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Comparing physical quality of tilled and no-tilled soils in an almond orchard in southern Italy

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Abstract

No-tillage (NT) is an alternative way of reducing costs and lessening the burden of working the land, but in essence it is a method of sustainable land use in dryland cropping systems. The physical quality of the soil is the fundamental factor that defines the sustainability of agro-ecosystems, and its evaluation can be obtained using both capacitive and dynamic indicators. The main objectives of this study were: i) to assess the physical quality of the soil in an almond orchard where long-term different soil tillage systems and weed control methods, such as NT with chemical control and surface tillage (ST), were used; and ii) to compare the indicators under consideration with the proposed reference values, using the information gathered to evaluate the effects of NT and ST. The following physical properties were determined: bulk density, air capacity, macroporosity, plant available water capacity, relative field capacity, Dexter's index, field saturated hydraulic conductivity, as well as the location (modal, median, and mean pore diameter) and shape (standard deviation, skewness, and kurtosis) parameters which corresponded to the equivalent pore size distribution functions. Our results showed that the physical soil indicators adopted were sufficiently sensitive to identify tillage-induced changes and then to quantify the physical quality of rigid to moderately expansive agricultural soils. After thirty years of NT, a set of capacitive indicators, along with measurements of hydraulic conductivity, used in conjunction with an optimal pore volume distribution and the water release curve, unanimously classified the quality of the studied soil as *optimal* or *near optimal*.

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Introduction

The use of the no-tillage (NT) method of land management has increased worldwide over the past few decades (Kassam *et al.,* 2012). Generally, NT is an alternative way of reducing costs and lessening the burden of working the land, but in essence it is a method of sustainable land use in dryland cropping systems, where it is recommended as a management practice to optimise soil water retention (Shaver *et al.,* 2002). Moreover, it is a useful way of minimising the negative impacts of climate changes (Olesen and Bindi, 2002) and is suggested as a method for improving carbon sequestration in the soil (Lal, 2000).

Several studies have found implementation of NT results in overcompaction of the soil (Tebrügge and Düring, 1999) but in other studies there was no significant soil compaction (Logsdon and Karlen, 2004; Blanco-Canqui *et al.,* 2004). Furthermore, when compared with surface tillage, long-term NT can also significantly improve water retention characteristics or aggregate stability, increasing the connectivity of the pores (Strudley *et al.,* 2008). In other words, when NT is used, soil compaction may still occur, but this does not always have a detrimental effect on crop production (Pelegrin *et al.,* 1990; Unger and Fulton, 1990). In any case, its effects should always be assessed for a specific site, taking into consideration the type of agricultural cultivation and the soil types, as well the particular climatic conditions. For example, Gómez *et al.* (1999) reported the results of a long-term experiment in an olive orchard submitted to conventional tillage methods and NT in southern Spain. They found that the yield was not affected by tillage, except in one year when precipitation was very low. In that year, yields from NT were significantly higher than those from conventional tillage.

Nonetheless, conventional or minimum tillage are still widely used as soil management practices because producers believe that only these methods ensure higher crop yields.

Evaluation of the physical properties of the soil, obtained from water retention curve [such as air capacity (AC), macroporosity, plant available water capacity, relative filed capacity, Dexter's index (S)], and also from the dry bulk density of the soil, have provided useful information for assessing the physical quality of the soil, and have confirmed their potential usefulness when comparative studies of soil management are made. For example, in a recent paper, Abu and Abubakar (2013) evaluated the effects on soil hydro-physical properties of four tillage techniques. The Authors highlighted the sensitivity of the physical indicators of the soil that were used in relationship to the modifications caused by different soil tillage methods, and concluded that the soil subjected to conventional tillage had poorer physical quality at all the depths measured. There are also many other examples of similar approaches to agricultural soils to be found in the literature, including those reported by Aparicio and Costa (2007), Cavalieri *et al.* (2009), Li *et al.* (2011), Oicha *et al.* (2010), Reynolds *et al.* (2007), and Silva *et al.* (2011).

Reynolds *et al.* (2009) have suggested identifying the changes in the physical quality of the soil by comparing the pore volume distribution function of the soil with an optimal reference curve. This provides the corresponding optimal values and the authors claim that the proposed approach may be used to assess the physical quality of the soil.

However, so far the approach proposed by Reynolds *et al.* (2009) has only been applied in a few cases (Shahab *et al.,* 2013) and further research is needed.

Determining the dynamic physical properties of the soil may be more crucial than determining its physical quality. It is also useful to measure the field saturated hydraulic conductivity since this provides supplementary information which helps us to better understand the complex mechanisms through which management of the soil affects its physical quality.

Several methods may be used to obtain hydraulic properties of the soil at the point scale, both in the laboratory and in the field. For example, the soil of a small field area (*i.e.* a few m^2) can physically and hydraulically be characterized by carrying out a few replicated measurements of the variables of interest, using both well-known (Bagarello *et al.*, 2013a) and innovative (Bagarello *et al.*, 2013b) techniques.

Two of the most rigorous methods for obtaining the hydraulic properties of the soil are the instantaneous profile method and the evaporation method. Both of these experimental methods require careful monitoring of both soil water content and soil pressure head. However, they each have different advantages and disadvantages. For example, the former may provide a highly representative evaluation of field conditions but it is cumbersome and time-consuming (Basile *et al.*, 2003). The latter is a very effective and rapid transient laboratory method for simultaneous determination of both $\theta(h)$ and $K(h)$ relationships and is adequate for modelling purposes (Pirastru and Niedda, 2010, 2013). But its validity depends heavily on the soil volume used for soil hydraulic characterisation being truly representative, and on the accuracy of the measurements taken close to water saturation. Another source of uncertainty may also be related to the use of measurements carried out in the laboratory to explain field conditions (Basile *et al.*, 2003). In 2006, Basile *et al.* addressed this important issue and proposed a robust scaling procedure for deducing field unsaturated hydraulic properties from laboratory measurements. They pointed out that the general unrestricted applicability of the proposed method.

However, regardless of the method adopted, studies aimed at defining and measuring the physical quality of the soil should make use of soil which is being examined in consistent, long-term field experiments, in order to ensure that quasi-steady soil quality conditions have been reached (Reynolds *et al.,* 2007). Evaluation of the physical quality of the soil also requires comparisons to be made between the measured values and one or more reference values or intervals. For the moment, the optimal values for physical quality of the soil in order to achieve maximum field crop production with minimum environmental degradation remain largely unknown (Reynolds *et al.,* 2007). However, various empirical guideline parameter values have been proposed in the literature (Topp *et al.,* 1997; Dexter, 2004; Dexter and Czyż, 2007; Reynolds *et al.,* 2009).

Thus the main objectives of this study were: i) to consider a long-term experiment to assess the physical quality of the soil of an almond orchard where different soil tillage systems and weed control methods were used, *i.e.* NT with chemical control and surface tillage; ii) compare Reynolds's indicators with the proposed reference values.

Materials and methods

Physical quality indicators of the soil: a brief review

The bulk density (ρ_b) (g cm^{-3}) is defined as the oven-dry soil mass (M$_s$, g) per unit bulk soil volume (V$_s$, cm^3). This is measured at h=-100 cm (corresponding to a field capacity) to allow for possible soil shrinking or swelling (Reynolds *et al.,* 2009):

$$\rho_b = M_s / V_s \tag{1}$$

It is an index of the mechanical resistance to root growth (Topp *et al.,* 1997), but it is often used as in indirect indicator of aeration and the ability to store and transmit water (Reynolds *et al.,* 2009). For soils of medium or fine texture, various authors report that, for maximum crop production, the optimal range for ρ_b is 0.9-1.2 g cm^{-3}. If ρ_b values exceed 1.3 g cm^{-3} then land productivity decreases due to inadequate soil aeration (Reynolds *et al.,* 2009). However, for most agricultural soils, values below 0.9 g cm^{-3} may cause inadequate plant anchoring and a reduction in plant-available water capacity (Reynolds *et al.,* 2009). This does, however, also depend on the specific soil conditions.

The AC (cm^3 cm^{-3}), is the ability of the soil to store and transmit air. It is traditionally defined as:

$$AC = \theta_s - \theta_{FC} \tag{2}$$

θ_s (cm^3 cm^{-3}) being is the saturated volumetric water content and θ_{FC} (cm^3 cm^{-3}) the volumetric water content corresponding to the field capacity at h=-100 cm (Reynolds *et al.,* 2002) (-0.33 bar, according to the pressure plate apparatus).

Soil aeration is, therefore, essential for good crop production and overall soil health (Topp *et al.,* 1997). According to Reynolds *et al.* (2009), a near surface $AC \geq 0.14$ cm^3 cm^{-3} is required in sandy loam or clay soils. However, a more traditional threshold level is typically recommended for agricultural soils (AC>0.10 cm^3 cm^{-3}) in order to reduce the incidence of crop-damage or yield-reducing aeration deficits in the root zone (Reynolds *et al.,* 2009).

The plant-available water capacity (PAWC) (cm^3 cm^{-3}) is traditionally defined as:

$$PAWC = \theta_{FC} - \theta_{PWP} \tag{3}$$

θ_{PWP} (cm^3 cm^{-3}) being is the volumetric water content corresponding to permanent wilting point (at h=-15,300 cm). This refers to the soil's ability to store and provide water that is available to plant roots. A $PAWC \geq 0.20$ cm^3 cm^{-3} is generally considered *ideal* for root growth and functions, while $0.15 \leq PAWC < 0.20$ cm^3 cm^{-3} is considered *good*, $0.10 \leq PAWC < 0.15$ cm^3 cm^{-3} is *limited*, and $PAWC < 0.10$ cm^3 cm^{-3} is considered *poor* or *droughty* (Reynolds *et al.,* 2009).

The macroporosity (P$_{MAC}$) (cm^3 cm^{-3}) is here defined as:

$$P_{MAC} = \theta_s - \theta_m \tag{4}$$

θ_m (cm^3 cm^{-3}) being is the volumetric water content of the soil matrix (at h=-10 cm). It refers to the ability of the soil to quickly drain excess water and facilitate root growth. Reynolds *et al.* (2009) reported that the optimal values for this index should be in the range of 0.05-0.10 cm^3 cm^{-3}, with $P_{MAC} \leq 0.04$ cm^3 cm^{-3} being the lower critical limit.

The relative field capacity (RFC) (dimensionless) is defined as the ratio between field capacity and soil porosity:

$$RFC = \theta_{FC} / \theta_s \tag{5}$$

Olness *et al.* (1998) suggested that the optimal value for *RFC* is 0.66. However, more recently Reynolds *et al.* (2009) suggested that a range of $0.6 \leq RFC \leq 0.7$ achieved the optimal balance between both air capacity and water capacity in the root zone of rain-fed agriculture soils.

Thus water limited or aeration limited soils have lower ($RFC<0.6$) or higher ($RFC>0.7$) *RFC* values, respectively. This results in low microbial production of nitrates (Reynolds *et al.,* 2009). In other words, in rain-fed agriculture, soils with this optimal ratio are likely to have the water and air content which is most desirable for good microbial production of nitrogen more frequently and for longer periods than do soils that have larger or smaller ratios (Reynolds *et al.,* 2002).

Dexter (2004) proposed the so-called *S index* to evaluate the physical quality of the soil. This index is defined as the slope value of the soil water retention curve at the inflection point, when the curve is expressed as gravimetric water content.

The fundamental assumption of the *S theory* is that the physical or structural quality of the soil is determined primarily by management-induced structural pores, rather than texture-induced matrix pores. The structural pores consist of 3-dimensional networks of micro-cracks, fractures and inter-aggregate spaces (*i.e.* secondary structures). These are created by tillage, freeze-thaw activity, addition of amendments, drainage, crop rotation and root development (Reynolds *et al.,* 2009).

For both temperate and tropical soils, an $S \geq 0.050$ indicates *very good* physical or structural quality of the soil, while $0.035 \leq S < 0.050$ is *good* physical quality, $0.020 \leq S < 0.035$ is *poor* physical quality, and $S<0.020$ is *very poor* or *degraded* physical quality (Dexter and Czyż, 2007).

Field saturated hydraulic conductivity (K_{fs}) is an indicator of the ability of the soil to absorb, transmit and drain water at saturated water content (Topp *et al.,* 1997; Reynolds *et al.,* 2008).

The K_{fs} value has also been used extensively as a critical parameter for indicating changes in structural quality of the soil due to changes in the crops and/or land management practices (Ankeny *et al.,* 1990).

However, K_{fs} is highly sensitive to changes in pore size, roughness, tortuosity, and connectivity (Hillel, 1998) and may, therefore, be greatly over-estimated, due to the preferential flow in the extensive worm-holes, root channels and shrinkage cracks (Reynolds *et al.,* 2008). Overestimations can also generally be expected when hydraulic conductivity is determined in the laboratory on undisturbed soil cores, with differences within a factor of five (Bagarello *et al.,* 2007), or with differences of one or more orders of magnitude greater than those measured in the field (Basile *et al.,* 2006).

In agreement with the references in the literature (Reynolds *et al.,* 2008), we considered optimal values of K_{fs} as being within the range 43.2-432 cm d^{-1}. This interval may be considered ideal for agriculture soils as it promotes rapid infiltration and redistribution of crop-available water required, as well as reducing surface runoff and soil erosion, and encouraging rapid drainage of excess soil water. However, a reasonable upper critical limit of K_{fs}=864 cm d^{-1} can be considered for *droughty* soils, such as soils with coarse texture or excessive cracks and biopores (Topp *et al.,* 1997), with a lower critical limit of K_{fs}<8.6 cm d^{-1} (Reynolds *et al.,* 2007).

Two fundamental assumptions are implicit in the capacity based indicators (*i.e.* ρ_b, *AC*, P_{MAC}, *PAWC*, *RFC*, *S*) of soil physical quality: i) it is assumed that the soil is rigid or with no appreciable shrinking or swelling behaviour, and the pore volume and size distribution relationships are not affected by the variations in soil water content; ii) the so-called optimal ranges and critical limits of the capacity-based indicators are sufficiently general to be applied to a wide range of agricultural soils and climates (Reynolds *et al.,* 2009).

The equivalent pore size distribution functions, $S_v(h)$, may be defined as the slope of the water release curve, expressed as volumetric water content θ_v ($cm^3\ cm^{-3}$) *versus* ln(h), and plotted against equivalent pore diameter d_e (μm) on a $\log_{10}$ scale. The parameter d_e may be determined by using the capillary rise equation ($d_e \approx 2980/h$; $h(\text{cm})>0$), and a normalised equivalent pore size distribution function, $S^*(h)$, can be defined by dividing $S_v(h)$ by S_{vi}, to obtain the following equation (Reynolds *et al.,* 2009):

$$S^*(h) = \frac{S_v(h)}{S_{vi}} = \frac{m(\alpha h)^n \left[1+m^{1}\right]^{(m+1)}}{\left[1+(\alpha h)^n\right]^{(m+1)}} ; 0 \leq S^*(h) \leq 1 \tag{6}$$

where:
S_{vi} is the slope of the water release curve, expressed as volumetric water content, at inflection point.

Moreover, if one assumes that the soil is rigid (*i.e.* no appreciable shrinkage-swelling behaviour), and assuming a constant ρ_b value throughout the tension head range of the $\theta(h)$, and given that, by definition, θ_v is equal to the product of ρ_b and gravimetric soil water content (θ_g), then:

$$S^*(h) = \frac{S_v(h)}{S_{vi}} = \frac{S_g(h)}{S_{gi}} \tag{7}$$

In other words, $S^*(h)$ is independent of ρ_b and porosity, and, therefore, provides a means for comparing pore volume distributions among different porous materials. In addition, Eq. (7) defines the links between $S^*(h)$, S_{vi} and the Dexter S-value, S_{gi}.

The location [modal (d_{mod}), median (d_{med}) and mean (d_m) pore diameter] and the shape [standard deviation (SD), skewness (Sk), and kurtosis (Ku)] of the pore volume distribution curve, linked to the water retention curve, were calculated according to the relationships proposed by Reynolds *et al.* (2009), while the optimal range is shown in Table 1.

Experimental site

The study was carried out at Bitetto, near Bari, southern Italy, (41°

Table 1. Location and shape parameters for equivalent pore size distributions of both treatments considered for weed control, with indication of optimal values.

Treatment	Location parameters			Shape parameters		
	d_{mod} (μm)	d_{med} (μm)	d_m (μm)	SD (-)	Sk (-)	Ku (-)
No-tillage	73	6	2	207	−0.64	1.14
Surface tillage	205	20	7	172	−0.64	1.14
Optimal range	60-140	3-7	0.7-2	400-1000	−0.43 to −0.41	1.13-1.14

d_{mod}, d_{med}, d_m modal, median and geometric mean equivalent pore diameters, respectively; SD, standard deviation; Sk, skewness; Ku, kurtosis.

02' latitude N, 16° 44' longitude E, approx. 126 m asl), at the Experimental Farm of the unit of the Agricultural Research Centre specialising in research into cultivation in hot-dry climates (*Consiglio per la Ricerca e la Sperimentazione in Agricoltura, Unità di ricerca per i Sistemi Colturali degli Ambienti caldo-aridi*, CRA–SCA). The average precipitation and temperatures recorded at the weather station of the experimental farm during the 20-year period from 1992 to 2012, were 455 mm and 16.2°C, respectively.

The experimental plots are situated in a zone of the Experimental Farm where the soil is deeper than the average (Ap horizon reaches up to 30 cm). The surface layer of the soil (the first 30 cm) consists of 42.2% clay, 28.2% silt and 29.6% sand, with a mean organic carbon content of 26.8 g kg^{-1}. According to the USDA classification (Gee and Or, 2002), the soil texture was clay. A pedological characterization near the experimental plots (about 20 m away) classified the soil profile as Alfisol-Lithic Haploxeralf (SSS-USDA-NRCS, 2003), characterised by few fine pores in the Ap horizon (0-8 cm), and common fine and medium pores in the Bt horizon (8-20 cm). The sub-soil (depths greater than 20-30 cm) mostly consists of fissured rock. This enables the almond rooting system to reach the deeper layers.

The long-term research used in this study started in 1977. Its main objective was to assess the different tillage and weed control systems for almond tree (*Prunus amygdalus*, Batsch) cultivation.

We selected two plots (21 m by 7 m) from among the three systems of tillage and soil management investigated in this long-term research project. They were farmed with surface tillage (ST), consisting of disc ploughing or five-share ploughing at a depth of 20 cm and a rotary plough at a depth of 10 cm, and with NT with pre-emergence chemical controls.

More details about the experimental design, tillage options and weed control methods and their corresponding combinations can be found in De Giorgio and Lamascese (2005).

Soil sampling and measurements

The experimental procedure consisted of a combination of both laboratory and field measurements, This was applied to obtain estimates of the physical quality of the soil which could be efficiently compared to those obtained in many other similar works (Abu and Abubakar, 2013; Aparicio and Costa, 2007; Cavalieri *et al.,* 2009; Li *et al.,* 2011; Oicha *et al.,* 2010; Reynolds *et al.,* 2007; Silva *et al.,* 2011).

In order to determine the soil water retention curve and soil ρ_b six undisturbed soil cores were collected for each plot (NT and ST) during the summer season by gently hand-hammering stainless steel cylinders (height 5 cm, diameter 8 cm) into the surface horizon of the soil, after the first few centimeters (<3 cm) had been removed.

In detail, desorption water retention data were obtained in the laboratory for each undisturbed soil core using a Buchner funnel apparatus (Figure 1) for pressure head values h=-5, -10, -20, -40, -70, -100 and -130 cm (Burke *et al.,* 1986). Shortly afterwards, each soil sample was dried using the Tempe pressure cell (Soil Moisture Equipment Corp., Goleta, CA, USA) (Figure 1) and applying a pre-determined sequence of pressure head values (h=-150, -200, -300, -400, -500, -650, -800 and -950 cm). The volumes drained during the drying process were logged using a CR10X Campbell Scientific Inc. data logger. After drying, a visual assessment of gravel content was carried out, but this fraction was always considered negligible. We also used a pressure plate apparatus (Dane and Hopmans, 2002) to determine the soil water content corresponding to h=-3060 and -15,300 cm (Figure 1) for the re-packed soil cores.

The infiltration experiments were carried out in conjunction with the soil sampling in both plots, ST and NT, approximately three months after last tillage. Six to 9 replicates of the infiltration experiment were carried out for each plot at randomly selected locations using a tension infiltrometer (TI) (Soil Measurement System, Tucson, AZ, USA). This consists of a separate water supply and base-plate units with a 20 cm diameter disc (Figure 1). At each location, the soil surface was carefully levelled and smoothed before each experiment, and attempts were made to prevent infiltration surface smearing. When necessary, the plants were cut at their base with scissors while the roots remained in the soil. A spirit level was used to ensure that the disc and the reservoir base were always at the same height (zero relative distance), so that the head between the bubbling outlet at the bottom of the water supply tube and the disc membrane was constant. A retaining ring (diameter 24 cm) was placed on the soil surface, and a 1 cm thick dry inert sand contact layer was prepared. The pressure heads set at the infiltrometer membrane were corrected to take into account the thickness of the contact material layer (Reynolds and Zebchuk, 1996). A dry-to-wet sequence of six potentials (h=-15, -10, -6, –4, -2 and 0 cm) was adopted to minimise the effects of hysteresis on soil hydraulic conductivity measured in the field with the TI (Bagarello *et al.,* 2005, 2007). Visual readings of the water level in the supply tube of the infiltrometer were taken at 0.5-2 min intervals. More details about the experimental procedure used can be found in Bagarello *et al.* (2005). The infiltration runs were completed within two days in order to exclude any temporal variability effect due to the different initial water content of the soil.

Data analysis

The indicators of the physical quality of the soil were calculated for each soil sample. To be precise, the $\theta(h)$ values were fitted using the RETC code (van Genuchten *et al.,* 1991), and the water retention function was described using the van Genuchten (1980) model. This theoretical function was then used to estimate P_{MAC}, AC, RFC and PAWC. Assuming the studied soil to be rigid (laboratory experiments revealed no appreciable shrinking or swelling), a value for the S index was obtained according to the procedure proposed by Dexter (2004), turn-

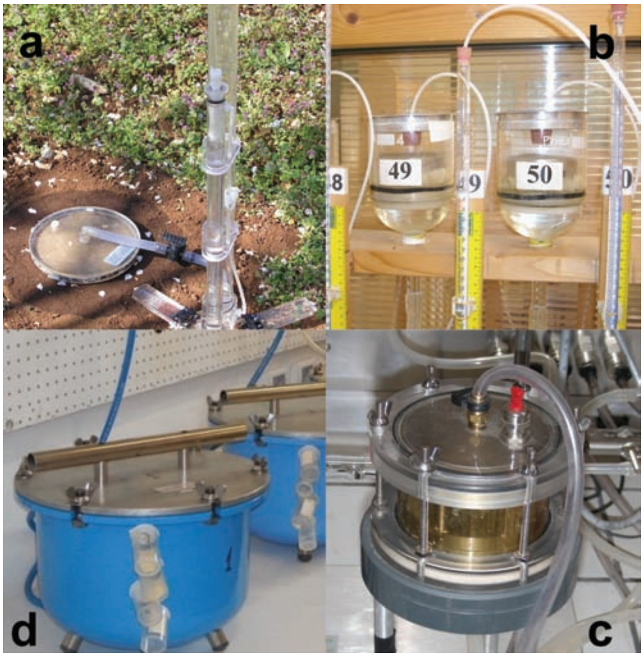

Figure 1. Tension infiltrometer (A), Buchner funnel apparatus (B), temperature cell (C) and pressure plate apparatus (D).

ing the volumetric water content into gravimetric water content using the corresponding measurements of ρ_b.

Pore volume distribution functions and water release curves were calculated using the procedure suggested by Reynolds *et al.* (2009) to obtain the corresponding location (d_{mod}, d_{med}, d_m) and shape (SD, Sk, Ku) parameters for each soil sample.

Soil hydraulic conductivity (K) corresponding to each imposed *h* value, was calculated by using the simultaneous equations method (Ankeny *et al.,* 1991; Castellini and Ventrella, 2012). Many papers confirm this to be a reliable method of estimatation (*e.g.* Bagarello *et al.,* 2010). Two estimates of K were obtained for each intermediate *h* value of the applied sequence. In this case, the best estimate of K was obtained as the arithmetic mean of the available estimates (Bagarello *et al.,* 2010). Field saturated hydraulic conductivity, corresponding to h=0, will be identified as K_{fs}.

Mean values and the associated coefficients of variation (CVs) were calculated for each indicator of the physical quality of the soil. To be more precise, ρ_b, P_{MAC}, AC, RFC, PAWC, S, d_{mod}, d_{med}, were all assumed to be normally distributed, as is common for these variables (Reynolds *et al.,* 2009), and the arithmetic mean and the associated CV value were

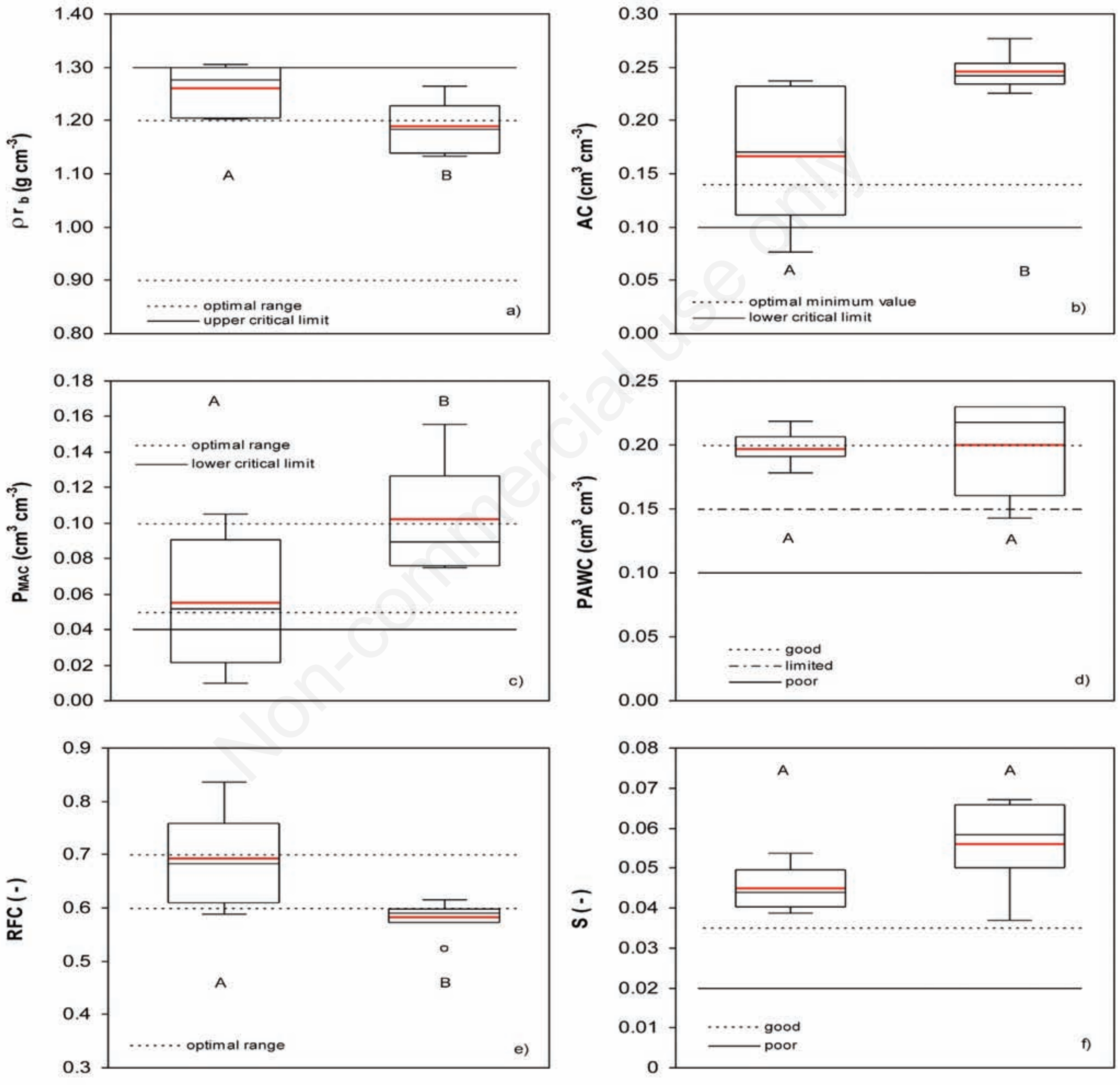

Figure 2. Comparison between no-tillage (left-hand box) and surface tillage (right-hand box) in terms of bulk density (A), air capacity (B), macroporosity (C), plant available water capacity (D), relative field capacity (E) and S index (F). Lines show proposed optimal/critical values. Mean values (lines in red-bold type within each box) with the same letter are not significantly different by Student's *t*-test (P=0.05).

calculated. The other data (d_m, SD, Sk, Ku and K_{fs}) were assumed to be ln-distributed (Reynolds *et al.,* 2009), and the geometric mean and the associated CV were determined (Lee *et al.,* 1985).

Each data set was summarized by a box plot in order to provide a visual presentation of the degree of the dispersion and skewness in the data (minimum, 1st, 2nd and 3rd quartile, mean, maximum) and to identify extreme observations (outliers, equal to 1.5 times interquartile range). For each indicator of the physical quality of the soil, the statistical differences between NT and ST were evaluated using Student's t-test (P=0.05).

Results and discussion

The comparison of the capacitive indicators of the physical quality of the soil is reported in Figure 2. As expected, the mean values of soil ρ_b observed in the NT plot were significantly higher than those in the ST plot, with differences that, at most, were equal to a factor (ratio between mean values) of 1.1. The associated coefficients of variation were, however, similar for the two treatments, with a factor (ratio between coefficients of variation) of 1.2 (Figure 2A). Mean values of ρ_b were within the optimal range ($0.9 \leq \rho_b \leq 1.2$ g cm^{-3}) only for the ST treatment (Olness *et al.,* 1998; Reynolds *et al.,* 2009). These are the values recommended for good root development and maximum crop production. NT had near optimal ρ_b values (Figure 2A). However, even though the observed ρ_b values in the NT plot (both mean and extreme values) were within the range that might cause loss of yield due to inadequate soil aeration ($\rho_b \approx 1.25$-1.30 g cm^{-3}), they can probably be considered optimal for orchards, and especially for almond trees, which have an extremely vigorous root system. ρ_b may also be considered to be a relatively significant predictor of dynamic soil properties when there are no cracks and, thus, there is no preferential flow. In this case, a decrease in the saturated hydraulic conductivity as ρ_b increases is to be expected (Blanco-Canqui *et al.,* 2004). As a result, the values for AC and macroporosity, P_{MAC}, were significantly higher in the ST plot by a factor of 1.5 and 1.9, respectively (Figure 2B and C). In agreement with the findings reported in the literature, we always found optimal air capacity conditions (AC>0.14 cm^3 cm^{-3}). These are recommended for minimum susceptibility to crop damage or yield-reducing aeration

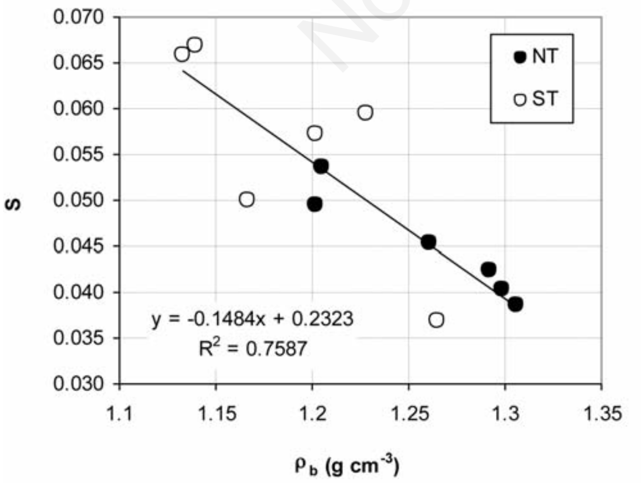

Figure 3. Linear regression between S index and soil bulk density (ρ_b), with indication of different points corresponding to both no-tillage (NT) and surface tillage (ST) treatments.

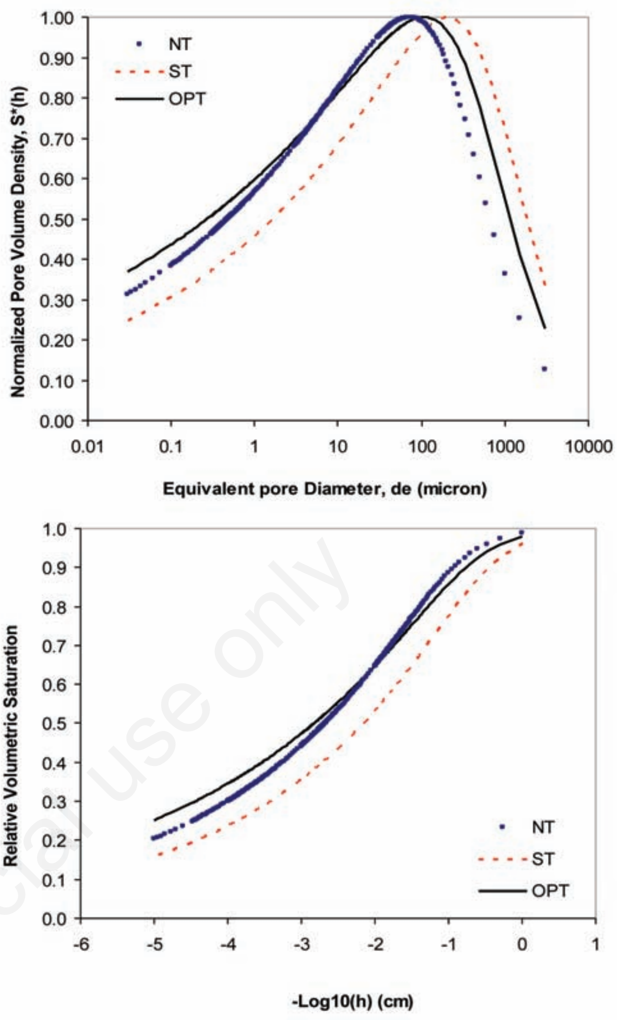

Figure 4. Pore volume distributions and water release curves for both no-tillage (NT) and surface tillage (ST) compared to the reference curve (OPT).

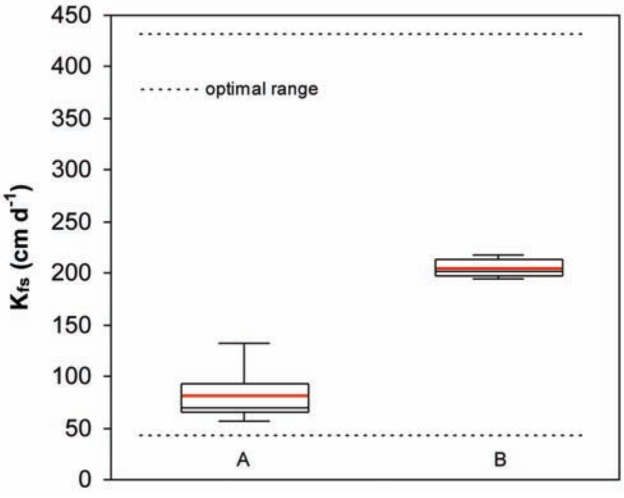

Figure 5. Comparison between no-tillage (left) and surface tillage (right) in terms of field saturated hydraulic conductivity. Mean values (lines in red-bold type within each box) with different letters are significantly different by Student's *t*-test (P=0.05).

deficits in the root zone. Macroporosity values were also optimal ($0.05 \leq P_{MAC} \leq 0.10$ cm^3 cm^{-3}). These results suggest that both tillage options provide adequate conditions to quickly drain excess water and facilitate root proliferation (Figure 2B and C). However, as expected, the results for NT treatment were more variable (CV=0.70 for P_{MAC}) than for ST, with differences equal to a factor of 5.5 or 2.2, respectively, for AC and P_{MAC}. This confirms the relatively higher levels of heterogeneity of undisturbed soils. PAWC were similar between NT and ST treatments and differences were without statistical significance (Figure 2D). For this indicator of the physical quality of the soil, we found *good* ($0.15 \leq$ PAWC <0.20 cm^3 cm^{-3}) or *ideal* (PAWC≥ 0.20 cm^3 cm^{-3}) values for maximum root growth and functions (Reynolds *et al.,* 2009) with CV differences that were 2-3 times higher for the ST plot.

An optimal balance between root-zone soil water capacity and soil AC ($0.6 \leq$ RFC≤ 0.7) was found only for no-tilled soil, while ST showed near optimal values (Olness *et al.,* 1998). To be precise, the mean values of RFC detected in no-tilled soil were 1.2 times higher than those measured in tilled soil, with differences between the corresponding CVs equal to a factor of 2.5 (Figure 2E). A Student's t-test showed these discrepancies were statistically significant. In other words, both treatments were, in practice, within the optimal range of the relative field capacity to provide the ideal proportions of soil/water and soil/air for producing maximum soil microbial activity, regardless of soil texture and ρ_b. However, relative field capacity values lower than 0.6, such as those measured in tilled soil, reduce microbial production of nitrates due to insufficient soil water (Reynolds *et al.,* 2009). Therefore, since potentially limiting conditions were recognised in the sampling date of the ST plot (about 3 months after the last tillage), it is reasonable to assume that there were insufficient relative field capacity values (water limited) immediately after tillage.

The overall good physical quality associated with the clay soil, for both NT and ST, was confirmed by the S index, which was always over 0.035, corresponding to conditions of good physical quality (Dexter and Czyż, 2007). In detail, mean values for physical quality of the soil, obtained for both treatments from Dexter's index, were similar (differences equal, at most, to a factor of 1.2) and not statistically different by Student's t-test (Figure 2F).

According to Dexter (2004), the S index decreases with increasing ρ_b (Figure 3), as widely reported in the literature and as also reported by Dexter and Czyż (2007), Cavalieri *et al.* (2009), and Silva *et al.* (2011). However, given that the S index is obtained from the water retention curve, it is mainly related to the pore-size distribution. This is greatly affected by soil management (such as tillage) and by soil compaction (such as raindrop effects or soil sampling). In other words, since no-tilled soil always showed optimal physical quality of the soil, with the exception of ρ_b, which was near optimal, it is plausible to hypothesise that the soil compacted slightly during sampling, especially for relatively larger pores. This reduced the macropore volume with a consequent alteration in the equivalent pore size distribution.

The location and shape parameters, and corresponding pore volume distributions and release curves, are reported in Table 1 and Figure 4, respectively. According to the results obtained from the capacitive indicators, the physical quality of the no-tilled soil was better than that of the ST, with location parameters of the soil pore volume distribution, *i.e.* d_{med}, d_{mod} and d_m (Table 1), within the optimal range (Reynolds *et al.,* 2009). SD that takes into account the range in pore diameters was always outside the optimal range suggested by Reynolds *et al.* (2009) for both the treatments, suggesting a relatively low level of heterogeneity in pore diameters. However, lower values for SD were observed for tilled (ST) than no-tilled soil, thus confirming that even only surface soil tillage may change the equivalent pore size distribution.

Negative and non-optimal values for Sk were observed in both cases, with small equivalent pore diameters being prevalent rather than those expected from a lognormal distribution (Sk=-0.64), whereas positive and optimal values of Ku were detected for both treatments, showing a leptokurtic distribution (Ku=1.14), higher in the centre and tailing off more at the extremes than the lognormal curve (Reynolds *et al.,* 2009).

The normalised pore volume distributions for the ST plot also showed lower densities of small pores and relatively higher densities of large pores than the optimal distribution (Reynolds *et al.,* 2009), and the normalised release curves always showed smaller degrees of saturation than the optimal one (Figure 4). Conversely, the NT plot had near optimal pore volume distribution, up to the modal diameter (corresponding to the distribution peak), while there were lower densities of larger pores, probably due to compaction during soil sampling. The soil retention characteristics of NT soil also almost coincided with those optimal characteristics, suggesting that conservative management of orchards, with NT wherever possible, is desirable.

The estimates of physical quality obtained from the water retention curve unanimously led us to classify the NT treatment as optimal but similar results were also obtained for field saturated hydraulic conductivity, K_{fs} (Figure 5). Mean values of K_{fs} were always within the optimal range proposed by Reynolds *et al.* (2007) for agricultural soils, ranging from 81 to 204 cm d^{-1} (Figure 5). This determined an infiltration and deep drainage rate that was not too quick (and thus allowed adequate water adsorption into the soil matrix) nor too slow (and thus did not cause reduced traffic or excessive ponding or damage to the crop due to the root zone becoming waterlogged).

The observed differences in unsaturated hydraulic conductivity ($-2 \leq h \leq -15$ cm) were always significant, with discrepancies between the mean values of NT and ST which were very similar to those obtained at saturation (ST>NT) and equal, at most, to a factor of 3.4. However, these findings were expected because the results for soil ρ_b were consistent for the two treatments (ST<NT).

Finally, it is worth noting that the K_{fs} of NT was relatively more variable than that of ST (CV_{NT}/CV_{ST} equal to a factor 8). This result is probably linked to the fact that preferential flow occurred through the meso-macropore system in the NT plot. Distribution of these macrospores is generally more uneven. By contrast, tillage reduced the heterogeneity of the soil in the ST plot, breaking up the continuity, interconnections and arrangement of its pore system, and determining the same probability of sampling finding surface meso-macropores.

Conclusions

The main objective of this work was to assess the physical quality of the soil of an almond orchard where different soil tillage systems and weed control methods were used. These were no-tillage with chemical control and surface tillage. Indicators of the physical quality of the soil were used to compare the tillage-induced changes, following the guidelines laid out in the literature.

After thirty years of no-tillage, both the ρ_b and the capacitive indicators of the physical quality (AC, P_{MAC}, PAWC, RFC), obtained from the water retention curve, unanimously classified the quality of the studied soil as good. The overall good physical quality of the soil associated with both treatments was confirmed by the S index, which always had mean values over 0.035. This corresponds to good physical quality of the soil. Moreover, with the NT treatment there were optimal values for field saturated hydraulic conductivity, which promotes rapid infiltration and redistribution along the soil profile.

Our findings suggest that the equivalent pore size distribution functions may be used to assess the physical quality of the soil, in conjunction with both capacitive indicators and measurements of the hydraulic conductivity. They provided detailed analysis of the physical quality of the soil and useful information about the rearrangement of soil particles and aggregates. They, therefore, improved our understanding of the relationships between capacitive indicators of physical quality, of equivalent pore size distributions and of the dynamic properties of the soil. Following the existing guidelines for evaluating the physical quality of the soil, and considering simultaneously all the thirteen indicators used, good physical quality was detected for 77% of NT and 46% of ST. These results support previous studies carried out on the same experimental plots (De Giorgio and Lamascese, 2005). No-tillage treatment with chemical weed control resulted in greater trunk growth and fruit yield.

The optimal intervals proposed in the literature may not be applicable for all soils or for a specific field site, because they are only general guidelines and are obtained from a wide range of soil types.

The experimental methods used in this research seemed to be suitable for detecting the effects of land use and thus may be used to compare different agricultural practices. However, even though the guidelines used were reasonably good for assessing the physical quality of the soil in the sampled area, further research is needed in order to obtain more realistic estimates of the physical quality of the soil on farms with high field crop production and minimum environmental degradation and to provide a more reliable assessment of the hydraulic properties of the soil. This will allow laboratory experiments to be conducted that will reproduce conditions in the field.

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