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Soil Physical Quality of Citrus Orchards Under Tillage, Herbicide, and Organic Managements

Simone DI PRIMA[1,*], Jesús RODRIGO-COMINO[2,3], Agata NOVARA[4], Massimo IOVINO[4], Mario PIRASTRU[1], Saskia KEESSTRA[5,6] and Artemi CERDÀ[7]

[1] *Dipartimento di Agraria, Università degli Studi di Sassari, Sassari 07100 (Italy)*
[2] *Instituto de Geomorfología y Suelos, Department of Geography, Málaga University, Campus of Teatinos s/n, Málaga 29071 (Spain)*
[3] *Department of Physical Geography, Trier University, Trier D-54286 (Germany)*
[4] *Dipartimento di Scienze Agrarie, Alimentari e Forestali, Universit\`à degli Studi di Palermo, Palermo 90128 (Italy)*
[5] *Team Soil Water and Land Use, Wageningen Environmental Research, Wageningen UR, Droevendaalsesteeg 3, Wageningen 6700 AA (The Netherlands)*
[6] *Civil, Surveying and Environmental Engineering, The University of Newcastle, Callaghan 2308 (Australia)*
[7] *Soil Erosion and Degradation Research Group, Department of Geography, Universitat de València, Valencia 46010 (Spain)*

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ABSTRACT

Soil capacity to support life and to produce economic goods and services is strongly linked to the maintenance of good soil physical quality (SPQ). In this study, the SPQ of citrus orchards was assessed under three different soil managements, namely no-tillage using herbicides, tillage under chemical farming, and no-tillage under organic farming. Commonly used indicators, such as soil bulk density, organic carbon content, and structural stability index, were considered in conjunction with capacitive indicators estimated by the Beerkan estimation of soil transfer parameter (BEST) method. The measurements taken at the L'Alcoleja Experimental Station in Spain yielded optimal values for soil bulk density and organic carbon content in 100% and 70% of cases for organic farming. The values of structural stability index indicated that the soil was stable in 90% of cases. Differences between the soil management practices were particularly clear in terms of plant-available water capacity and saturated hydraulic conductivity. Under organic farming, the soil had the greatest ability to store and provide water to plant roots, and to quickly drain excess water and facilitate root proliferation. Management practices adopted under organic farming (such as vegetation cover between the trees, chipping after pruning, and spreading the chips on the soil surface) improved the SPQ. Conversely, the conventional management strategies unequivocally led to soil degradation owing to the loss of organic matter, soil compaction, and reduced structural stability. The results in this study show that organic farming has a clear positive impact on the SPQ, suggesting that tillage and herbicide treatments should be avoided.

Key Words: Beerkan estimation of soil transfer parameter, capacitive indicator, organic farming, soil management, soil quality assessment, structural stability index

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INTRODUCTION

In the Mediterranean region, millennia-old agriculture has resulted in the degradation of soil structure, organic matter depletion, and increased soil losses (Iovino *et al.*, 2016). There is an urgent need to restore agricultural soils to avoid floods, reduce carbon loss, and minimize reservoir siltation. Soil capacity to support life and to produce economic goods and services is strongly linked to the maintenance of good soil physical quality (SPQ) (Lal, 1993). Assessing SPQ may help researchers and decision-makers to identify agriculture practices, aiming to alleviate land degradation and increase sustainable land use (Dexter, 2004). Good SPQ implies the maintenance of a good soil structure and a high capacity to store and transmit water, air, and nutrients. Soils with such characteristics have the potential to adequately support crops and to reduce degradation (Reynolds *et al.*, 2007). The ability of soil to store and transmit water is expressed in terms of water retention curve, $\theta(h)$, and hydraulic conductivity function, $K(h)$, respectively (Castellini *et al.*, 2016). Soil water retention is a key factor in determining SPQ, which can be assessed using capacity-based indicators such as plant-available water capacity and relative water capacity (Topp *et al.*, 1997; Reynolds *et al.*, 2002, 2007). The capacity-based indicators are estimated from water retention data, which can be ob-

*Corresponding author. E-mail: sdiprima@uniss.it.

tained with different experimental methods both in the laboratory and the field. In the laboratory, it is common to use the hanging water column apparatus (Burke *et al.*, 1986) and the pressure plate apparatus (Dane and Hopmans, 2002) for high- and low-pressure heads, respectively. However, these measurement techniques rely on time-consuming experimental procedures (Angulo-Jaramillo *et al.*, 2016). Simpler methods can now be applied to fully characterize soil hydraulics in the field (Cullotta *et al.*, 2016). In particular, a simple field method has been reported to allow for the simultaneous characterization of both soil hydraulic characteristics, $\theta(h)$ and $K(h)$. This method, called the Beerkan estimation of soil transfer parameters (BEST), was developed by Lassabatere *et al.* (2006) to simplify soil hydraulic characterization. The BEST method estimates the shape parameters of the hydraulic characteristic curves, which are texture dependent, from particle size analysis and certain physical-empirical pedotransfer functions. Structure-dependent scale parameters are estimated by a three-dimensional field infiltration experiment, using the two-term transient infiltration equation described by Haverkamp *et al.* (1994). The BEST facilitates the hydraulic characterization of unsaturated soils, and it is gaining popularity in soil science (Xu *et al.*, 2009; Gonzalez-Sosa *et al.*, 2010; Yilmaz *et al.*, 2010; Nasta *et al.*, 2012; Aiello *et al.*, 2014; Souza *et al.*, 2014; Alagna *et al.*, 2016; Angulo-Jaramillo *et al.*, 2016; Coutinho *et al.*, 2016; Di Prima *et al.*, 2017b). Recent studies have demonstrated that the BEST is a promising method for the simple assessment of SPQ in agricultural, pasture, and forest soils (Bagarello *et al.*, 2011; Castellini *et al.*, 2016; Cullotta *et al.*, 2016; Souza *et al.*, 2017). The increasing interest in this methodology is mainly due to its simplicity, since it permits minimal field and laboratory efforts (Di Prima *et al.*, 2017b). Another reason for the interest is that more SPQ indicators can be collected, since hydrodynamic parameters can also be easily determined (Cullotta *et al.*, 2016).

Citrus production has important economic, social, and cultural significance in the Mediterranean, and in Spain, oranges are one of the largest exported agriculture crops. Citrus orchards are especially important near Valencia, where they produce more than 70% of the total Spanish citrus crops (5 461 Gg year^{-1}). Moreover, the area covered by citrus orchards has increased by 20% since 1982. Other Mediterranean regions of southern Spain, such as Murcia and Andalucía, have shown similar increases. Most of the recent orchards are located on slopes to avoid frost damage caused by temperature gradient inversions, which often occur during the coldest days in winter. This new strategy has also been used in other citrus orchards in the Mediterranean, such as southern Italy, Greece, Morocco, Turkey, and Israel; this is now possible thanks to drip or sprinkler irrigation, which wets the soil on sloping terrain. However, 50% of irrigated land in the Valencia region remains under flood irrigation, as the original citrus orchards were located on alluvial plains, fluvial terraces, or alluvial fans. Since the beginning of the 1860s, citrus orchards could be planted on slightly higher land, where they were irrigated using groundwater pumped up by steam engines. In the 1930s, the use of electricity allowed citrus production to further expand in inland districts; however, the land was always levelled with terraces to enable the use of flood irrigation and to avoid soil water erosion. The use of drip irrigation after the 1980s caused a large expansion of irrigated citrus orchards to many inland areas with sloping terrain instead of levelled terraces, since drip irrigation can be performed on any terrain.

The traditional soil management on flood-irrigated land was tillage. During the 1970s, the use of herbicides was initiated and currently it is the most commonly used management strategy, as 92% of the orchards use herbicides and only 5% are under tillage nowadays. Some orchards use no-tillage with cover crops, but they comprise only 3% of the Mediterranean region and are registered as European Union supervised organic farms. Since the 1990s, the regulation of organic farming has resulted in the use of catch crops, spontaneous cover crops, and no-tillage, which was negligible before (Hole *et al.*, 2005). There is an urgent need to determine the advantages that organic farming can bring to society. Changes in soil system as a consequence of organic management result in the biological enrichment of the ecosystem (Tuck *et al.*, 2014; Säle *et al.*, 2015). Furthermore, organic farming provides valuable ecosystem services (Bruggisser *et al.*, 2010; Cavigelli *et al.*, 2013) that feed into the recently adopted UN Sustainable Development Goals (Keesstra *et al.*, 2016a). The impact of soil management is also relevant to understand soil degradation and soil formation processes (Keesstra *et al.*, 2016b; Rodrigo Comino *et al.*, 2017); however, the influence of organic farming on soil quality has not been given the emphasis it deserves (Salomé *et al.*, 2014, 2016).

The objective of this research was to investigate the impacts of conventional and organic farming management practices, including no-tillage using herbicides, tillage under chemical farming, and no-tillage under organic farming, on soil physical quality under citrus crops.

MATERIALS AND METHODS

Location and soil managements

In 1996, the Soil Erosion and Degradation Research Group from the University of Valencia established the L'Alcoleja Experimental Station, 60 km from the Mediterranean coast, in L'Alcúdia de Crespins, southwest of Valencia Province in eastern Spain (Universal Transverse Mercator coordinate system: 709191X, 4316356Y; zone 30, altitude 156 m above sea level) (Fig. 1). The research station is devoted to studying the impact of citrus and persimmon plantations on soil degradation and restoration. Mean annual rainfall and temperature are 550 mm and 16 °C, respectively. The soil has been classified as a Xerorthent (Soil Survey Staff, 2014). The parent material is fluvial sediment from the nearby Riu de Sants, 50 m from the talweg.

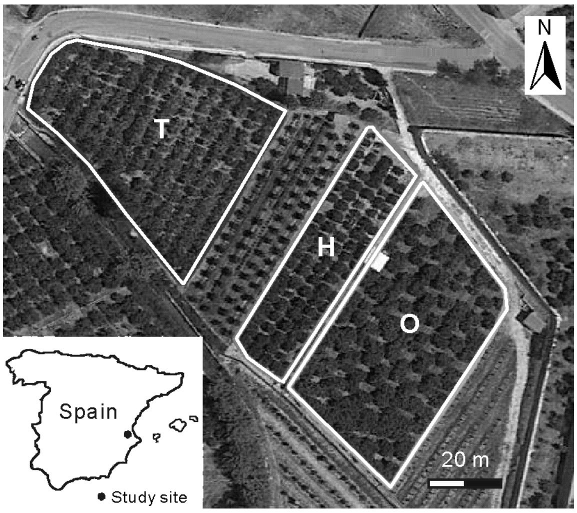

Fig. 1 Location of the study site at the L'Alcoleja Experimental Station in eastern Spain. Three plots under different soil managements, namely no-tillage using herbicides (H), tillage under chemical farming (T), and no-tillage under organic farming (O), were selected in this study.

Three plots were selected, all of which were planted with citrus (Naveline variety, 35-year-old trees), to compare the impacts of three different soil managements on soil physical quality. The planting pattern is 5 m × 4 m in each plot. The orchards have been flood-irrigated with water from the Riu de Sants. Pruning and irrigation were performed as follows: pruning in March–April and irrigation every 20 d during summer. There were three soil managements: i) no-tillage using herbicides (herbicide treatment, H), kept weed free with herbicide (glyphosate, *N*-(phosphonomethyl)glycine, applied four times per year) and under chemical fertilization (150 g kg^{-1} NPK, 0.8 Mg ha^{-1} year^{-1} in four doses from April to July); ii) tillage under chemical farming (tillage treatment, T), established 35 years ago and performed four times per year with chemical fertilizers applied before flooding (150 g kg^{-1} NPK, 0.8 Mg ha^{-1} year^{-1}); and iii) no-tillage under organic farming (organic farming treatment, O), established 12 years ago on a 35-year-old citrus plantation that was previously ploughed. The O management comprised of chipped pruned branches, weeds, and manure from sheep and goats, applied annually at 8 Mg ha^{-1} (0.8 g kg^{-1} N, 0.2 g kg^{-1} P_2O_5, and 0.8 g kg^{-1} K_2O) in winter.

Soil sampling

In July 2013, 10 sampling plots were established at intervals of 5 m along a row for each soil management. At each sampling point, a 100-cm^3 cylinder was used to collect an undisturbed soil core at 0–5 cm soil depth. The cores were used to determine soil bulk density (ρ_b, g cm^{-3}), soil porosity (ε, m^3 m^{-3}), initial volumetric soil water content (θ_0, m^3 m^{-3}), grain size distribution, and organic matter content. Vegetation cover (VC, %) was determined using a 25-mm square frame with 100 measurement pins (Cerdà *et al.*, 2009b). Soil organic carbon content (OC, g kg^{-1}) was determined by the Walkley and Black method (Nelson and Sommers, 1996). Soil moisture was calculated after drying the soil samples at 105 °C. Grain size distribution was determined by conventional methods following H_2O_2 pre-treatment to eliminate organic matter and clay deflocculation using sodium metaphosphate and mechanical agitation (Gee and Bauder, 1986). In particular, fine-sized fractions were determined by the hydrometer method, whereas the coarse fractions were obtained by mechanical dry sieving.

At each sampling point, a measurement was made with a ring infiltrometer (Reynolds and Elrick, 1990; Reynolds, 1993). The superficial herbaceous vegetation was cut with a knife while the roots remained *in situ*. Litter and plant residues were gently removed from soil surface before the measurements. A 0.1-m inner diameter ring was inserted 0.01 m deep into the soil to ensure water tightness and to avoid leaks, without perturbing the 3-D water flow (Gonzalez-Sosa *et al.*, 2010) and the sampled soil volume (Reynolds, 1993; Bagarello and Sgroi, 2004). At the start of the experiment, water was poured into the ring and the initial height was measured using a ruler. At set time intervals, the water level was measured and a new volume of water was poured within the ring. During the first few minutes, short time intervals were used. The time interval was increased up to 5 min in the late-phase of the experiment. Flow rates were monitored, and steady-states

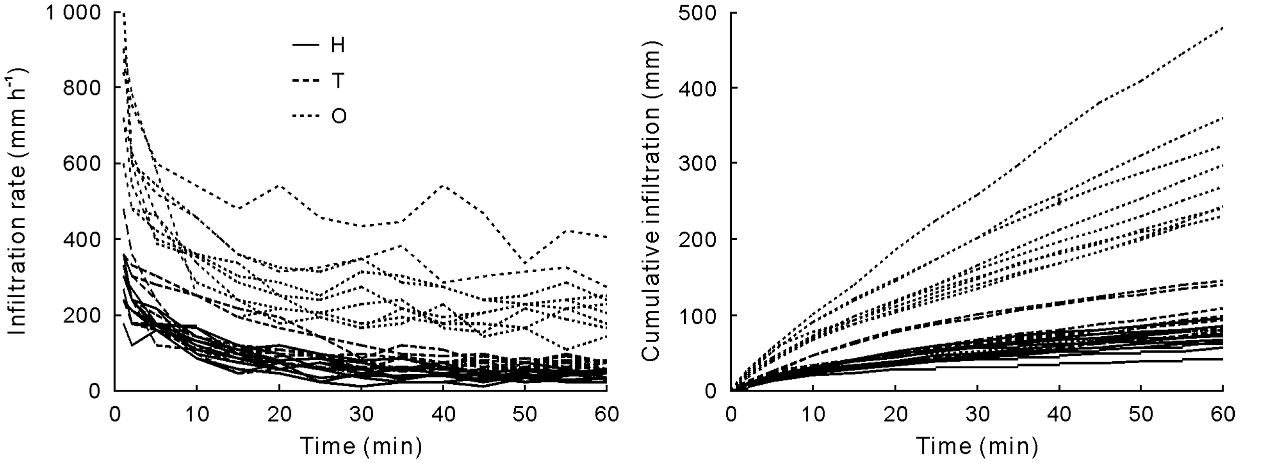

Fig. 2 Infiltration rates and cumulative infiltrations at the study site under three soil managements, namely no-tillage using herbicides (H), tillage under chemical farming (T), and no-tillage under organic farming (O).

were attained within 60 min for all soil managements (Fig. 2). A total of 30 experimental cumulative infiltrations ($I(t)$, mm), *vs* time (t, min), were then deduced and 10 for each soil management (Fig. 2). The equilibration time (t_s, min), namely the duration of the transient phase of the infiltration process, was estimated according to Bagarello *et al.* (1999) to analyze cumulative infiltration data. Specifically, the t_s value is determined as the first value for which:

$$\left|\frac{I(t)-I_{\mathrm{reg}}(t)}{I(t)}\right| \times 100 \leq E \tag{1}$$

where $I(t)$ is the cumulative infiltration during time t; $I_{\mathrm{reg}}(t)$ is the cumulative infiltration estimated from the regression analysis of the $I(t)$ *vs* t plot; and E is the criterion for establishing the onset of linearity. Equation 1 is applied starting from $t = 0$ and progressively excluding the first data points until $E \leq 2$ (Angulo-Jaramillo *et al.*, 2016; Bagarello *et al.*, 2017). An illustrative example of t_s estimation is shown in Fig. 3.

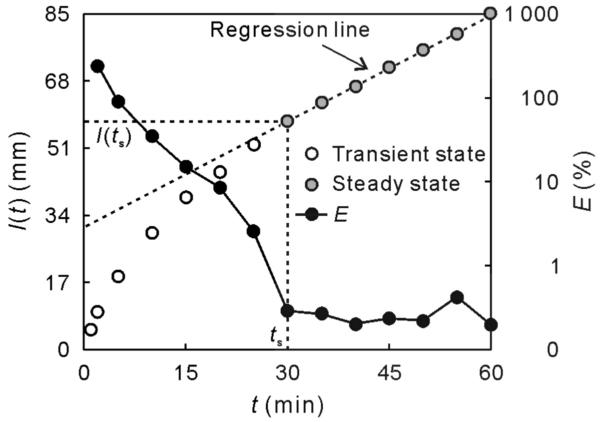

Fig. 3 Procedure for estimating equilibration time (t_s) and infiltrated depth at the equilibration time ($I(t_\mathrm{s})$) from cumulative infiltrations ($I(t)$). E is the criterion for establishing the onset of linearity.

Soil hydraulic characterization

The infiltration tests along with the BEST method (Lassabatere *et al.*, 2006) were used to determine simultaneously the water retention curve, $\theta(h)$, and the hydraulic conductivity function, $K(h)$. The BEST focuses specifically on the Van Genuchten (1980) relationship with the Burdine (1953) condition for the water retention curve, and on the Brook and Corey (1964) relationship for hydraulic conductivity:

$$\frac{\theta-\theta_\mathrm{r}}{\theta_\mathrm{s}-\theta_\mathrm{r}} = \left[1+\left(\frac{h}{h_\mathrm{g}}\right)^{n}\right]^{-m} \tag{2}$$

$$m = 1-\frac{2}{n} \tag{3}$$

$$\frac{K(h)}{K_\mathrm{s}} = \left(\frac{\theta-\theta_\mathrm{r}}{\theta_\mathrm{s}-\theta_\mathrm{r}}\right)^{\eta} \tag{4}$$

$$\eta = \frac{2}{nm}+3 \tag{5}$$

where θ is the soil water content (m^3 m^{-3}); h is the water pressure head (mm), usually taken to be negative; h_g is the van Genuchten pressure scale parameter (mm); θ_s is the saturated soil water content (m^3 m^{-3}); θ_r is the residual soil water content (m^3 m^{-3}), assumed to be zero in BEST; K_s is the saturated soil hydraulic conductivity (mm h^{-1}); and n, m, and η are the hydraulic shape parameters. According to other investigations, θ_s can be approximated by the total soil porosity, determined from ρ_b (Mubarak *et al.*, 2009; Xu *et al.*, 2009; Yilmaz *et al.*, 2010; Bagarello *et al.*, 2011; Di Prima, 2015). The shape parameter n, which is texture dependent, was determined from the sand (%) and clay (%) contents (Bagarello *et al.*, 2011), whereas the structure-dependent scale parameters (*i.e.*, h_g and K_s)

were estimated by the infiltration tests.

In this study, the BEST-steady algorithm (Bagarello *et al.*, 2014c) was applied to estimate soil sorptivity (S, mm h$^{-0.5}$) and K_s as follows (Di Prima *et al.*, 2016):

$$S = \sqrt{\frac{i_s}{A + \frac{C}{b_s}}} \tag{6}$$

$$K_s = \frac{C i_s}{A b_s + C} \tag{7}$$

where i_s and b_s are the slope and the intercept, respectively, of the straight line fitted to the data describing steady-state conditions on the cumulative infiltration *vs* time plot and the constants A (mm^{-1}) and C are defined for the specific case of the Brooks and Corey (1964) relationship, taking into account initial conditions as follows (Haverkamp *et al.*, 1994):

$$A = \frac{\gamma}{r(\theta_s - \theta_0)} \tag{8}$$

$$C = \frac{1}{2\left[1 - \left(\frac{\theta_0}{\theta_s}\right)^{\eta}\right](1-\beta)} \ln\left(\frac{1}{\beta}\right) \tag{9}$$

where θ_0 is the initial volumetric soil water content (m^3 m^{-3}); γ (parameter for geometrical correction of the infiltration front shape) and β are coefficients commonly set at 0.75 and 0.6, respectively, for $\theta_0 < 0.25\theta_s$; and r is the ring radius (mm).

Finally, h_g is estimated by the following relationship (Lassabatere *et al.*, 2006):

$$h_g = \frac{S^2}{c_p(\theta_s - \theta_0)\left[1 - \left(\frac{\theta_0}{\theta_s}\right)^{\eta}\right] K_s} \tag{10}$$

where:

$$c_p = \Gamma\left(1 + \frac{1}{n}\right)\left[\frac{\Gamma\left(m\eta - \frac{1}{n}\right)}{\Gamma(m\eta)} + \frac{\Gamma\left(m\eta + m - \frac{1}{n}\right)}{\Gamma(m\eta + m)}\right] \tag{11}$$

where Γ stands for the Gamma function.

Several researchers have reported that the BEST method is the simplest field method for a complete soil hydraulic characterization (Yilmaz *et al.*, 2010; Aiello *et al.*, 2014; Bagarello *et al.*, 2014b, 2017; Di Prima *et al.*, 2017b; Castellini *et al.*, 2018). Among the three alternative BEST algorithms, namely BEST-steady (Bagarello *et al.*, 2014c), BEST-slope (Lassabatere *et al.*, 2006), and BEST-intercept (Yilmaz *et al.*, 2010), the first one was chosen because it allows a very simple estimation of K_s. Additionally, it is expected to yield a higher percentage of success in the analysis of the infiltration runs, implying more experimental information (Di Prima *et al.*, 2016).

The calculation approach of one ponding depth (OPD) (Reynolds and Elrick, 1990) was also applied to calculate K_s for each infiltration run. The OPD approach makes use of the steady infiltrating flux (Q_s, mm^3 h^{-1}), which is estimated from the flow rate *vs* time plot. It also requires an estimate of the so-called α^* parameter (mm^{-1}), which is equal to the ratio between K_s and the field-saturated soil matric flux potential. In this study, a value of $\alpha^* = 0.012$ mm^{-1} was considered, since the soil had a sand content of 37.5% to 46.3% (Bagarello *et al.*, 2012, 2017). Following Elrick and Reynolds (1992), differences between K_s data that did not exceed a factor of 2 or 3 were considered indicative of satisfactory predictions.

Soil physical quality indicators

Table I summarizes the SPQ indicators considered in this study and the suggested optimal ranges or critical limits. The SPQ indicators are soil parameters allowing to quantify the level or degree of SPQ (Topp *et al.*, 1997). In agricultural soils, for example, SPQ indicators directly or indirectly quantify the ability of soil to store and provide crop-essential water, air, and nutrients (Reynolds *et al.*, 2007). Several indicators and their associated optimal ranges or critical limits have been suggested to evaluate SPQ (Topp *et al.*, 1997; Reynolds *et al.*, 2002). The indicators considered in this study and the associated optimal ranges or critical limits were selected based on the study of Reynolds *et al.* (2009). Several authors have successfully used the selected indicators for similar purposes (Agnese *et al.*, 2011; Bagarello *et al.*, 2011; Kelishadi *et al.*, 2014; Castellini *et al.*, 2016; Iovino *et al.*, 2016). Among the selected SPQ indicators, three were independently measured, including ρ_b, OC, and structural stability index (SSI), while the others were derived from the application of the BEST procedure. In particular, the capacity-based indicators, *i.e.*, plant-available water capacity (PAWC) and relative field capacity (RFC), were calculated from the soil water retention curve estimated with the BEST. As suggested by Castellini *et al.* (2016), a further distinction should be made between the capacity-based indicators and K_s, which was derived from the experimental infiltration test. Bagarello *et al.* (2014d) and Di Prima *et al.* (2016) showed that if the soil is relatively dry at the beginning of experiment (*i.e.*, $\theta_0 \ll \theta_s$), estimation of S and K_s is independent of the shape parameters of the soil hydraulic functions (namely the textural information), and is only affected

TABLE I

Selected soil physical quality (SPQ) indicators and corresponding optimal ranges or critical limits

SPQ indicator[a)]	Characterization	Evaluation class	Range or critical limit
ρ_b (g cm^{-3})	Indicator of aeration, strength, and ability to store and transmit water	Optimal	$0.9 \leq \rho_b \leq 1.2$
		Near-optimal	$0.85 \leq \rho_b < 0.9$ and $1.2 < \rho_b \leq 1.25$
		Poor	< 0.85 and > 1.25
OC (g kg^{-1})	Strong indirect effects on soil physical quality	Optimal	$30 \leq$ OC ≤ 50
		Intermediate	$23 \leq$ OC < 30 and $50 <$ OC ≤ 60
		Poor	< 23 and > 60
SSI (%)	Indicator of soil structure	Stable	> 9
		Low risk of degradation	$7 <$ SSI ≤ 9
		High risk of degradation	$5 <$ SSI ≤ 7
		Degraded soil	< 5
PAWC (m^3 m^{-3})	Ability of soil to store and provide water available to plant roots	Ideal	≥ 0.20
		Good	$0.15 \leq$ PAWC < 0.20
		Limited	$0.10 \leq$ PAWC < 0.15
		Poor	< 0.10
RFC	Ability of soil to store water and air relative to the soil's total pore volume	Optimal	$0.6 \leq$ RFC ≤ 0.7
		Water limited	< 0.6
		Aeration limited	> 0.7
K_s (mm h^{-1})	Ability of soil to imbibe and transmit plant-available water to crop root zone, and to drain excess water out of the root zone	Ideal	$18 \leq K_s \leq 180$
		Intermediate	$0.36 \leq K_s < 18$ and $180 < K_s \leq 360$
		Poor	< 0.36 and > 360

[a)] ρ_b is the bulk density; OC is the organic carbon content; SSI is the structural stability index, equal to 1.724OC/(silt + clay) × 100; PAWC is the plant-available water capacity, with PAWC = $\theta_{FC} - \theta_{PWP}$, where θ_{FC} is the field capacity (gravity drained) soil water content (m^3 m^{-3}), corresponding to water pressure head (h) of −1 m, and θ_{PWP} is the permanent wilting point soil water content (m^3 m^{-3}) (h = −150 m) (Reynolds *et al.*, 2002); RFC is the relative field capacity, with RFC = θ_{FC}/θ_s, where θ_s is the saturated soil water content (m^3 m^{-3}); K_s is the saturated soil hydraulic conductivity.

by the infiltration experiment. Therefore, considering both K_s and the parameters expressing water retention curve has obvious advantage to account separately for the effects of structure (K_s) and both texture and structure (water retention parameters) on the SPQ assessment.

Data analysis

For each variable considered in this study (clay, silt, sand, ρ_b, OC, SSI, PAWC, RFC, S, K_s, and h_g), a given dataset was summarized by calculating the mean and the associated coefficient of variation (CV). Arithmetic means were calculated, since the characterization of an area of interest for SPQ assessment is generally based on arithmetic averages of individual determinations (Reynolds *et al.*, 2009). Geometric means were calculated for K_s and h_g, since a log-normal distribution generally describes these variables better than a normal distribution (Lee *et al.*, 1985; Mohanty *et al.*, 1994). For comparing mean values, untransformed and natural log-transformed data were used for the normally and the natural log-normally distributed variables, respectively. The soils of the three soil managements were compared with reference to the considered variables using the Tukey's honestly significant difference test at $P < 0.05$. A SPQ assessment of each soil management was performed using the evaluation criteria described by Reynolds *et al.* (2009) (Table I). For statistical analyses, the Minitab© computer program (Minitab Inc., USA) was used. Additionally, the hydraulic characteristic curves were compared by root mean square residual (RMSR). This indicator has been used frequently to evaluate the performance of $\theta(h)$ and $\ln[K(h)]$ in describing the measured soil hydraulic properties (Vereecken *et al.*, 2010). The RMSR is defined as:

$$\mathrm{RMSR} = \sqrt{\frac{\sum_{i=1}^{n} (\mathrm{dev}_i)^2}{n}} \quad (12)$$

where dev_i is the ith deviation between θ_i or $\ln(K_s)_i$ values of different curves and n is the number of considered potential values. A linear regression analysis between datasets was also carried out. Statistical significance was assessed at a $P < 0.05$ level, and the 95% confidence intervals for the intercept and the slope were calculated.

RESULTS AND DISCUSSION

Soil properties

Table II summarizes soil physical and chemical properties of the three soil management plots. Despite the plots displaying similar soil properties, a lower pH was observed under organic farming management due to the addition of manure and chipped branches over a decade that developed a 5 mm litter layer and a 3 mm organic layer. This is similar to the results found by Vakali *et al.* (2011). There was no difference in grain size distribution between the three management strategies, since more time is needed for soil texture to be altered by soil formation processes. According to the USDA standards, the three fractions, *i.e.*, clay (0–2 μm), silt (2–50 μm), and sand (50–2 000 μm), averaged for the plots were 17.4%, 40.8%, and 41.8%, respectively (corresponding standard deviations = 2.8%, 2.1%, and 2.3%, respectively), and the soil of the study area was classified as loam (Gee and Bauder, 1986).

TABLE II

Minimum (Min), maximum (Max), mean (n = 10), and coefficient of variation (CV, %) of vegetation cover (VC), soil pH, and sand, silt, and clay contents (USDA classification system) in the plots under different soil managements, namely no-tillage using herbicides (H), tillage under chemical farming (T), and no-tillage under organic farming (O)

Variable	Soil management	Min	Max	Mean	CV
VC (%)	H	0.0	5.2	2.4a[a)]	70.6
	T	0.0	1.6	0.6a	117.5
	O	29.2	78.4	48.2b	30.8
pH	H	8.1	8.6	8.3b	1.9
	T	8.0	8.6	8.3b	2.1
	O	7.4	8.1	7.8a	3.2
Sand (%)	H	37.5	45.0	40.9a	5.7
	T	38.7	46.3	42.0a	5.5
	O	38.1	46.3	42.4a	5.3
Silt (%)	H	37.3	45.0	40.7a	5.5
	T	37.2	45.2	40.8a	6.1
	O	38.7	43.8	41.0a	4.2
Clay (%)	H	11.5	22.3	18.3a	17.5
	T	14.1	20.2	17.2a	13.5
	O	12.6	21.6	16.7a	17.5

[a)] Means followed by the same letter for a given variable are not significantly different according to the Tukey's honestly significant difference test at $P < 0.05$.

Infiltration experiment

An infiltration experiment in the O plot yielded a negative b_s value, with a convex shape of the cumulative infiltration curve, which is specific for hydrophobic soils (Di Prima *et al.*, 2017a). Such locally detected hydrophobia could be attributed to the high OC content in the O plot (Goebel *et al.*, 2011). In this case, Eq. 6 was unable to provide a result, showing that BEST-steady can only be used when the soil does not exhibit hydrophobic effects. This was also reported by Lassabatere *et al.* (2013) for the other BEST algorithms. In particular, the transient model used by the BEST always produces a concave shape and cannot be fitted to convex-shaped data. The other 29 cumulative infiltrations exhibited usual shapes (Fig. 2), with a concave part corresponding to the transient state and a linear part at the end of the curves related to the steady state (Di Prima *et al.*, 2016). For these cumulative infiltrations, the BEST-steady algorithm was successfully applied.

Table III shows the results of the infiltrated depth and equilibration time in the three soil management plots. After 60 min, the total infiltrated depth (I_{end}) was, on average, 71.3, 102.3, and 276.2 mm for the H, T, and O plots, respectively. Water flow reached steady-state rates after 15–50 min, depending on the run. The equilibration time (t_s) for the organic farming management was, on average, 39 min, with the infiltrated depth ($I(t_s)$) of 194 mm, *i.e.*, 3.0–3.7 times more water than the other managements. Therefore, for all soil managements, steady-state infiltration rates (i_s) were reached before the end of all runs, and then were estimated considering the last data points of the infiltration curves. The average i_s value in the O plot was 5.0 and 2.8 times, respectively, higher than those in the H and T plots; whereas the average i_s values were relatively similar in the H and T plots (*i.e.*, differing by no more than a factor of 2).

TABLE III

Minimum (Min), maximum (Max), mean (n = 10), and coefficient of variation (CV, %) of the equilibration time (t_s), infiltrated depth at the equilibration time ($I(t_s)$), and total infiltrated depth (I_{end}) in the plots under different soil managements, namely no-tillage using herbicides (H), tillage under chemical farming (T), and no-tillage under organic farming (O)

Variable	Soil management	Min	Max	Mean	CV
t_s (min)	H	20	40	32	19.8
	T	15	40	29	26.7
	O	25	50	39	19.9
$I(t_s)$ (mm)	H	32	73	52	24.6
	T	32	116	66	40.6
	O	73	343	194	37.0
I_{end} (mm)	H	44	96	71	21.4
	T	79	145	102	22.9
	O	81	479	276	37.2

The mean soil water content at the beginning of the infiltration experiment (θ_0) varied between 0.097 and 0.130 m^3 m^{-3}. The soil was significantly wetter in the O plot than in the other plots (Table IV). The ratio between the means of θ_0 and θ_s varied from 0.19 to 0.21 and was always lower than the upper limit of 0.25 suggested by Lassabatere *et al.* (2006) for an accurate application of the BEST procedure. Therefore, the initial soil water content was not considered to affect the reliability of the predicted soil hydraulic parameters

TABLE IV

Minimum (Min), maximum (Max), mean, and coefficient of variation (CV, %) of the initial volumetric soil water content (θ_0), soil porosity (ε), hydraulic shape parameters (m, n, and η), soil sorptivity (S), saturated soil hydraulic conductivity (K_s), and van Genuchten pressure scale parameter (h_g) in the plots under different soil managements, namely no-tillage using herbicides (H), tillage under chemical farming (T), and no-tillage under organic farming (O)

Variable	Soil management	Min	Max	Mean	CV
θ_0 (m^3 m^{-3})	H	0.083	0.111	0.097a	9.1
	T	0.089	0.124	0.104a	11.5
	O	0.114	0.152	0.130b	12.0
ε (m^3 m^{-3})	H	0.419	0.543	0.498a	7.4
	T	0.502	0.585	0.540b	5.1
	O	0.589	0.630	0.609c	1.9
m	H	0.083	0.105	0.091a	7.0
	T	0.087	0.099	0.093a	5.0
	O	0.085	0.103	0.094a	6.2
n	H	2.18	2.23	2.20a	0.7
	T	2.19	2.22	2.21a	0.5
	O	2.18	2.23	2.21a	0.6
η	H	11.55	14.01	13.05a	5.7
	T	12.06	13.47	12.76a	4.2
	O	11.75	13.83	12.65a	5.3
S (mm h$^{-0.5}$)	H	17.7	33.1	26.1a	17.3
	T	28.6	43.2	34.8a	15.4
	O	30.1	100.9	69.4b	27.9
K_s (mm h^{-1})	H	8.5	19.1	14.2a	27.8
	T	18.1	37.8	27.9b	28.7
	O	17.4	100.5	50.5c	72.7
h_g (mm)	H	−74.2	−38.9	−50.1ab	22.2
	T	−96.5	−24.0	−47.6b	52.4
	O	−150.5	−47.3	−86.1a	46.4

[a)]Means followed by the same letter for a given variable are not significantly different according to the Tukey's honestly significant difference test at $P < 0.05$.

(Castellini *et al.*, 2016; Cullotta *et al.*, 2016; Di Prima *et al.*, 2016).

The statistics for the shape and scale parameters estimated with the BEST are reported in Table IV. Similar values for the shape parameters (m, n, and η) were obtained between the studied plots, due to the homogeneity of soil texture (Table II) (Castellini *et al.*, 2016). No differences were detected between the H and T plots in terms of soil sorptivity (S); whereas a significantly higher mean S value was detected in the O plot, highlighting the greater ability of the soil to rapidly capture water (Shaver *et al.*, 2013). Specifically, the S values varied by a factor of 2.0–2.7 between the O and the other plots. The O plot also yielded significantly higher K_s values; the mean K_s was 1.8–3.6 times higher than those obtained in the T and H plots. Table IV also provides the statistics of the van Genuchten pressure scale parameter, which significantly differed between the T and O plots.

Before assessing SPQ by using the BEST-deduced parameters, the K_s values obtained by the BEST-steady algorithm were compared with those determined by the OPD approach for the single ring pressure infiltrometer technique. This choice was made to increase our confidence with the results. In fact, the OPD approach is commonly applied for single ring infiltrometers, and is one of the simplest means for K_s estimation (Bagarello *et al.*, 2014a). The BEST-steady method yielded less variable results than the OPD approach (CV = 74.8 and 93.3, respectively). Moreover, the two estimates of K_s at a sampling point did not exceed a factor of 2 in 66% of the cases and a factor of 3 in 100% of the cases, which can be considered negligible for many hydrological applications (Elrick and Reynolds, 1992). The mean K_s values between the two procedures differed by a factor of 1.3–2.1, depending on the site. Therefore, the two calculation procedures were similar, supporting the soundness of the BEST-steady algorithm.

As expected, the K_s values were better correlated with the soil structural variables (OC and ρ_b) than the soil textural variables (clay, silt, and sand) (Fig. 4). Both S and K_s values directly increased with OC and inversely with ρ_b, thus yielding results consistent with the literature (Rawls *et al.*, 2003; Lassabatere *et al.*, 2006; Shaver *et al.*, 2013). These relations increase our confidence with the obtained results, highlighting the reliability of BEST predictions.

The soil characteristic curves for the three soil managements are depicted in Fig. 5. The curves were determined by averaging the shape and scale parameters estimated with the BEST for a given plot. The regression between water retention curves or hydraulic conductivity functions for the three soil managements (Fig. 6) always differed from the identity line according to the calculated 95% confidence intervals for the intercept and the slope (Table V). In general, the O plot yielded significantly higher θ and K values than the other plots. Differences of $\theta(h)$ and $K(h)$ between the studied plots were also quantified in terms of RMSR (Table V). The comparison of $\theta(h)$ between the H and T plots provided the lowest RMSR value, equal to 0.020 m^3 m^{-3}, suggesting some similarity between the water retention curves for these plots. Larger discrepancies were detected when comparing $\theta(h)$ between H *vs* O and T *vs* O, with the RMSR values equal to 0.082 and 0.065 m^3 m^{-3}, respectively. Similar results were obtained in terms of $K(h)$. Comparison of $K(h)$ between H and T yielded RMSR to be 0.481 ln(mm h^{-1}). In contrast, comparing $K(h)$ between H *vs* O and T *vs* O, the obtained RMSR values were equal to

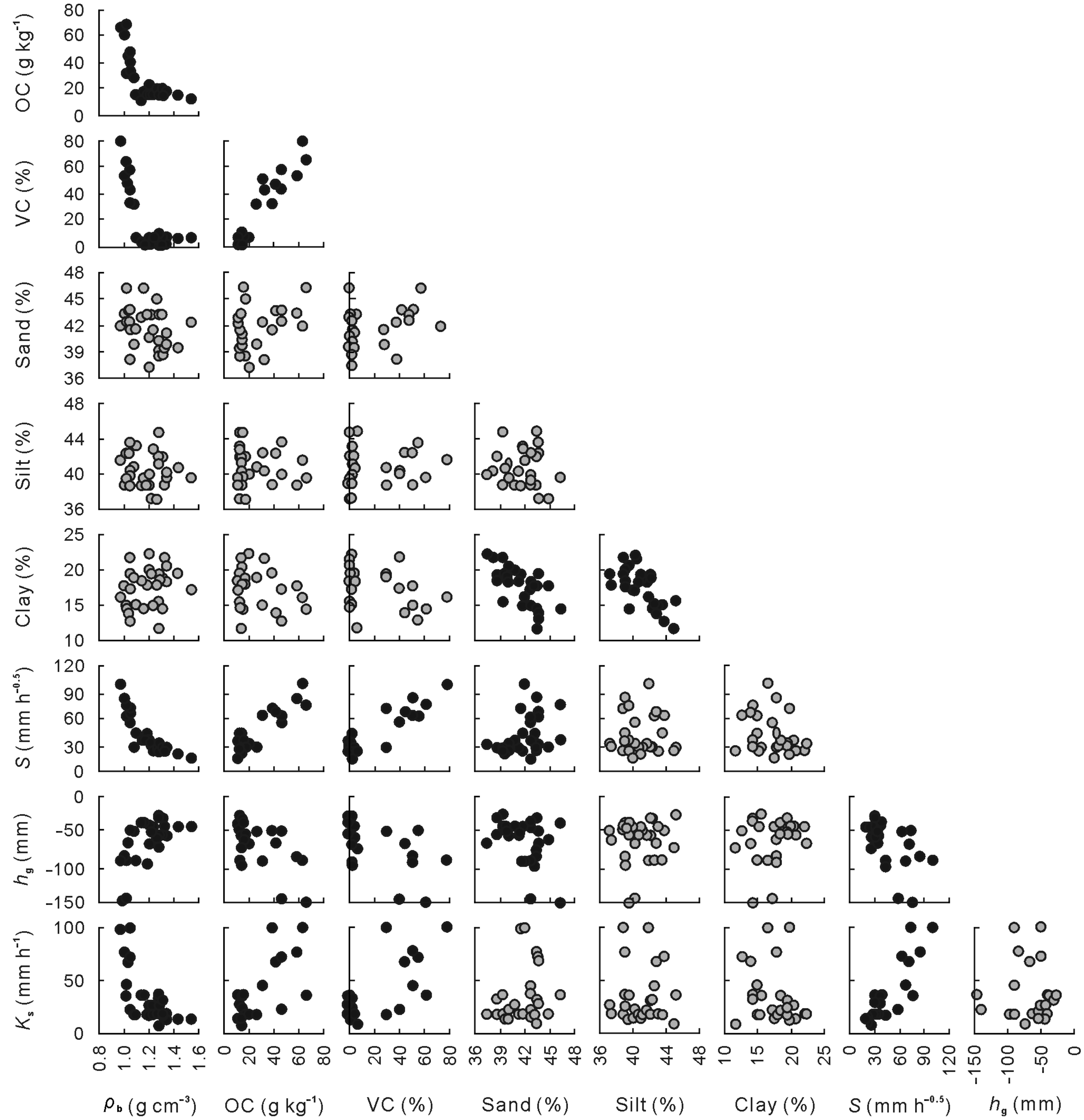

Fig. 4 Matrix showing correlations between soil characteristics. Black plots indicate a significant correlation at $P < 0.05$. ρ_b is the bulk density; OC is the organic carbon content; VC is the vegetation cover; S is the soil sorptivity; h_g is the van Genuchten pressure scale parameter; K_s is the saturated soil hydraulic conductivity.

1.994 and 1.639 ln(mm h^{-1}), respectively. Therefore, these results suggested that the different soil managements affected the estimated soil water retention curves and soil hydraulic conductivity functions. Specifically, comparison between the O plot and the other two plots showed a more marked difference, with higher soil water retention and hydraulic conductivity for the former plot. The difference was less noticeable between the H and T plots.

Soil physical quality assessment

In total, 29 field-determined water retention curves were considered for SPQ assessment. The H and T plots generally had a poor SPQ according to the considered criterion (Fig. 7). The O plot had optimal ρ_b value. The optimal range for ρ_b in the SPQ assessment implies that ρ_b values were not high enough to impede root growth (Jones, 1983; Drewry *et al.*, 2008), or too

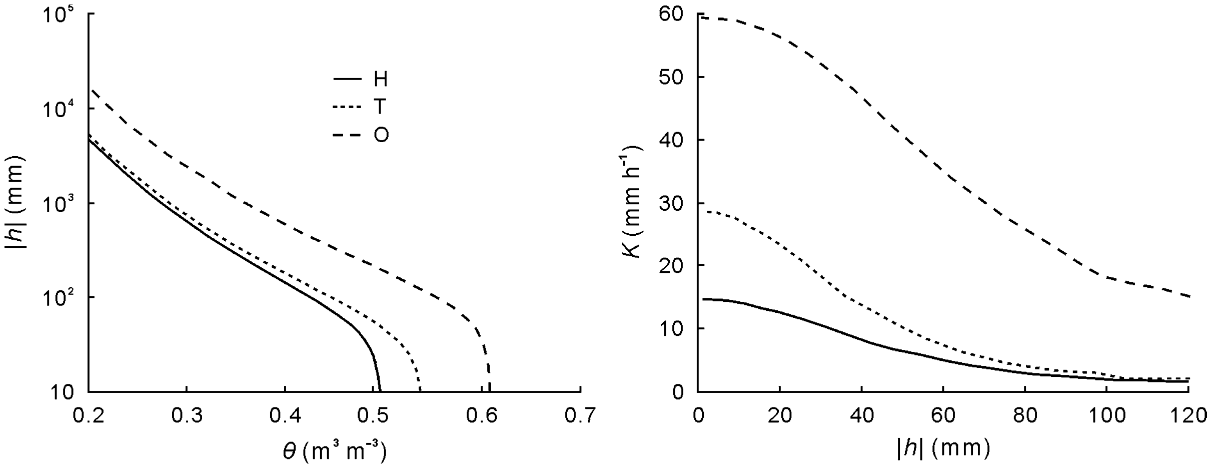

Fig. 5 Water retention curves ($\theta(h)$) and hydraulic conductivity functions ($K(h)$) in the plots under different soil managements, namely no-tillage using herbicides (H), tillage under chemical farming (T), and no-tillage under organic farming (O). h is the water pressure head; θ is the soil water content; K is the soil hydraulic conductivity.

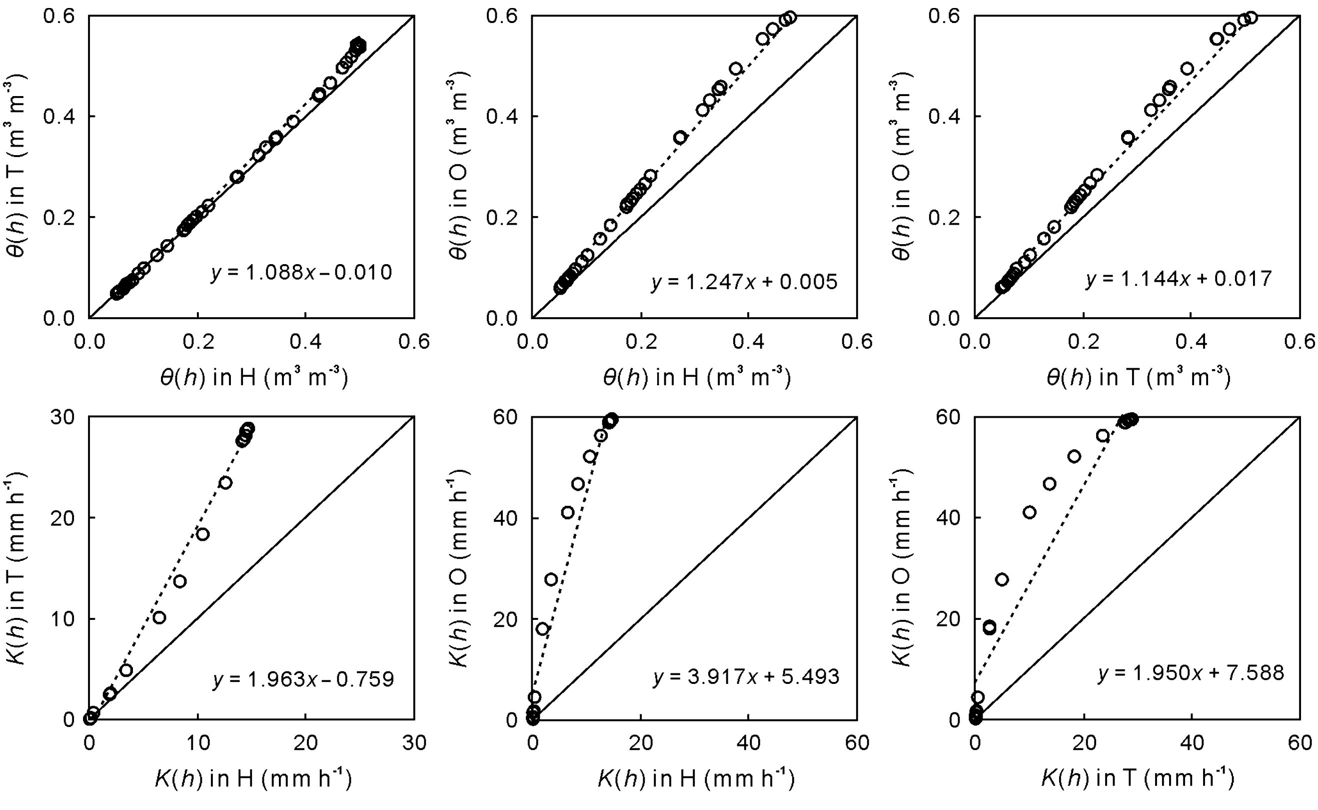

Fig. 6 Comparisons of water retention curves ($\theta(h)$) and hydraulic conductivity functions ($K(h)$), determined using the Beerkan estimation of soil transfer parameter method for soil hydraulic characterization, between the three soil managements, namely no-tillage using herbicides (H), tillage under chemical farming (T), and no-tillage under organic farming (O). h is the water pressure head; θ is the soil water content; K is the soil hydraulic conductivity.

low to adversely affect plant anchoring, owing to the low soil strength (Reynolds *et al.*, 2008). For the O plot, 70% and 90% of the OC and SSI values ranged in the optimal and stable classes, respectively, suggesting that independently measured SPQ indicators (ρ_b, OC, and SSI) in this plot detected good agricultural soil (Reynolds *et al.*, 2009; Pieri, 2012). The increase in OC content indicated vegetation cover between the trees and residue accumulation on the topsoil (Sisti *et al.*, 2004). A higher concentration of decomposing crop residues also improved surface soil structure and aeration (Shukla *et al.*, 2006), and reduced soil compaction (Ball *et al.*, 1996). Management practices adopted under organic farming (such as vegetation cover between

TABLE V

Statistic comparisons of water retention curves and hydraulic conductivity functions, determined using the Beerkan estimation of soil transfer parameter method for soil hydraulic characterization, between the three soil managements, namely no-tillage using herbicides (H), tillage under chemical farming (T), and no-tillage under organic farming (O)

Statistic[a)]	Water retention curve			Hydraulic conductivity function		
	H *vs* T	H *vs* O	T *vs* O	H *vs* T	H *vs* O	T *vs* O
RMSR	0.020	0.082	0.065	0.481	1.994	1.639
Intercept	−0.010	0.005	0.017	−0.759	5.493	7.588
Slope	1.088	1.247	1.144	1.963	3.917	1.950
R^2	0.999	0.997	0.993	0.994	0.955	0.919
95% confidence interval						
Intercept	−0.013 to −0.007	−0.002 to 0.012	0.007 to 0.027	−1.505 to −0.012	1.457 to 9.530	2.313 to 12.862
Slope	1.078 to 1.098	1.225 to 1.269	1.114 to 1.174	1.883 to 2.043	3.484 to 4.350	1.654 to 2.247

[a)]RMSR is the root mean square residual; R^2 is the coefficient of determination.

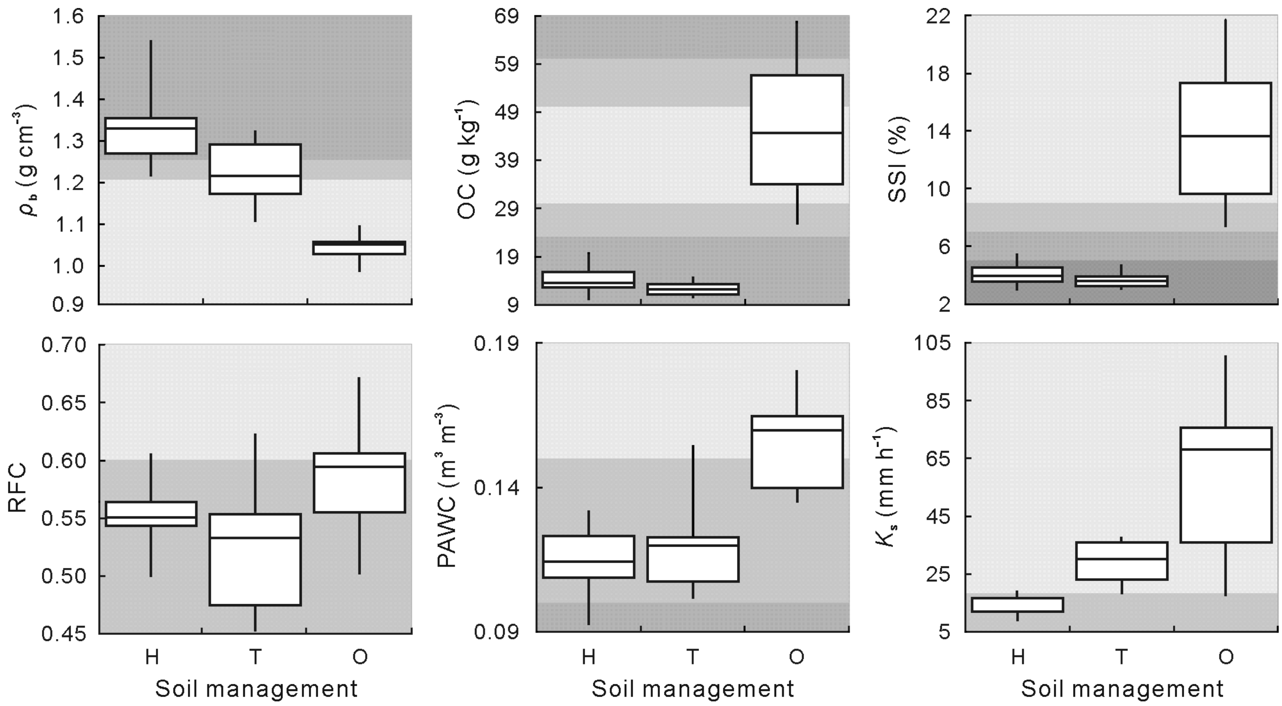

Fig. 7 Box plots of soil bulk density (ρ_b), organic carbon content (OC), structural stability index (SSI), plant-available water capacity (PAWC), relative field capacity (RFC), and saturated soil hydraulic conductivity (K_s) for the three soil managements, namely no-tillage using herbicides (H), tillage under chemical farming (T), and no-tillage under organic farming (O). On the box plots, boundaries indicate the 25th quantile, median, and 75th quantile, respectively, and the top and bottom whiskers indicate the minimum and maximum values. Background grey colors indicate ranges or critical limits, and lighter tones indicate better soil physical quality conditions.

the trees, chipping after pruning, and spreading the chips on soil surface rather than burning them) allowed the improvement of SPQ, consistent with the findings of other researchers (Cerdà *et al.*, 2016; Prosdocimi *et al.*, 2016; Hondebrink *et al.*, 2017). The influence of vegetation cover in the recovery of organic matter in the soils is clearly shown in Fig. 4. There was a positive correlation between the VC and OC parameters. Under the organic farming management, the vegetative growth and residue accumulation led to a significantly higher OC (45.6 g kg^{-1}). An increase in organic matter had a macrostructure-producing function that decreased bulk density (Fig. 4) and increased soil structure (Reynolds *et al.*, 2009). Vegetation and the associated ecosystem (including biota) created a higher SPQ with more macropores, better soil structure, and higher soil fertility (Reicosky and Forcella, 1998). Conversely, herbicides and tillage with no vegetation cover or residue accumulation resulted in a poor OC content (12.1–13.9 g kg^{-1}). Herbicides also likely contributed to soil compaction due to wheel traffic during application (Bayhan *et al.*, 2002). Therefore, the conventional management strategies (herbicides and tillage) unequivocally led to soil degradation as a consequence of loss of organic matter and reduced structural stability. Generally speaking, the independently measured SPQ indicators suggested that tillage and herbicides resulted in a non-sustainable agricultural system in terms of SPQ, and the sustainability was not improved (Keesstra *et al.*, 2016b). The results show that, in particular, the soils under herbicide treatment produced the poorest SPQ. Other studies have also reported similar consideration concerning the misuse and abuse of herbicides in orchards (Gómez *et al.*, 2004, 2009; Cerdà *et al.*, 2009a) and the risk of losing a sustainable and robust agricultural system, such as the United Nations Goals for sustainability advise (Keesstra *et al.*, 2016a).

Statistically similar results were obtained in the H and T plots for OC, SSI, PAWC, and RFC, suggesting a similar and generally poor SPQ (Table VI). Conversely, good SPQ conditions were generally detected in the O plot (Fig. 7). Differences between the O and the other two plots were particularly clear with reference to PAWC and K_s, suggesting the soil in the O plot had a greater ability to store and provide water to plant roots and to quickly drain excess water and facilitate root proliferation. Specifically, in the O plot, 67% and 33% of the PAWC values ranged in the good and limited classes, respectively, whereas 90% of the values were limited for the T and H plots. The K_s values were generally ideal (*i.e.*, $18 < K_s < 180$ mm h^{-1}) for the O and T plots, with only one value (17.4 mm h^{-1}) close to the lower limit of the ideal class. However, the mean K_s value of the T plot (27.9 mm h^{-1}) was significantly lower than that of the O plot (50.5 mm h^{-1}), and was closer to the lower limit of the ideal class (Table IV). For the H plot, 80% of the K_s values were intermediate and only 20% were ideal. The O plot also yielded a mean RFC value higher than that of the other plots. However, the differences between plots were less noticeable in this case. A high PAWC is indicative of the relative prevalence of small pores where capillary flow mainly occurs; therefore, it is indicative of a good SPQ (Iovino *et al.*, 2016). Specifically, PAWC accounts for the ability of the soil to store water in a portion of the total soil porosity that is formed by micropores 0.2–30 µm in diameter. Soil management is known to affect soil hydraulic conductivity due to changes in soil structure, different root densities, and different biological activities (Zimmermann *et al.*, 2006; Siltecho *et al.*, 2015). For instance, the physiological stage of root affects the saturated hydraulic conductivity (Fuentes *et al.*, 2004). Indeed, root growth can create new pores, while decayed roots leave empty pores, which promote rapid infiltration and redistribution of water for crop growth, as well as reducing surface runoff and soil erosion and encouraging the rapid drainage of excess soil water (Murphy *et al.*, 1993; Reynolds *et al.*, 2008).

TABLE VI

Minimum (Min), maximum (Max), mean, and coefficient of variation (CV, %) of soil bulk density (ρ_b), organic carbon content (OC), structural stability index (SSI), plant-available water capacity (PAWC), and relative field capacity (RFC) for the three soil managements, namely no-tillage using herbicides (H), tillage under chemical farming (T), and no-tillage under organic farming (O)

Variable	Soil management	Min	Max	Mean[a)]	CV
ρ_b (g cm^{-3})	H	1.21	1.54	1.33c[b)]	7.3
	T	1.10	1.32	*1.22*b	6.0
	O	0.98	1.09	**1.04**a	3.0
OC (g kg^{-1})	H	9.9	19.8	13.9a	20.6
	T	10.2	14.7	12.1a	12.1
	O	25.6	67.8	**45.6**b	32.4
SSI (%)	H	2.98	5.46	4.06a	19.4
	T	3.01	4.72	3.61a	14.6
	O	7.33	21.75	**13.77**b	35.0
PAWC (m^3 m^{-3})	H	0.09	0.13	*0.11*a	10.5
	T	0.10	0.15	*0.12*a	14.4
	O	0.13	0.18	**0.16**b	10.4
RFC	H	0.50	0.60	*0.55*ab	5.2
	T	0.45	0.62	*0.52*a	11.3
	O	0.50	0.67	*0.59*b	9.2

[a)] Means in bold and italic indicate that the means fall in the optimal and intermediate ranges, respectively.
[b)] Means followed by the same letter for a given variable are not significantly different according to the Tukey's honestly significant difference test at $P < 0.05$.

This study demonstrates that the two types of indicators, namely the independent and BEST-derived indicators, yielded similar results, suggesting their ability to distinguish SPQ between contrasting soil managements. The differences between the studied plots were due to the differences in soil management (Cherubin *et al.*, 2016). The data clearly showed that the organic field had an overall better SPQ, with higher infiltration rates and better water holding capacity, making it a healthy soil from a physical point of view. It was also clear that both the conventional management strategies (H and T) had negative impacts on soil health. This study demonstrated that organic farming can be understood as a nature-based solution to restore degraded land affected by agricultural abuse and mismanagement (Keesstra *et al.*, 2018).

CONCLUSIONS

Organic farming improved SPQ, whereas herbicide management had the most negative effect on the SPQ. Under the organic farming management, the changes in soil properties resulted in higher K_s values, which were probably due to macropore flow. Therefore, fauna (burrowing and nesting) and plants (root decay and leaves cover) were also positively affected. Moreover, organic farming consistently improved the ability of the soil to store and provide water to plant roots. In addition, the SPQ assessment carried out in this study is cheap, rapid, and parsimonious in terms of both the devices that have to be transported and the measurements that have to be carried out in the field. Characterizing an area of interest by the BEST method is very simple and rapid given that many replicated experiments can easily be performed; therefore, the BEST is a suitable candidate method for easily assessing the impact of different soil managements (*i.e.*, land uses) on SPQ.

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