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Physical properties of soils under conservation agriculture: A multi-site experiment on five soil types in south-western France

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ABSTRACT

Soil properties, under the major influence of agricultural practices in cultivated fields, influence the distribution and quality of water and vary greatly in space and time. In conservation agriculture (CA), the combination of practices implemented can modify water retention and circulation. In this study, fields managed under CA and adjacent fields with regular ploughing (CONV) were used to characterize the water functioning of soils in the Adour-Garonne basin in south-western France. Hydraulic conductivity (K_S), bulk density and available water capacity (AWC) of the soils were measured to a depth of 50 cm on multiple dates to assess their temporal dynamics. Mean K_S was 1.5–3.0 times as high under CA (100–160 mm h^{-1}) as under CONV (50–70 mm h^{-1}), depending on the soil. CA had less temporal variability in infiltration capacity than CONV. Under CONV, infiltration was generally high after ploughing but decreased rapidly (by a factor of 2–20) depending on the soil and depth studied. AWC was significantly higher in the surface horizon (0–5 cm) under CA than under CONV, but the difference remained small (≤10 %) at the scale of the soil profile. In contrast, rooting depth, and thus the ability to use this AWC, was higher under CA. Thus, the changes in soil water functioning under CA seem to be related more to improved functioning of the AWC (through greater and more stable infiltration over time) and use by crops (through increased root exploration) than to an increase in the AWC itself. These elements make it possible to better evaluate effects of CA implementation on crop water supply and quantitative water management under CA.

1. Introduction

In most of the scenarios considered, climate change leads to a scarcity of water resources in certain regions of Europe that already have a water deficit, such as south-western France (Lehner et al., 2006; Garcia-Ruiz et al., 2011). Agricultural systems play an important role in regulating and modifying water flows at a regional scale through the choice of crop rotations and associated agricultural practices, such as the use of irrigation. Developing more agro-ecological systems, i.e. those that rely more on natural ecological processes of agro-ecosystems than on synthetic inputs (e.g. pesticides, fertilizers, fuel), could help improve water management and thus be of interest for addressing impacts of climate change.

Conservation agriculture (CA), based on decreasing tillage greatly, diversifying crops and maintaining maximum cover of living plants or residues on the soil surface (Scopel et al., 2013; Nichols et al., 2015; Ranaivoson et al., 2017), reduces soil disturbance by agricultural practices and promotes carbon storage in soils via cover crops, thus helping to mitigate climate change impacts (Pellerin et al., 2019). However, water dynamics under CA remain relatively unknown, especially for the wide range of soils and climates that can be found at the scale of large catchments. As a result, current crop models do not represent the functioning of CA systems well, whereas explicitly considering it would allow scenarios of CA establishment to be assessed over broad spatial and temporal scales.

At the scales of an agricultural field and a catchment, water is distributed in environmental compartments according to a variety of mechanisms: evaporation from the soil, plant transpiration, runoff (a potential source of erosion), and infiltration, which can recharge the soil's water reserve but lead to drainage through the unsaturated zone

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and to leaching of nitrate or pesticides. Physical, chemical, and biological properties of soils, under the strong influence of agricultural practices in cultivated fields, strongly influence the distribution and quality of water through a variety of mechanisms. These properties generally have high spatial and temporal variabilities, whose magnitudes usually depend on the scale at which they are observed (Starr, 1990; van Es et al., 1999; Horn, 2004), and they interact with agricultural practices. Thus, improving knowledge about soil properties and the magnitudes of their temporal and spatial variabilities is fundamental to (i) better describe soil processes, such as infiltration, runoff, aquifer recharge, and migration of nutrients or pollutants, and (ii) optimise the design and management of irrigation and drainage systems (van Es et al., 1999; Bagarello et al., 2005; Hu et al., 2009). Both are therefore important prerequisites for modelling impacts of climate change on these processes and the resulting effects on agricultural production.

In brief, tillage is a major source of variability in the physical properties of the surface horizon, both spatially and temporally (Messing and Jarvis, 1993; Prieksat et al., 1994; Coutadeur et al., 2002; Alletto and Coquet, 2009). The mechanical action of tillage alters soil structure, aggregation, porosity, organic-matter and crop-residue distributions, and surface roughness, among other things. Bulk density (ρ_b) is generally lower immediately after tillage and increases over time under the influence of precipitation (Onstad et el., 1984) and rearrangement of organo-mineral particles (Fohrer et al., 1999; Leij et al., 2002; Osunbitan et al., 2005). Hydraulic conductivity (*K*), one of the main soil properties that controls the movement of water and solutes, depends soil structure, and thus on tillage practices. Generally, under systems with mouldboard ploughing (the conventional practice in France, especially on spring crops), *K* is higher immediately after tillage and then decreases during the cropping season by natural densification and reorganisation of the porosity created by tillage and rearrangement of organo-mineral particles (Angulo-Jaramillo et al., 1997; Azevedo et al., 1998). Water dynamics in these intensive-tillage systems are usually considered “lateral dominant”, due to the lateral heterogeneity of water properties caused by ploughing (Coutadeur et al., 2002; Roger-Estrade et al., 2004; Alletto et al., 2010). Tillage can lead to high subsurface flows that result in a local lack of oxygen (due to water saturation) for plants, solute leaching by gravity flow, and a strong decrease in the available water capacity (AWC), which is the maximum quantity of water that soil can theoretically store (Cousin et al., 2022). Moreover, due to the low stability of soil aggregates, tillage systems often appear to be the source of large amounts of runoff, which generates erosion that is of concern for the sustainability of the soil (especially in south-western France).

Conservation tillage (Hobbs et al., 2008), and more broadly CA (Palm et al., 2014), minimises soil disturbance by tillage and modifies all water dynamics, in particular by strengthening “vertical dominant” functioning (Wahl et al., 2004). The presence of organic residues influences the structure of the soil surface by increasing sinuosity and roughness, which can increase infiltration capacity (Findeling et al., 2003). Crop residues absorb energy from rainfall and protect the soil surface from clogging (Blevins and Frye, 1993; Baumhardt and Lascano, 1996; Baumhardt and Jones, 2002). They also decrease the “splash” effect of rainfall and generally increase the stability of aggregates (Mamedov et al., 2000; Six et al., 2000a; Six et al., 2000b; Pinheiro et al., 2004). In parallel, soil biological activity, particularly of macrofauna, usually increases under CA. These processes create a stable bioporosity that also favours vertical water infiltration (and thus decreases runoff) (Edwards et al., 1990; Edwards et al., 1992). However, not all results for CA in the literature on this subject agree, and contradictions appear, with CA practices showing higher (Arshad et al., 1999; Dexter and Birkas, 2004), equivalent (Blanco-Canqui et al., 2004; Fuentes et al., 2004) or even lower (Heard et al., 1988; Gomez et al., 1999) infiltration capacities than those observed in tilled systems. These differences may be related to the failure to consider temporal dynamics of properties, as described in a previous study (Alletto and Coquet, 2009), and ultimately result in assessing soil water dynamics poorly. Several studies have used pedotransfer functions to predict certain variables, in particular *K* at saturation (K_S) as a function of ρ_b (Chen et al., 1998; Blanco-Canqui et al., 2004; Parasuraman et al., 2007; Lilly et al., 2008), but some of these studies show that the relation between them is valid for systems with conventional tillage but not with reduced tillage or no-tillage (Chen et al., 1998). This disconnect between measurements of ρ_b and K_S under CA may be due to inaccurate estimates of pore connectivity under no-tillage when using the cylinder method to measure ρ_b. Furthermore, the larger the pore diameter, the smaller the ratio between their contribution to the decrease in ρ_b and their contribution to the increase in *K*. Thus under CA, it appears necessary – in the absence of field measurements – to develop new models to predict certain variables that are more difficult to access (or more costly), such as *K*, ideally based on existing data sets.

Along with these effects on infiltration capacities, content, amount and redistribution of organic matter can modify soil water retention and thus the AWC, which is retained mainly on the soil’s organo-clay aggregates, and thus depends strongly on soil texture and structure (Assouline and Or, 2014; Cousin et al., 2022). One of the main mechanisms for relocating organic matter to the soil surface is to reduce tillage intensity. No-tillage systems often increase AWC, but this effect depends on the agro-pedoclimatic situation (Arshad et al., 1999; Drury et al., 1999; Green et al., 2003), and studies that rigorously compare systems under equivalent initial soil conditions remain scarce (Strudley et al., 2008). Given the results published to date, effects of tillage on soil water properties, in particular the soil’s capacity to let water infiltrate and then to store it, are still not clearly established (Or and Ghezzehei, 2002; Green et al., 2003; Strudley et al., 2008). Much hope, however, is placed on storing carbon in soils to increase water retention and thus make cropping systems more resilient to climate change. The *meta*-analysis of Minasny and McBratney (2018) recently showed that effects of soil carbon content alone on water retention were positive but much more moderate than expected, especially for increasing soil AWC. Other studies show more encouraging results for retaining water by storing carbon, particularly for coarse and fine-textured non-calcareous soils (Bagnall et al., 2022). These two studies differ significantly in both measurement methods, based on undisturbed soil cores for Bagnall et al. (2022) vs disturbed and undisturbed soil cores for Minasny and McBratney (2018), and in the scope of the experimental designs, with the Bagnall et al. (2022) study more specifically targeting the effects and variability of soil management practices. Nevertheless, knowledge about effects of combinations of practices, as practiced in CA, on the circulation and storage of water in the soil remains scarce, as most studies have focused on one factor (often tillage) and assumed “all other things being equal”. The coherence of cropping systems under CA, however, is based on combining no-tillage, diversified crop rotations, and cover crops, which likely changes the behaviour of soil water greatly, but it has been studied little to date. For example, in no-tillage, introducing a cover crop between the growing seasons of main crops maintains higher water content in surface horizons, because evaporation decreases more than transpiration increases (Drury et al., 1999), and could increase soil water retention (Basche et al., 2016). In shallow tillage (<10 cm), introducing a cover crop during the fallow period can also lead to drying of deeper horizons (30–60 cm), due to water uptake by the cover crop, which decreases recharge of the AWC when the main crop is planted (Unger and Vigil, 1998; Meyer et al., 2019; Meyer et al., 2020).

The objectives of the on-farm experiments were to better characterize the effects of CA cropping systems, based on no-tillage, crop diversification, and maximum soil cover, on soil physical properties that influence water dynamics in different soil types in the Adour-Garonne basin of France. The research hypotheses were that, regardless of soil type, CA systems would (i) increase the amount of retained water available to plants and (ii) improve water infiltration capacity through greater porosity throughout a cropping season compared to conventional systems with regular tillage and low soil cover and plant diversification. To test these hypotheses, the measurements included estimating the AWC of a variety of soils and their K_S at multiple depths and areas of the field, as well as on different dates to assess their temporal dynamics.

2. Materials and methods

2.1. Study sites

The experiments were conducted at 7 sites in the southern part of the Adour-Garonne basin, south-western France (Fig. 1). The dominant climate at these sites is an altered oceanic climate, with some continental influence for the sites in the eastern part of the basin. Soil types are mainly Calcisols, Umbrisols, and Luvisols (ISSS Working Group WRB, 2015), with some specific features depending on the location (Tables 1 and 2). At 4 "couple" sites each, two adjacent agricultural fields were monitored, one under CA and the other under a conventional system (CONV) with ploughing at least every other year. At 3 other "single" sites, only fields under CA were monitored. The sites under CA were chosen to study soils with a long history of CA and include farmers who had mastered CA practices. Thus, the fields selected had been under CA for 9–28 years at the start of the project (Table 1). Details of crop rotations are given in Table 1. The crops grown during the project period (2016–2019) did not always represent all crops in each rotation, as some rotations lasted longer than 4 years (Table 1).

Briefly, at sites 1 and 2, the CONV systems were maize monocultures, with no cover crop during the fallow period, and the CA systems, only cultivated with no-till, were slightly more diversified, with soya bean and cover crops (composed of mixtures of 3–5 species, including faba bean, oat, and phacelia). At both sites, for the CA systems, cover crops produced high biomass (>5 t dry matter/ha) over the 4 years of monitoring, and winter crops (a triticale/wheat/pea/vegetable mixture at site 1 and a triticale/pea mixture at site 2) were grown outside the project period in 2015 and 2020. At site 3, the rotations and use of cover crops differed less between the CONV and CA systems. In addition, the CA plot was cultivated with strip-tillage. Sites 4–7, all under CA, were located on Calcisols and mainly on hillsides. Sites 4 and 6 were no-tillage only. Site 5 was no-tillage for wheat and strip-tillage for soya bean. Site 6 was no-tillage for wheat as a sole crop and shallow tillage (<8 cm) for the other crops in the rotation or for mixtures.

2.2. Measurement and adjustment of soil physical properties

Measurements were performed at different times and frequencies (1–5 measurement campaigns) at the sites (Table 1). During each campaign, small pits were dug in 3 areas per field, and measurements were made in triplicate at depths of 0–5, 5–10, 10–25, and 25–50 cm.

2.2.1. Estimating available water capacity

Water-retention curves ($\theta(h)$) were determined using Richards pressure plates (Klute, 1986) using undisturbed soil samples collected with stainless steel cylinders (diameter: 5 cm, height: 2.5 cm, volume: 50 cm^3). These samples were gradually saturated with water in the laboratory (saturation time ≈ 4 d). Once saturated, the samples were weighed and then placed on porous plates covered with kaolinite to

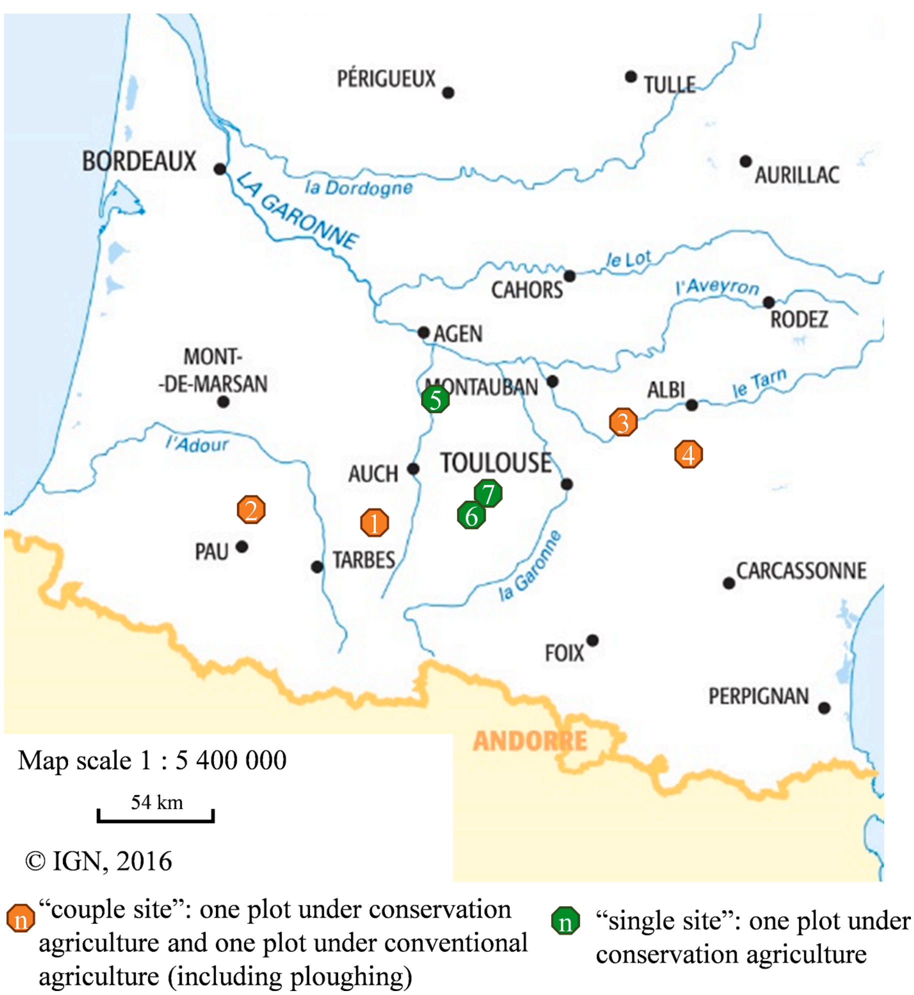

Fig. 1. Locations of the 4 "couple" sites and 3 "single" sites in the Adour-Garonne basin of south-western France.

Table 1
Main characteristics of the study sites under conservation agriculture (CA) or conventional agriculture with mouldboard ploughing (CONV). CC: soil covered with a cover crop during the fallow period.

Site*	Department	Soil type**	Soil depth (cm)	Cropping system***	Crop rotation (years)	Crops 2016	Crops 2017	Crops 2018	Crops 2019	Irrigation	Soil physical property measurement campaign
Site 1 (couple)	Gers	Gleyic Luvisol	50–60	CA (1999)	5	Maize (CC)	Maize**** (CC)	Soya bean (CC)	Maize (CC)	Yes	4 (Fall 2016; Spring-Fall 2017; Summer 2018)
				CONV	1	Maize (bare soil)	Maize (bare soil)	Maize (bare soil)	Maize (bare soil)		
Site 2 (couple)	Pyrénées-Atlantiques	Vermic Umbrisol	>90	CA (2006)	5	Maize (CC)	Maize (CC)	Maize (CC)	Soya bean (CC)	No	5 (Fall 2016; Spring-Fall 2017; Spring-Fall 2018)
				CONV	1	Maize (bare soil)	Maize (bare soil)	Maize (bare soil)	Maize (bare soil)		
Site 3 (couple)	Tarn	Gleyic Luvisol	80–90	CA (2000)	2	Barley (CC)	Maize	Barley (CC)	Maize	Yes	3 (Fall 2016; Spring-Fall 2017)
				CONV	3	Barley (CC)	Maize (CC)	Soya bean	Maize		
Site 4 (couple)	Tarn	Cambic Calcisol	60–80	CA (1988)	6	Wheat (CC)	Maize	Wheat (CC)	Soya bean	Yes	2 (Fall 2016; Spring 2019)
				CONV	2	Wheat	Maize	Wheat	Maize		
Site 5 (single)	Gers	Vertic Calcisol	50–60	CA (2007)	2	Soya bean	Wheat (CC)	Soya bean	Wheat (CC)	No	2 (Spring 2018; Spring 2019)
Site 6 (single)	Gers	Cambic Calcisol	80–90	CA (2006)	6	Faba bean	Wheat	Rapeseed (CC)	Pea (CC)	Yes	1 (Summer 2019)
Site 7 (single)	Gers	Calcisol	70–80	CA (2007)	6	Bird's-foot trefoil	Wheat	Barley/pea/vetch	Wheat	No	1 (Spring 2018)

*: Couple site: two adjacent agricultural fields were monitored, one under CA and the other under a conventional system (CONV) with ploughing at least every other year; Single site: only one field under CA was monitored.
**: soil type according to the World Reference Base for Soil Resources (ISSS Working Group WRB, 2015).
***: in brackets, the year when CA began.
****: Underlined maize crops are those whose root development was observed.

increase contact between the sample and the plate and thus establish hydraulic continuity. The matric potentials (h, in cm) chosen to establish the water-retention curves were 0, −16, −33, −100, −330, −1000, −6300, −10 000, and −16 000 cm (i.e. pF from −1.0 to 4.2, with pF = $\log_{10}|h|$, $|h|$ in cm). The AWC (mm) of each soil horizon was calculated from the volumetric water contents (θ) measured at pF 2.5 (field capacity) and pF 4.2 (permanent wilting point). AWC was measured 731 times during the study.

2.2.2. Measuring saturated hydraulic conductivity and bulk density

K was measured using disc infiltrometers at matric potentials from −1.0 to −0.1 kPa (Perroux and White, 1988; Ankeny et al., 1991). The soil surface was prepared according to recommendations of Coquet et al. (2005). Water was infiltrated successively at matric potentials of –1.0, –0.6, −0.3, and −0.1 kPa. K was estimated from the infiltration data using Wooding's (1968) steady-state solution under constant matric potential:

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

with q_{∞} the steady-state infiltration flux [L T^{-1}], $K(h)$ the K [L T^{-1}] at a given matric potential h [L], and r the radius of the infiltrometer disc [L].

The exponential model of Gardner (1958) was used to calculate the K curve:

$$K(h) = K_S \exp(\alpha h) \quad [2]$$

with α [L^{-1}] a characteristic soil constant.

To measure ρ_b, undisturbed soil samples were collected with 250 cm^3 cylinders (diameter: 8 cm, height: 5 cm) near the sites where K was measured and then oven-dried (105 °C for 48 h) before analysis. Soil ρ_b and $K(h)$ were measured 1074 times each during the study.

2.2.3. Adjustment of soil physical properties

Soil hydraulic properties were described using van Genuchten (1980) type analytical functions that use the statistical pore-size-distribution model of Mualem (1976) to describe the water-retention curve ($\theta(h)$) (n = 731) and estimate $K(h)$ (n = 1074):

$$\theta(h) = \begin{cases} \theta_r + \dfrac{\theta_s - \theta_r}{[1 + |\alpha h|^n]^m} & h < 0 \\ \theta_s & h \geqslant 0 \end{cases} \quad [3]$$

$$K(h) = K_s S_e^l [1 - (1 - S_e^{1/m})^m]^2 \quad [4]$$

with θ_r and θ_s the residual (r) and saturated (s) volumetric soil water content [L^3 L^{-3}], respectively; α [L^{-1}], m, and n shape parameters (m = 1–1/n), with α the inverse of the air-entry value and n the pore-size distribution index; S_e the effective saturation ($S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r}$); and l a pore-connectivity parameter estimated as 0.5 by averaging conditions in a range of soils (Mualem, 1976).

These parameters were calibrated with the data for soil–water retention and from the *in-situ* tension disc infiltrometer using Gauss-Newton optimisation for fitting experimental data to theoretical equations. Samples from the 3 areas per site were merged, and thus the number of retention curves used to calculate the mean and standard deviation varied from 4 to 50.

2.3. Root-development observations

At sites 1, 2, and 3, maize root-development was observed in 2017, 2018, and 2019 in CA and CONV fields (Table 1) from flowering (ca. mid-July), when vegetative development peaked, until the beginning of senescence. Three small pits, 60 cm wide and 60–80 cm deep (depending on the soil), were dug in each field to estimate the density and depth of maize root-development and identify possible obstacles to it.

Table 2
Main soil characteristics of the study sites under conservation agriculture (CA) or conventional agriculture with mouldboard ploughing (CONV).

Site	Soil type	Cropping system	Depth (cm)	Clay content (g kg^{-1})	Silt content (g kg^{-1})	Organic carbon content (g kg^{-1})	pH
Site 1 (couple)	Gleyic Luvisol	CA	0–10	164 ± 22	596 ± 44	11.4 ± 1.8	5.8 ± 0.4
			10–30	180 ± 11	587 ± 25	8.7 ± 1.1	6.0 ± 0.4
			30–60	200 ± 46	601 ± 79	5.3 ± 0.5	6.5 ± 0.3
		CONV	0–10	123 ± 14	604 ± 17	7.5 ± 1.7	6.8 ± 0.2
			10–30	121 ± 9	593 ± 26	7.6 ± 1.6	6.8 ± 0.2
			30–60	167 ± 10	607 ± 35	3.2 ± 1.5	7.1 ± 0.1
Site 2 (couple)	Vermic Umbrisol	CA	0–10	156 ± 8	720 ± 10	19.0 ± 0.6	6.3 ± 0.0
			10–30	155 ± 11	724 ± 14	18.4 ± 0.5	6.4 ± 0.1
			30–60	156 ± 10	724 ± 14	9.7 ± 0.8	6.3 ± 0.1
		CONV	0–10	164 ± 12	718 ± 21	17.4 ± 2.2	6.5 ± 0.3
			10–30	158 ± 12	732 ± 11	17.4 ± 2.0	6.8 ± 0.3
			30–60	161 ± 8	727 ± 23	9.7 ± 0.7	6.9 ± 0.7
Site 3 (couple)	Gleyic Luvisol	CA	0–10	180 ± 12	431 ± 19	8.6 ± 0.4	6.7 ± 0.2
			10–30	180 ± 15	425 ± 24	7.4 ± 0.4	6.9 ± 0.1
			30–60	275 ± 20	419 ± 13	5.3 ± 0.4	7.3 ± 0.1
		CONV	0–10	195 ± 32	351 ± 60	8.2 ± 1.4	7.1 ± 0.7
			10–30	204 ± 42	347 ± 65	8.0 ± 1.4	7.0 ± 0.7
			30–60	302 ± 12	311 ± 94	5.4 ± 0.9	7.9 ± 0.8
Site 4 (couple)	Cambic Calcisol	CA	0–10	383 ± 40	377 ± 22	12.6 ± 3.7	8.5 ± 0.1
			10–30	349 ± 28	394 ± 20	16.7 ± 2.6	8.4 ± 0.0
			30–60	373 ± 28	385 ± 8	12.2 ± 0.2	8.5 ± 0.0
		CONV	0–10	345 ± 27	427 ± 64	11.1 ± 0.9	8.5 ± 0.0
			10–30	330 ± 27	425 ± 61	8.9 ± 0.4	8.6 ± 0.0
			30–60	331 ± 54	417 ± 64	5.4 ± 0.9	8.6 ± 0.1
Site 5 (single)	Vertic Calcisol	CA	0–10	449 ± 38	398 ± 12	13.7 ± 0.5	7.9 ± 0.9
			10–30	455 ± 29	397 ± 9	9.7 ± 0.6	8.0 ± 0.7
			30–60	455 ± 39	403 ± 11	6.5 ± 0.6	8.1 ± 0.5
Site 6 (single)	Cambic Calcisol	CA	0–10	421 ± 22	355 ± 13	13.2 ± 0.8	8.2 ± 0.0
			10–30	417 ± 18	355 ± 16	8.9 ± 0.6	8.3 ± 0.1
			30–60	464 ± 24	366 ± 15	4.1 ± 0.6	8.4 ± 0.0
Site 7 (single)	Calcisol	CA	0–10	370 ± 34	445 ± 23	9.6 ± 0.7	8.5 ± 0.1
			10–30	377 ± 33	437 ± 24	7.2 ± 0.1	8.6 ± 0.0
			30–60	307 ± 113	519 ± 88	9.7 ± 7.7	8.9 ± 0.1

2.4. Data analysis

Unbalanced analyses of variance (ANOVA) were performed for three couple sites (sites 1, 2 and 3) to test the effects of soil type (i.e. site), cropping system, depth, and measurement period on ρ_b and $K(h)$. Since $K(h)$ values were exponentially distributed, they were $\log_{10}$-transformed, and the normal distribution of their residuals was verified before statistical analyses. The significance level of the tests was set to 0.01. The total variance was broken down to classify the factors by the degree to which each one explained the variance.

3. Results

3.1. Soil water retention

AWC varied from 43 ± 8 to 91 ± 11 mm to a soil depth of 50 cm. Soil type had the strongest influence on AWC, which was highest in silty or clayey-silt soils and lowest in clayey-limestone soils. A significant but relatively weak correlation ($r = 0.40$, $p < 0.05$) was found between AWC and the carbon stock of soil horizons.

An effect of the cropping system was observed at some "couple" sites, with CA soils having AWC 5–32 % higher than CONV soils, depending on the horizon (Appendix 1). From 0 to 50 cm, these differences represented an increase in AWC from 6 mm at site 1 to 10 mm at site 4. At site 2, located on a loamy soil, AWC differed by only 5 mm between the two cropping systems, mainly due to an increase from 10 to 25 cm under CA. At site 3, AWC did not differ between cropping systems, but CA there included relatively deep tillage (25 cm) along the seed line (i.e. strip tillage), whereas at the other "couple" sites, CA crops were sown directly.

Mean parameter values for retention curves varied greatly depending on the depth of sampling and the system (Table 3a). Soil porosity was 5–7 % lower from 25 to 50 cm than from 0 to 5 cm under CA (Table 3a, Fig. 2). Only sites 2 (loamy soil) and 6 (clay soil) showed uniform porosity profiles, similar to the profiles under CONV. Under CA, θ_s was 3–4 % lower than that in adjacent CONV fields, and porosity was also lower. In contrast, θ_r was significantly higher under CA, especially from 0 to 5 cm, where differences between systems were largest. Residual water content can be considered a good indicator of intra-aggregate porosity and thus of structural stability, which appeared to be much lower under CONV (data not shown). The inverse of the air-entry value (α) also differed, with fields under CA having lower values than CONV fields, which, in particular, increases the potential for deep water to rise by capillary action. Finally, the pore-size distribution index (n) was relatively constant regardless of the depth or system. Water-retention curves of the 7 sites (Fig. 2) highlighted (i) higher macropore porosity under CONV (albeit without assessing its temporal variability, as it was not measured dynamically); (ii) slightly higher mesopore porosity under CA (i.e. the inter-aggregate fraction, with water relatively immobile but easily taken up by crops) and (iii) higher micropore porosity under CA.

3.2. Bulk density and saturated hydraulic conductivity

The ρ_b varied from 1.27 to 1.71 Mg m^{-3} depending on the cropping system, depth and measurement period (Table 4). While the study site alone did not influence ρ_b, the interaction between site and system explained the largest percentage of its variance (32 %) (Table 5).

In general, ρ_b was higher and less variable over time under CA than under CONV (i.e. a significant site × system interaction) (Table 5). Under CONV, ρ_b was lower after tillage (i.e. spring on loamy soils), with densification identified over cropping seasons (Table 4).

K_S ranged from 2.4 to 1600 mm h^{-1}, with means (all sites, depths, and measurement periods combined) of 63.2 ± 65.3 mm h^{-1} under CONV and 157.2 ± 163.0 mm h^{-1} under CA. At sites 1–3, mean K_S was

Table 3
Values of van Genuchten's parameters obtained by fitting (a) $\theta(h)$ or (b) $K(h)$ to the experimental data set.

Site	Soil type	Cropping system	Depth (cm)	N	(a) van Genuchten's parameters				R^2	N	ρ_b	N	(b) van Genuchten's parameters				R^2
					θ_s	θ_r	α	n					K_s	Log (K_s)	α	n	
					%v/v	%v/v	(cm^{-1})				(Mg/m^{-3}(—|-))		(mm h^{-1})		(cm^{-1})		
Site 1 (couple)	Gleyic Luvisol	CA	0–5	50	43.2 ± 4.1	9.2 ± 2.5	0.06 ± 0.016	1.22 ± 0.028	0.998	49	1.53 ± 0.13	46	171 ± 108	2.16 ± 0.26	0.39 ± 0.16	2.72 ± 0.77	0.99
			5–10	28	40.3 ± 2.3	8.9 ± 2.3	0.06 ± 0.012	1.22 ± 0.035	0.998	42	1.56 ± 0.14	45	169 ± 65	2.19 ± 0.18	0.44 ± 0.31	3.00 ± 0.73	0.99
			10–25	23	35.9 ± 2.5	7.3 ± 2.4	0.07 ± 0.029	1.21 ± 0.043	0.997	46	1.57 ± 0.13	46	154 ± 69	2.14 ± 0.22	0.48 ± 0.40	2.92 ± 0.71	0.99
			25–50	23	34.7 ± 1.6	8.7 ± 2.6	0.06 ± 0.022	1.21 ± 0.030	0.997	44	1.55 ± 0.13	44	143 ± 50	2.13 ± 0.17	0.49 ± 0.33	3.22 ± 0.80	0.99
		CONV	0–5	48	42.6 ± 3.4	2.4 ± 4.5	0.13 ± 0.061	1.18 ± 0.038	0.993	47	1.47 ± 0.13	47	53 ± 46	1.56 ± 0.41	0.24 ± 0.13	2.47 ± 1.27	0.99
			5–10	33	43.9 ± 4.7	2.2 ± 4.4	0.14 ± 0.061	1.17 ± 0.047	0.991	44	1.45 ± 0.12	44	50 ± 40	1.57 ± 0.35	0.23 ± 0.14	3.14 ± 2.33	0.99
			10–25	19	41.4 ± 4.3	4.9 ± 3.8	0.10 ± 0.046	1.18 ± 0.040	0.990	46	1.44 ± 0.16	46	57 ± 50	1.61 ± 0.38	0.23 ± 0.13	2.80 ± 2.26	0.98
			25–50	21	35.0 ± 2.0	8.6 ± 2.5	0.08 ± 0.056	1.20 ± 0.026	0.992	45	1.51 ± 0.12	45	28 ± 26	1.31 ± 0.38	0.17 ± 0.12	2.11 ± 0.86	0.99
Site 2 (couple)	Vermic Umbrisol	CA	0–5	26	38.9 ± 2.3	10.9 ± 1.7	0.05 ± 0.014	1.23 ± 0.036	0.997	36	1.47 ± 0.11	36	201 ± 100	2.25 ± 0.23	0.35 ± 0.08	3.35 ± 1.10	0.99
			5–10	18	40.7 ± 2.0	10.1 ± 4.1	0.08 ± 0.025	1.20 ± 0.045	0.996	36	1.50 ± 0.13	36	136 ± 61	2.08 ± 0.25	0.36 ± 0.04	3.10 ± 0.74	0.99
			10–25	8	41.5 ± 3.0	6.1 ± 3.0	0.09 ± 0.037	1.19 ± 0.033	0.996	36	1.51 ± 0.11	36	141 ± 70	2.08 ± 0.26	0.36 ± 0.04	3.35 ± 1.01	0.99
			25–50	9	41.7 ± 1.6	8.9 ± 1.9	0.06 ± 0.012	1.21 ± 0.018	0.998	36	1.52 ± 0.12	36	106 ± 56	1.96 ± 0.26	0.37 ± 0.04	3.01 ± 0.86	0.99
		CONV	0–5	31	42.3 ± 3.0	4.7 ± 3.9	0.10 ± 0.039	1.2 ± 0.044	0.990	31	1.45 ± 0.14	31	83 ± 69	1.78 ± 0.35	0.27 ± 0.12	2.29 ± 0.70	0.99
			5–10	18	42.9 ± 3.5	5.7 ± 4.8	0.11 ± 0.061	1.17 ± 0.033	0.993	30	1.42 ± 0.14	30	76 ± 66	1.75 ± 0.33	0.22 ± 0.19	2.25 ± 1.24	0.99
			10–25	11	43.9 ± 3.1	5.2 ± 3.9	0.11 ± 0.050	1.17 ± 0.033	0.994	30	1.44 ± 0.13	30	83 ± 64	1.78 ± 0.38	0.27 ± 0.15	2.34 ± 0.89	0.99
			25–50	12	43.4 ± 2.5	7.8 ± 2.5	0.07 ± 0.021	1.21 ± 0.022	0.998	30	1.48 ± 0.13	30	37 ± 39	1.44 ± 0.30	0.20 ± 0.14	1.94 ± 0.59	1.00
Site 3 (couple)	Gleyic Luvisol	CA	0–5	37	40.2 ± 3.4	7.3 ± 4.6	0.10 ± 0.048	1.17 ± 0.045	0.982	26	1.49 ± 0.11	26	116 ± 63	1.98 ± 0.31	0.31 ± 0.14	2.58 ± 0.87	0.99
			5–10	23	35.9 ± 2.5	11.9 ± 4.2	0.08 ± 0.030	1.17 ± 0.037	0.991	30	1.47 ± 0.10	30	114 ± 50	2.02 ± 0.20	0.32 ± 0.12	2.66 ± 0.89	0.99
			10–25	15	35.8 ± 2.2	8.8 ± 3.8	0.08 ± 0.033	1.18 ± 0.032	0.989	30	1.52 ± 0.10	30	94 ± 43	1.93 ± 0.20	0.25 ± 0.13	2.36 ± 0.74	0.99
			25–50	9	32.6 ± 1.2	12.9 ± 2.8	0.06 ± 0.012	1.2 ± 0.022	0.991	30	1.51 ± 0.10	30	91 ± 48	1.89 ± 0.27	0.28 ± 0.15	2.47 ± 0.73	0.99
		CONV	0–5	36	39.4 ± 4.0	3.3 ± 3.9	0.10 ± 0.068	1.22 ± 0.092	0.962	24	1.52 ± 0.16	24	72 ± 57	1.71 ± 0.39	0.23 ± 0.13	2.26 ± 0.73	0.99
			5–10	23	37.0 ± 4.7	6.3 ± 3.1	0.10 ± 0.125	1.18 ± 0.078	0.966	30	1.51 ± 0.11	30	59 ± 46	1.66 ± 0.32	0.25 ± 0.15	2.22 ± 0.69	0.99
			10–25	15	37.9 ± 3.5	3.4 ± 5.9	0.15 ± 0.086	1.15 ± 0.043	0.986	30	1.49 ± 0.17	30	107 ± 123	1.76 ± 0.49	0.24 ± 0.19	2.65 ± 1.56	0.99
			25–50	9	34.5 ± 2.6	9.4 ± 4.5	0.08 ± 0.020	1.17 ± 0.016	0.996	30	1.63 ± 0.11	30	38 ± 17	1.53 ± 0.25	0.15 ± 0.11	1.92 ± 0.54	0.99
Site 4 (couple)	Cambic Calcisol	CA	0–5	24	43.6 ± 3.9	11.0 ± 6.2	0.08 ± 0.040	1.18 ± 0.032	0.989	26	1.49 ± 0.12	26	160 ± 134	2.02 ± 0.43	0.27 ± 0.15	1.90 ± 0.27	1.00

(*continued on next page*)

Table 3 (*continued*)

Site	Soil type	Cropping system	Depth (cm)	N	(a) van Genuchten's parameters				R^2	N	ρ_b	N	(b) van Genuchten's parameters				R^2
					θ_s	θ_r	α	n					K_s	Log (K_s)	α	n	
					%v/v	%v/v	(cm^{-1})				(Mg/m^{-3}(−|-))		(mm h^{-1})		(cm^{-1})		
			5–10	9	38.8 ± 2.9	17.5 ± 3.5	0.06 ± 0.012	1.20 ± 0.023	0.996	10	1.49 ± 0.09	10	239 ± 395	1.98 ± 0.56	0.3 ± 0.28	1.86 ± 0.45	1.00
			10–25	9	35.4 ± 1.9	15.7 ± 3.0	0.05 ± 0.006	1.21 ± 0.016	0.997	10	1.52 ± 0.15	11	90 ± 103	1.69 ± 0.50	0.26 ± 0.12	1.89 ± 0.07	1.00
			25–50	9	34.2 ± 1.2	16.8 ± 2.6	0.05 ± 0.010	1.21 ± 0.027	0.995	9	1.45 ± 0.11	9	154 ± 163	2.04 ± 0.37	0.19 ± 0.14	1.83 ± 0.20	0.98
		CONV	0–5	15	42.4 ± 2.7	3.2 ± 4.1	0.10 ± 0.090	1.22 ± 0.103	0.954	12	1.43 ± 0.10	12	167 ± 105	2.15 ± 0.25	0.20 ± 0.09	1.92 ± 0.04	0.99
			5–10	4	42.5 ± 1.3	14.0 ± 2.2	0.08 ± 0.022	1.17 ± 0.028	0.995	0		0					
			10–25	4	43.9 ± 2.9	14.6 ± 2.8	0.09 ± 0.017	1.15 ± 0.021	0.983	0		0					
			25–50	4	41.4 ± 3.9	17.1 ± 4.7	0.06 ± 0.028	1.19 ± 0.054	0.991	0		0					
Site 5 (single)	Vertic Calcisol	CA	0–5	9	44.5 ± 2.6	14.3 ± 4.3	0.08 ± 0.021	1.17 ± 0.033	0.990	9	1.44 ± 0.06	9	438 ± 438	2.46 ± 0.44	0.30 ± 0.14	1.98 ± 0.11	1.00
			5–10	9	39.2 ± 2.8	17.0 ± 3.5	0.07 ± 0.015	1.18 ± 0.026	0.994	9	1.46 ± 0.10	9	274 ± 218	2.33 ± 0.31	0.30 ± 0.13	1.99 ± 0.14	1.00
			10–25	9	37.4 ± 2.2	14.4 ± 3.8	0.06 ± 0.017	1.19 ± 0.029	0.996	10	1.57 ± 0.14	10	71 ± 66	1.66 ± 0.45	0.22 ± 0.07	1.99 ± 0.14	1.00
			25–50	9	38.2 ± 1.1	15.6 ± 1.9	0.06 ± 0.017	1.19 ± 0.035	0.995	9	1.56 ± 0.07	9	56 ± 20	1.72 ± 0.16	0.11 ± 0.06	1.84 ± 0.17	0.99
Site 6 (single)	Cambic Calcisol	CA	0–5	9	41.5 ± 4.6	14.8 ± 3.2	0.08 ± 0.026	1.17 ± 0.041	0.991	17	1.52 ± 0.13	17	375 ± 329	2.38 ± 0.53	0.34 ± 0.18	1.96 ± 0.14	1.00
			5–10	9	42.4 ± 5.5	14.0 ± 1.2	0.08 ± 0.030	1.17 ± 0.041	0.990	18	1.48 ± 0.10	18	322 ± 282	2.27 ± 0.60	0.24 ± 0.13	1.87 ± 0.14	0.99
			10–25	9	40.1 ± 1.5	18.6 ± 3.3	0.05 ± 0.014	1.22 ± 0.037	0.996	18	1.65 ± 0.15	18	110 ± 189	1.61 ± 0.63	0.17 ± 0.07	1.88 ± 0.18	1.00
			25–50	9	40.5 ± 2.2	20.4 ± 3.6	0.05 ± 0.016	1.22 ± 0.033	0.995	21	1.68 ± 0.11	21	75 ± 65	1.72 ± 0.39	0.20 ± 0.08	1.94 ± 0.20	1.00
Site 7 (single)	Calcisol	CA	0–5	9	44.5 ± 2.0	13.2 ± 6.2	0.08 ± 0.031	1.17 ± 0.039	0.991	8	1.48 ± 0.15	9	450 ± 359	2.48 ± 0.49	0.39 ± 0.19	1.95 ± 0.19	1.00
			5–10	9	41.4 ± 2.3	15.9 ± 6.9	0.07 ± 0.050	1.2 ± 0.046	0.995	9	1.49 ± 0.15	9	271 ± 420	1.97 ± 0.67	0.34 ± 0.13	1.91 ± 0.07	1.00
			10–25	9	36.8 ± 1.8	17.8 ± 1.8	0.05 ± 0.012	1.22 ± 0.029	0.996	9	1.62 ± 0.08	9	28 ± 33	1.23 ± 0.44	0.29 ± 0.13	2.01 ± 0.20	1.00
			25–50	9	36.0 ± 1.7	17.7 ± 3.7	0.06 ± 0.012	1.21 ± 0.032	0.995	10	1.57 ± 0.13	10	41 ± 26	1.54 ± 0.27	0.21 ± 0.05	1.96 ± 0.07	1.00

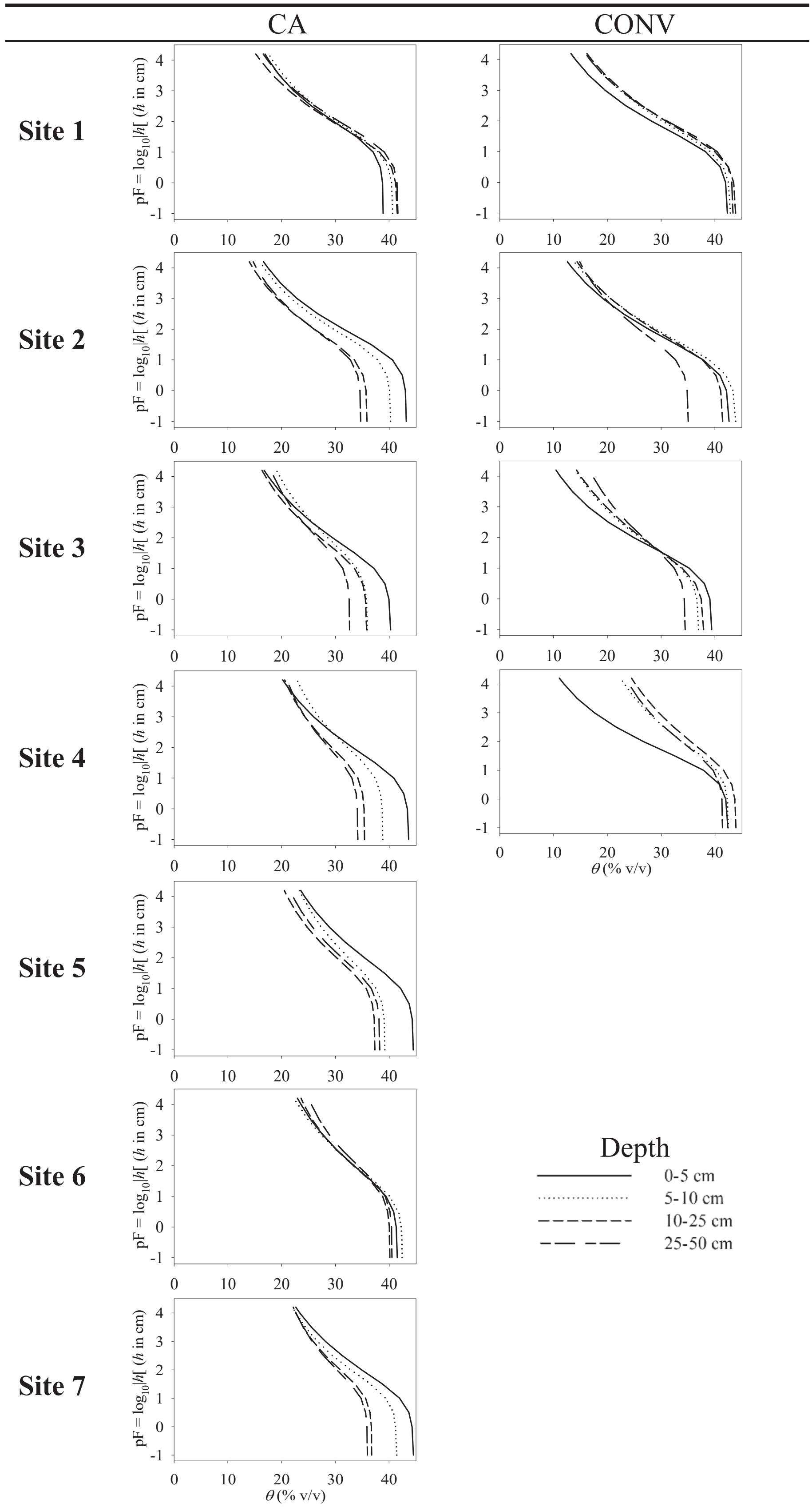

Fig. 2. Water retention curves of the 7 study sites, obtained by fitting of van Genuchten's function, with a comparison of conservation agriculture (CA) and conventional agriculture (CONV).

Table 4
Mean bulk density ($\rho_{b,}$ Mg/m^{-3} (±1 SD) of the soils from 0 to 50 cm for the 7 study sites.

Site	Period	CA	CONV
Site 1 (couple)	Fall 2016	1.57 ± 0.09	1.49 ± 0.10
	Spring 2017	1.55 ± 0.15	1.38 ± 0.13
	Fall 2017	1.55 ± 0.15	1.48 ± 0.10
	Summer 2018	1.54 ± 0.12	1.53 ± 0.16
Site 2 (couple)	Fall 2016	1.50 ± 0.10	1.47 ± 0.12
	Spring 2017	1.51 ± 0.11	1.34 ± 0.09
	Fall 2017	1.47 ± 0.12	1.55 ± 0.09
	Spring 2018	1.52 ± 0.14	1.35 ± 0.10
	Fall 2018	1.50 ± 0.13	1.54 ± 0.09
Site 3 (couple)	Fall 2016	1.53 ± 0.10	1.61 ± 0.10
	Spring 2017	1.49 ± 0.10	1.42 ± 0.15
	Fall 2017	1.47 ± 0.11	1.57 ± 0.11
Site 4 (couple)	Fall 2016	1.51 ± 0.12*	1.43 ± 0.10*
	Spring 2019	1.48 ± 0.12	–
Site 5 (single)	Spring 2018	1.63 ± 0.11	–
	Spring 2019	1.54 ± 0.16	–
Site 6 (single)	Summer 2019	1.50 ± 0.11	–
Site 7 (single)	Spring 2018	1.54 ± 0.14	–

* only the 0–5 cm horizon was measured.

Table 5
Variance components of bulk density (ρ_b) and saturated hydraulic conductivity (K_s) by study site (SITE) (only for sites 1, 2, and 3), cropping system (conservation agriculture (CA) and conventional agriculture (CONV)) (SYSTEM), measurement period (PERIOD), and measurement depth (DEPTH) ($p < 0.01$).

Effect	ρ_b	K_s
SITE	NS	NS
SYSTEM	26.3 %	51.8 %
PERIOD	11.3 %	2.6 %
DEPTH	6.9 %	4.2 %
SITE × SYSTEM	32.3 %	2.8 %
SITE × PERIOD	NS	NS
SITE × DEPTH	NS	NS
SYSTEM × PERIOD	8.4 %	28.5 %
SYSTEM × DEPTH	NS	NS
PERIOD × DEPTH	NS	NS

higher under CA (by a factor of 2–4, depending on the period and depth), explained nearly 52 % of the variance in K_S (Table 5), and was more stable over time (illustrated by the system × period interaction) (Fig. 3a). Under CONV, K_S was highest immediately after ploughing and decreased greatly during the cropping season (Fig. 3a). Values of van Genuchten's parameters used to fit $K(h)$ (Table 6, Appendix 2) provide additional evidence about the relation between K and pF, indicating that water flows decreased sharply when pF exceeded 0.5, with differences between systems. Permeability decreased more abruptly under CA than under CONV, which suggests that CA had a bimodal distribution of pore diameters.

K_S did not differ significantly among the 7 sites under CA, but did vary more in clayey-limestone soils than in loamy soils (Fig. 3b).

Based on all data, ρ_b and K_S were negatively correlated, but the relation explained only a small proportion of the variance (r = -0.25, $p < 0.01$). In contrast, when distinguishing among sites and between systems, correlations between ρ_b and K_S were stronger under CONV than under CA for all sites that could be compared (Table 6). Correlations were also stronger when the sites were analysed separately, regardless of the system.

3.3. Hysteresis in K(h) and θ(h)

Regardless of the study site or cropping system, hysteretic behaviour of water retention and K was identified using in-lab retention-curve measurements ($\theta(h)$) to characterize the drying phase and in-field infiltrometry measurements ($K(h)$) to characterize the wetting phase (Table 3b) of the soil horizons studied. The hysteresis between drying and wetting curves was large, with differences that could exceed 2 pF units depending on whether the soil was drying or wetting (Fig. 4, Appendix 3). In the wetting phase, pF responded strongly to an increase in soil water and more moderately afterwards. For a given AWC, CA always had lower pF, which suggests that it had more efficient hydraulic loading, due to greater pore connectivity. Furthermore, hydraulic loading occurs during the wetting phase, long before the soil becomes saturated: on average, the relative permeability (K/K_S) remained>0.1 for θ_s-$\theta < 10$ %. Water flows remained much higher under CA during the wetting phase when θ_s-$\theta < 10$ %. During the drying phase, flows stopped rapidly for θ_s-$\theta > 3$ %, regardless of the system or depth. The hysteresis was smaller in deeper horizons, however, presumably because pore hydraulic loading during the wetting phase occurs at higher water content. This pertained more to sites 5, 6 and 7, whose soils had high contents of swelling clays and $CaCO_3$, and were thus more predisposed to pore clogging in the sub-soil. The hysteresis of $K(h)$ was smaller from 25 to 50 cm under CONV, perhaps because the soil structure was degraded and because biological regeneration of porosity was less effective under CONV than under CA.

3.4. Root development of maize

Root development of maize, observed at sites 1, 2 and 3 in different crop years, differed among sites. At site 1, maize roots reached the bottom of the soil profile under CA (60 cm) but were limited mainly to the ploughed horizon (25 cm) under CONV. At site 2, maize roots reached a depth of at least 50 cm under CONV and 70–80 cm under CA, in particular by using the many galleries (of earthworms and previous crop roots) identified in the profiles. At site 3, maize roots under CONV behaved like those at site 1 and colonized mainly the ploughed horizon, with few roots exploring deeper (maximum depth: 55 cm). Under CA at site 3, maize roots explored mainly the tilled horizon of the strip tillage, but also went deeper to a depth of ca. 55 cm, as under CONV.

4. Discussion

Soil hydraulic properties play an important role in determining soil and environmental quality, including the ability of soil to support various ecosystem services. In particular, they control water retention and water-flow velocity, which in turn influence the fate of nutrients and pollutants in the soil, and determine water availability to plants for uptake and crop growth. These properties result from the intrinsic nature of soils and how they are managed. The results from the network of sites studied show first that the soil type determines its AWC, which is already well known (Minasny and McBratney, 2018; Cousin et al., 2022). In particular, silty soils had higher water-retention capacity than clay soils, especially clayey-limestone soils. More surprisingly, the results show that the type of agricultural management can also modify this retention capacity, albeit to a lesser degree than the soil type can, but they raise agronomic pathways for better management and improvement of water-retention capacities. It appears that implementing agroecological practices of CA can increase AWC (e.g. by ca. 5–19 % to a depth of 50 cm in this study), depending on the soil and its initial AWC. These effects are due mainly to (i) the increase in organic carbon content at the soil surface, which may increase water retention slightly (Minasny and McBratney, 2018) or more significantly (Lal, 2000; Rawls et al., 2003; Ankenbauer and Loheide, 2017), but also improves structural stability, and (ii) more broadly, a change in soil porosity, particularly an increase in micro- and mesoporosity (Bescansa et al., 2006; Strudley et al., 2008) and a decrease in macroporosity. The *meta*-analysis of Minasny and McBratney (2018), which analysed effects of increasing soil carbon content on water retention in soils by comparing a wide variety of situations, concluded that the effects were positive but lower than expected, with an increase mainly in the water content at saturation, related to an increase in macroporosity. In our study, comparison of

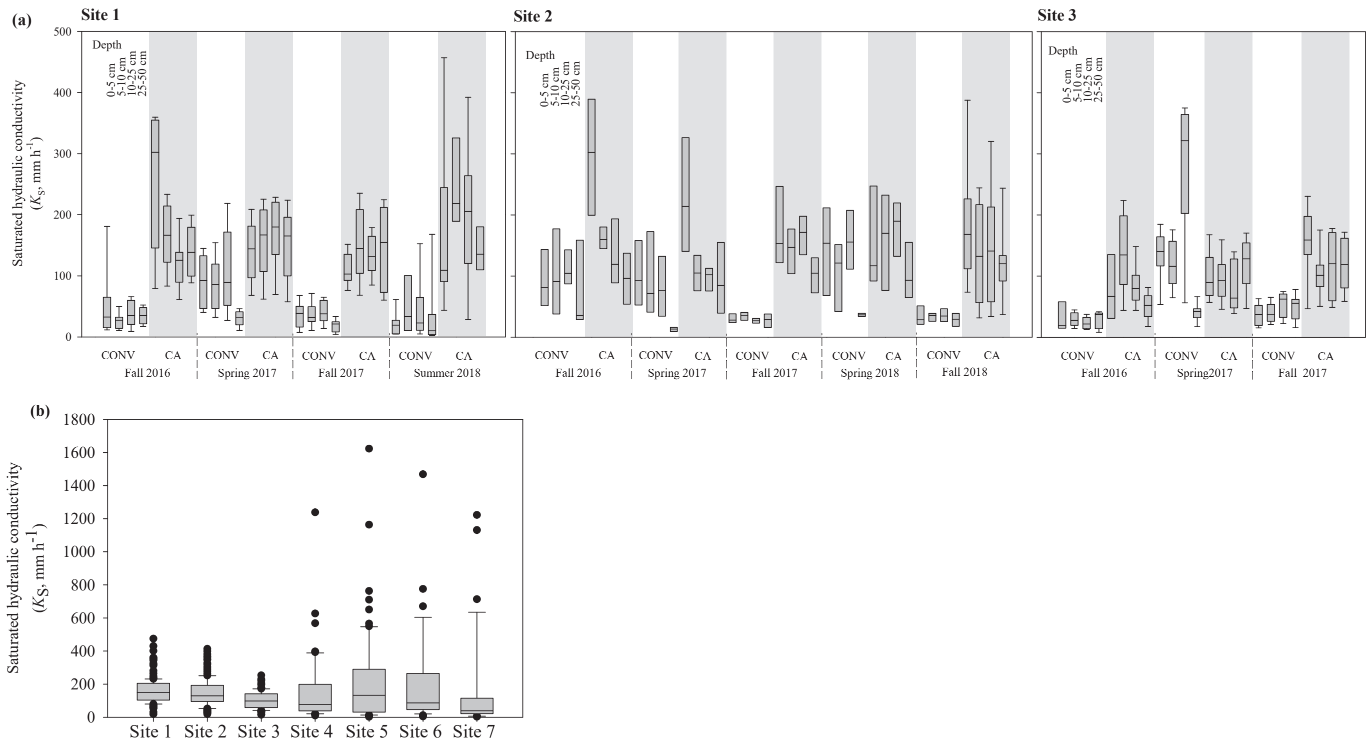

Fig. 3. Boxplots of saturated hydraulic conductivity (K_S, mm h^{-1}) measured (a) during different periods at 3 "couple" sites and (b) at a depth of 0–50 cm at different times from 2016 to 2018 at the 7 sites under conservation agriculture (CA). Error bars represent 1.5 times the interquartile range.

Table 6
Correlation coefficients between bulk density (ρ_b) and saturated hydraulic conductivity (K_s) in conservation agriculture (CA) and conventional agriculture (CONV) ($p < 0.01$) by study site.

Site	CA	CONV
Site 1 (couple)	−0.32	−0.65
Site 2 (couple)	−0.29	−0.60
Site 3 (couple)	−0.39	−0.71
Site 4 (couple)	−0.33	−0.67
Site 5 (single)	−0.54	–
Site 6 (single)	−0.34	–
Site 7 (single)	−0.51	–

plots with similar initial soils showed that implementing CA practices can increase water retention significantly and decrease macroporosity. Although more marked than the results obtained by Minasny and McBratney (2018), the magnitude of the effects of this additional carbon under CA on AWC observed in this study is consistent with those in the literature (Eden et al., 2017; Bagnall et al., 2022). The variability in effects observed among soil types is also consistent, with other studies indicating increases in AWC of 7–23 % depending on the initial AWC and the practices implemented (Chen et al., 2005; Moebius-Clune et al., 2008; So et al., 2009), with the largest proportional effects observed in soils with low AWC (e.g. sandy soils) (Rawls et al., 2003). Some differences between studies may be due to overall changes in soil functioning caused by combining CA practices (i.e. not only changing tillage), including increased water retention by cover crops (Basche et al., 2016)

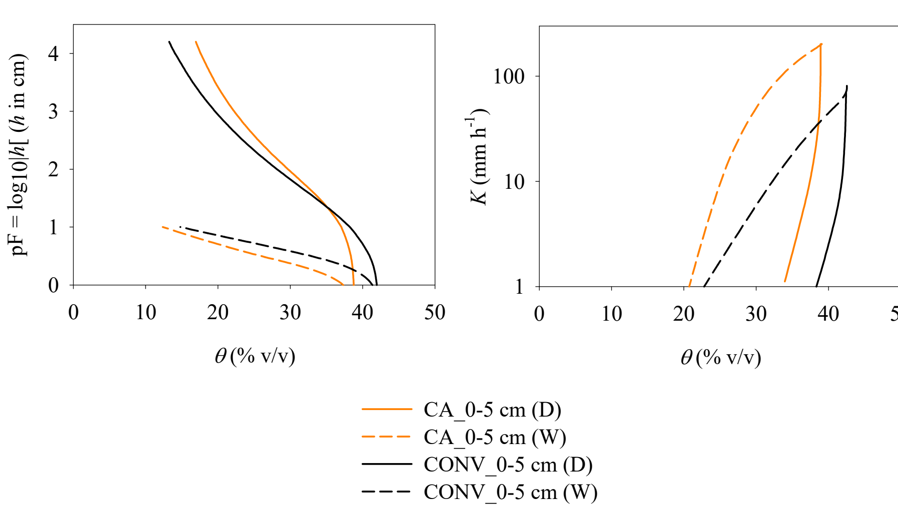

Fig. 4. Illustration of hysteresis in water retention and hydraulic conductivity for site 2 for conservation agriculture (CA) and conventional agriculture (CONV) in the 0–5 cm soil horizon (mean values of all measurement periods for $K(h)$).

or by micropores formed by mycorrhizal filaments (Gianinazzi et al., 2010; Philippot et al., 2013).

The effects of soil type on water infiltration capacity are less clear, but our results indicate that clay soils tend to have greater variability in infiltration capacity than loam soils. In the latter, the type of agricultural management modifies infiltration capacity greatly, with a strong increase infiltration capacity in all soil horizons under CA (at least down to 50 cm), mainly due to their greater temporal stability and the dominance of biological tubular porosity, which increases the vertical connectivity of macropores (Wardak et al., 2022). As indicated by Liao et al. (2022) part of the observed infiltration differences could be related to the measurement method used. They indeed found that measurements based on infiltrometers tend to accentuate the differences between systems with and without tillage, but mainly for subsoil horizons. In our study, we simultaneously performed infiltration measurements using the BeerKan method (Braud et al., 2005) (data not shown) and the trends observed were similar to those obtained with the infiltrometers which allows us to be confident in the effects observed between cropping systems. Nevertheless, based on the infiltration curves obtained, this tubular porosity, which transfers water rapidly under CA, seems to be associated with less connected porosity. In contrast, under CONV, K_S is usually lower, but water flows seem to depend less on the hydraulic load of interconnected biopores, and instead use other pathways such as soil-shrinkage cracks or tillage-induced macropores that are connected to mesopores. Although mechanical operations, in particular tillage, aim to aerate the soil by creating macropores, which leads to low ρ_b and high post-tillage infiltration capacities, the effects are transient (Alletto and Coquet, 2009). Relatively quickly, due to reconsolidation (or redensification) of the environment, the beneficial effects of tillage on water infiltration are lost (Green et al., 2003; Bodner et al., 2013). Finally, as mentioned, while effects of carbon storage in soils on water retention, although positive, are heterogeneous and still widely debated, the main effect of implementing CA seems to be higher infiltration capacity (here, by a factor of 2–4), as highlighted by Basche and DeLonge (2019), and greater temporal stability than those in tilled systems. These changes in the dynamics of soil water functioning, particularly recharge/drainage, could have more significant effects than increasing water retention capacity. Experimental data that illustrate these temporal dynamics remain rare (Strudley et al., 2008), whereas representing soil physical properties dynamically could improve simulation of soil water functioning in models (especially as a function of soil management), which still rely largely on constant values of K (and ρ_b) over time (Angulo-Jaramillo et al., 1997). Soil-infiltration capacities, which are time-consuming to measure, can be estimated using indicators such as ρ_b, as described in several studies (Jabro, 1992; Schaap and Leij, 1998). However, while the latter approach appears to be of interest for estimating K_S in tilled soils, it is less so for systems under CA. This nuance, highlighted in this study, but also in other studies (Chen et al., 1998; Alletto and Coquet, 2009), testifies to the need to develop new descriptors for soils with little or no disturbance from mechanical operations. They could, for example, consider connectivity of the pore network better (Amer et al., 2009), even though CA soils may have less total porosity than tilled soils. This is consistent with Cueff et al. (2021) regarding estimating AWC from pedotransfer functions. Furthermore, calculation of van Genuchten's parameters for $\theta(h)$ and $K(h)$ revealed that two of them, α and n, differ greatly depending on whether the wetting curve (corresponding to $K(h)$) or drying curve (corresponding to $\theta(h)$) is considered. Applying unsaturated-flow models that assume single-valued functions for $\theta(h)$ and $K(h)$ to characterize hydraulic properties at a given depth in the soil is thus unacceptable in this context. A more realistic description that involves hysteresis in soil hydraulic properties is required, following the pioneering studies of Scott et al. (1983) and Kool and Parker (1987), who introduced the consideration of hysteresis to estimate the water-retention curve and K.

The cropping systems implemented also influence the root development of crops. In this study, maize roots explored to at least the same depth under CA as under CONV, and usually to greater depths, even though ρ_b was often higher and soil mechanical strength much greater under CA. Observations in pits highlight that roots use mainly biologically derived galleries, abundant under CA, which has been well demonstrated in the literature (Soane et al., 2012). Consequently, roots likely explore soil AWC better under CA, and along with an increase in this AWC and infiltration capacity, which suggest improved dynamics of AWC recharge, uptake of water (from rainfall or irrigation) under CA is likely to exceed that of soils cultivated after ploughing. Surveying roots when estimating AWC is crucial, as discussed in the review of Cousin et al. (2022), but rarely performed because doing so is time consuming. Finally, these combined effects can increase the resilience of cropping systems under CA to the effects of climate change, which are reflected mainly in (i) an increase in the frequency of high-intensity rainfall events, requiring high and stable infiltration capacities of soils, and (ii) more intense and longer droughts, for which the increase in water-retention capacity, along with good use of this water stored near roots, could help limit adverse effects on crops.

5. Conclusion

The objective of this study was to quantify effects of cropping systems that used CA or conventional agriculture including ploughing on soil physical properties that influence water dynamics of different soil types in the Adour-Garonne basin. The results show that after several years of implementing agroecological practices that aimed in particular to store carbon in the soil and decrease mechanical disturbance:

- An increase in water-retention capacities: to a depth of 50 cm, this increase varied from 6 to 10 mm (i.e. + 5 % to + 25 %) of AWC between CA and conventionally tilled systems, depending on the soil type with the highest increases observed on clay-limestone soils (Cambic Calcisol) and the lowest observed on organic loamy soils (Vermic Umbrisol). This effect may contribute to improve the water supply of the plants, by 1 to 2 days during summer depending on evapotranspiration.
- An increase in infiltration capacities and their temporal stability: despite higher bulk density of the soil under CA, hydraulic conductivity was significantly higher, by a factor of 2–4, under CA (mean ≈ 160 mm h^{-1}) than that under tilled systems (mean ≈ 60 mm h^{-1}) with high intra-plot spatial variability, depending on the soil type. This increased infiltration can reduce runoff from intense rainfall events that occur more frequently in connection with climate change.
- An equivalent or deeper root exploration under CA: despite lower total porosity under CA, maize roots generally explored the soil more deeply than they did under ploughed systems, in which the roots colonized mainly the tilled zone (0–25 cm).

Thus, combining these three effects – higher water retention × higher infiltration capacities and their temporal stability × equivalent or deeper root exploration – suggests better use of water under CA than under ploughed systems, which can be of great interest in adapting cropping systems to effects of climate change and the contribution of these systems to mitigating these effects.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.geoderma.2022.116228.

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