils. This study aimed at (a) quantifying the temporal variations in soil physical properties, such as the saturated hydraulic conductivity (K_s), bulk density (ρ_b) and soil water retention during the growing season of an irrigated maize crop conventionally tilled with a moldboard plow, and (b) modeling the observed water dynamics. For modeling, the effect of temporal variations of soil properties was explored and compared to results with constant values of soil properties during the simulation period and with results after an optimization of soil parameters by inverse modeling. Field and laboratory experiments were performed to measure the soil physical properties of five soil compartments (defined according to the position relative to crop row and the depth) at three dates during the maize season (sowing, flowering and just before harvest). During the maize season, ρ_b values ranged from 1.21 to 1.56 g cm^{-3} and increased with time (by 15–25% of the initial value). K_s values, ranging from 2.9 to 56.3 mm h^{-1}, significantly decreased with time (by a factor of 3 to 6) according to the soil compartment, and were negatively correlated with ρ_b. In the first step to model water dynamics, the initial values of soil physical properties (measured at maize sowing) were used as constant input parameters for the model HYDRUS-2D during the maize season. This simulation led to a poor description of soil water potentials and water content dynamics, without any drainage at 100 cm depth during the maize season. After an optimization of soil physical parameters, the description of the water dynamics was significantly improved, but optimized parameters, especially K_s and θ_s, were not within the range of field measurements. In a last modeling step, the simulation period was divided into three periods with a specific parameterization of soil physical properties for each period. The description of the water dynamics was improved compared to the simulation with constant values for soil physical properties. Such results argue for taking into account time-variable soil physical properties in modeling to correctly assess the water and solute dynamics in soils.

1. Introduction

Soil hydraulic properties can vary in space and time due to numerous natural and human influences (Green et al., 2003; Stange and Horn, 2005). Therefore improving knowledge of their spatial and temporal variability is fundamental to accurately describe soil processes such as rainfall infiltration and runoff, aquifer recharge, migration of nutrients and pollutants through the soil profile, and to design and monitor irrigation and drainage systems (Bagarello et al., 2005; Hu et al., 2009; van Es et al., 1999).

Soil cultivation practices are among the main factors affecting soil hydraulic properties and their effects have been frequently studied in recent decades (Green et al., 2003; Sauer et al., 1990; Strudley et al., 2008), but the results remain unclear and the literature clearly shows inconsistencies across locations, soils and agricultural practices (Strudley et al., 2008). Moreover few studies have addressed temporal and management-induced changes in soil hydraulic properties (Alletto and Coquet, 2009; Angulo-Jaramillo et al., 1997; Cameira et al., 2003; Messing and Jarvis, 1993), although it has been shown that variation in soil hydraulic properties over time can exceed differences induced by the cropping system management such as tillage operations, crop rotation, or land use (Alletto and Coquet, 2009; Angulo-Jaramillo et al., 1997; Hu et al., 2009; Strudley et al., 2008).

Within a cropping season, soil physical properties vary in response to environmental conditions such as the amount and intensity of rainfall or wetting–drying and freezing–thawing cycles (Angulo-Jaramillo et al., 1997; Bodner et al., 2013). Moreover, it has been shown that near-saturated soil hydraulic conductivity ($K(h)$), one of the most studied soil physical properties, often increases with tillage and then decreases

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during the growing season due to the settling of the soil structure created by tillage (Angulo-Jaramillo et al., 1997; Azevedo et al., 1998; Bormann and Klaassen, 2008) and irrigation (Alletto and Coquet, 2009). Soil water retention is classically used to predict the soil water storage and water available to plants. Most studies on its sources of variation have focused on the effects of agricultural management (Arshad et al., 1999; Mapa et al., 1986), while its temporal dynamics within a tilled soil remain poorly documented (Jirku et al., 2013).

Improving quantitative and qualitative water management at the field scale involves properly evaluating this temporal variation in field experiments and taking it into account in modeling approaches (Alletto and Coquet, 2009; Strudley et al., 2008). Indeed, in most modeling studies temporal dynamics of soil properties are not taken into account, mainly because their evaluation is time-consuming, so that most models assume constant values for soil physical parameters (Angulo-Jaramillo et al., 1997).

In this study the objectives were (a) to investigate the temporal dynamics of soil hydraulic properties in a conventional maize monoculture with a spring moldboard plowing and (b) to model the water dynamics in the upper part of the soil (0–100 cm-depth). In the modeling approaches, the effect of temporal variations of soil properties was explored and compared to results with constant values of soil properties during the simulation period and with results after an optimization of soil parameters by inverse modeling.

2. Materials and methods

2.1. Field experiment

2.1.1. Location, climate and soil

The field experiment was carried out at the experimental farm of Lamothe (INP Ecole d'ingénieurs de Purpan, 20 km S–SW of Toulouse, France) situated in the wide alluvial corridor of the Garonne River. A 3-ha field is dedicated to a long-term cropping system experimentation and is divided into two blocks of 15 plots (12 m × 60 m), each with a different cropping system (Fig. 1). For this study, only the two plots corresponding to the conventional maize monoculture (called MM_{REF}) were studied.

The site has an oceanic climate with both Atlantic and Mediterranean influences, with an average annual precipitation of 650 mm and a mean annual temperature of 13.2 °C. Meteorological data including daily air temperature (°C), rainfall (mm, plus irrigation), relative humidity (%), wind speed ($m\ s^{-1}$) and direction, and global and photosynthetically active radiation (PAR, $MJ\ m^{-1}$) were recorded by an automated weather station (SMA100, Campbell Sci., Antony, France) at the experimental site.

According to the World Reference Base for Soil Resources (IUSS, 2007), the soil was a stagnic Luvisol with an illuvial clay horizon between 35 and 60 cm. The substratum was an alluvial pebbly layer at around 150 cm. With low organic carbon contents and high silt contents, these soils are very susceptible to crusting. The main soil characteristics of the instrumented zones where soil physical property measurements were performed on each of the two plots are given in Table 1.

2.1.2. Agricultural practices

On the two MM_{REF} plots, maize was managed with conventional practices including a spring moldboard plowing (25 cm depth), followed in April by a surface tillage with a cultivator and a rotary harrow for seedbed preparation (8 cm-depth) and sowing. Details on MM_{REF} management in 2012 are given in Table 2.

During its development, the maize received 9 irrigations with a frontal irrigation sprinkler system for a total amount of 310 mm with a mean intensity of 8 $mm\ h^{-1}$. The cumulative natural rainfall was 280 mm during the same period (Fig. 2). After maize harvest, a surface tillage with a disk harrow was done to bury maize residues and the soil was then maintained bare during the fallow period.

2.1.3. Soil physical properties and water dynamics measurements

2.1.3.1. Bulk density and hydraulic conductivity measurements. Undisturbed soil samples were collected using 250 cm^3 (8 cm diameter, 5 cm height) cylindrical cores. Soil samples were taken as close as possible to the hydraulic conductivity measurement sites. Soil cores were dried in an oven (105 °C, 48 h) and bulk density ρ_b ($g\ cm^{-3}$) determined.

Tension disk infiltrometers were used to measure hydraulic conductivity $K(h)$ between -15 and -1 cm at the soil surface and at 20-cm depth. An 8-cm diameter base infiltrometer was used and the contact between the disk and the soil surface was ensured by fine well-sorted Fontainebleau sand (Alletto and Coquet, 2009). Surfaces for infiltration were prepared as flat as possible by scraping the soil with a knife blade. Infiltrations were done at -15, -6, -3 and -1 cm matric potentials successively. The unsaturated hydraulic conductivity was estimated (Ankeny et al., 1991) from the infiltration data using Wooding's (1968) solution for steady-state infiltration from a circular source at the soil surface with a constant matric potential h:

$$q_\infty(h) = K(h)\left[1+\frac{4}{\pi r \alpha}\right] \qquad (1)$$

where q_∞ is the steady-state infiltration rate ($L\ T^{-1}$), $K(h)$ is the unsaturated hydraulic conductivity ($L\ T^{-1}$) for a given soil water pressure head h

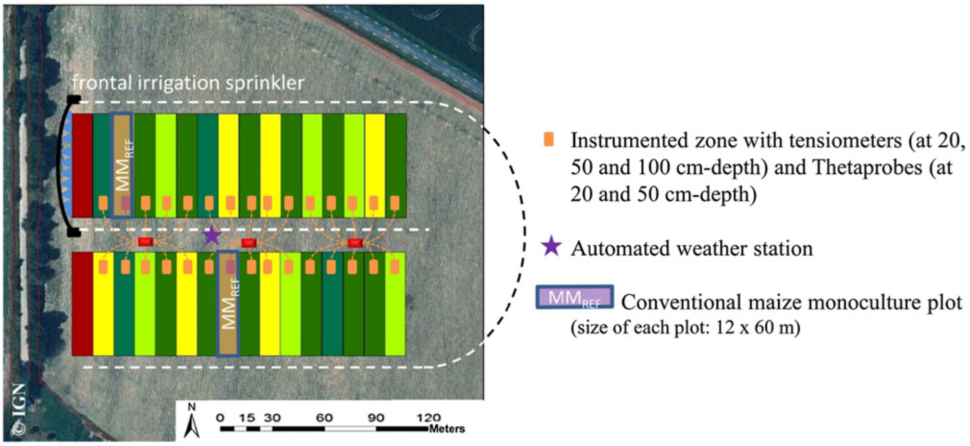

Fig. 1. Plan of the experimental field on sustainable cropping systems.