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Influence of tillage on soil macropore size, shape of top layer and crop development in a sub-humid environment**

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Abstract: Topsoil macropores of two plots under no-tillage and conventional tillage were analyzed. A leguminous-cereal rotation was applied for six cycles under dry-land farming system (crop residues were removed). The clay-loam soil shows some vertic characteristics. The main goal is to identify the relationship between the top soil macro and meso-pore distribution for the two tillage systems (at the end of sixth cycle of cultivation) with the annual crop production (rainfall in normal growing period and crop production values are included). Unaltered topsoil samples were taken from 0 to 60 mm (row and interrow positions) and from the immediate depth (60 to 110 mm) in both plots (conventional and no-tillage). The morphometric analyses of 66 polished slices were carried out with the aim to identify differences in soil macro and meso-pore organisation.
Soil macropores were classified by size (area) and elongation ratio and by form factor and equivalent pore diameter. No appreciable differences were observed. Soil macro and meso pore distributions of samples were also compared. The main difference observed between topsoil's treatments was a different macropore size distribution between topsoil positions. The presence of larger macropores was higher in conventional tillage compared to no tillage. Samples taken from row and deeper positions of conventional tillage show a somewhat higher amount of macropores in the range between 2 to 2.3 mm equivalent pore diameter. Soil macropores contribute to increase soil aeration and soil drying when topsoil is too wet in critical periods of crop development. Conventional tillage (crop residues removed), provides to the topsoil of a larger lateral and vertical variability of macropore distribution than no-tillage topsoil.

Key words: conventional tillage; crop residues removal; legume-cereal rotation; Mediterranean climate; no tillage; soil macropore classification

Introduction

Variation of soil moisture content through the growing season is a key factor for plant growth in dry-land farming of the Mediterranean and semiarid regions but soil aeration is critical for plant root growth as well. Pore size determines pore function in soil-plant relationships. Larger pores (soil macropores) act as non-capillary pores; they become suddenly dry and air can flow at low pressure gradients (Horn & Peth, 2009). Intrinsic soil properties (mainly particle size and organic matter) and environmental and management conditions (climatic conditions, tillage system, etc.) determine soil porosity and soil pores distribution over the agricultural cycle (Mati & Kotorova 2007). In cereal crops, stubble acts as mulch and upon decomposition its organic matter increases water efficiency (Greb 1979). Application of no-tillage (or conservation tillage) together with crop residues management contribute to soil and water conservation. Results are more uncertain when organic residues are removed (Unger 1990). On the other hand, the long-term effects (one decade or more) can be less pronounced and sometimes impossible to distinguish from natural and management-induced variability (Strudley et al. 2008). Some parameters are used to identify the effects of the tillage system on soil: frequency of pores of equivalent diameter larger than 100 μm (Kay 1990), equivalent pore size distribution (Or et al. 2000; Kosugi 1999) among others. Pores that are smaller than 1 μm are not strongly affected by increases in bulk density resulting from stresses (Greenland 1977), specially under mechanical stress application. The volume of macro- and mesopores (> 30 μm) and their connectivity have a major influence on soil water and solute flows, aeration, a range of soil mechanical characteristics and root development (Dohnal et al. 2009). Water infiltration and surface water storage have all been shown to be directly affected by tillage and sur-

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Table 1. Grain yields during the experimental period.

			CT			NT					
Cycle	Crop	Cumulative rainfall NGP (mm)	N	Mean kg/ha	STD	N	Mean kg/ha	STD	t-value	p-value	CT:NT
First	Peas	nd	12	3428	762	12	1880	341	–6.43	0.000	1.823
Second	Wheat	518	4	2446	94	4	1904	271	–3.78	0.032	1.285
Third	Wheat	589	6	2940	566	6	2930	231	–0.04	0.970	1.003
Fourth	Barley	623	8	2045	626	8	1060	336	–3.92	0.003	1.929
Fifth	Peas	529	nd	nd	nd	nd	nd	nd			
Sixth	Wheat	320	6	2142	471	6	1876	188	–1.28	0.246	1.142

CT: Conventional tillage; NT: no-tillage; NGP: Normal Growth Period (September to May); N = number of plots; STD = Standard Deviation; nd= no data.

face cover residue of soil (Bradford & Peterson 2000). Macropore flow is frequently generated at, or very close to the surface in no-till arable management, and it is of great importance for root growth and soil transmission properties (Bouma & Dekker 1978), particularly soil pores with effective diameters greater than 100 μm (Gibbs & Reid 1988).

The aim of this paper is to evaluate the macro and meso-pore size distribution of a ploughed soil horizon resulting from conventional tillage and no-tillage (dry-land farming and crop residues removed) on crop production parameters after six years of legume-cereal rotation. The soil macropore (> 50 μm) distribution on crop parameters was assessed under the two treatments.

Material and methods

The experiment was carried out at Torre Marimon (Barcelona, NE Spain, E430447m -N4606920m, UTM: 31N / ETRS89 and 195 m a.s.l.) under Mediterranean climatic conditions (wet autumns and winters, dry summers and very high inter-annual variability). Soils are Calcic Cambisols, general and local slope is 7%. Soil morphology reveals some vertic characters (some cracks can appear during dry periods). Topsoil texture is clay loam, and OM content was 1.77%. EC (soil: water extract ratio 1 : 5) was 0.207 dS/m at 25℃. The same rotation of legume-cereal [pea (*Pisum sativum* L.) – wheat (*Triticum aestivum* L.) – wheat *(Triticum aestivum* L.) – barley (*Hordeum vulgare* L.)] was applied for six years (1994-2000) in two plots of 0.27 ha each under dry-land farm conditions. In the first plot, continuous conventional tillage (CT) was applied (mouldboards, ploughing and vertical axis rotary harrow to provide a proper seedbed, and weeds controlled as needed with appropriate herbicides). Simultaneously, a no-tillage (NT) was used in the second plot (glyphosate at a rate of 0.72 L active ingredient ha^{-1}). In both plots, sowing was generally made in December, or in February (wet years), with a no-till drill (John Deere – 270) in rows 186 mm apart. The grain was harvested in mid-June (peas) and early July (wheat and barley) using a 1.25 m wide F. Walter. H Winteresteiger plot combine (11.2 m^2 / sample, 4–12 samples/plot). Crop residues were removed, and stubble was left in the plots (7 to 15 cm high). Additional information about the site, soil, climate, tillage works, and rotation conditions can be obtained from Josa & Hereter (2005).

Undisturbed and oriented samples were taken with metallic Kubiena boxes driven carefully through the soil in early September of the 6^{th} crop rotation cycle (Josa et al. 2011). Three samples were taken from 0 to 60 mm in each position: drilling-row (R) and drilling interrow (I), and two samples from 60 to 110 mm (D) depth. Under vacuum condition, air-dried samples were impregnated with an unsaturated polyester resin (diffractive index = 1.52) containing a fluorescent dye (Uvitex DB, Ciba-Geigy). Three to five slices of each one of 16 blocks of resin-impregnated samples were obtained. The two faces of each cut were analysed separately. Sixty-six polished slices (45 mm × 65 mm) were illuminated with both tungsten and UV lights and photographed with a digital camera (without geometric distortion) at a resolution of nearly 2 megapixels per image. Binary images were processed and analysed with OPTIMAS 5.2 software (Optimas Corp.) to measure the two-dimensional porosity parameters (Torrentó & Solé 1992; Raducu et al. 2002). Pixel size was 35 μm (Josa et al. 2011). Total macro- and mesopores number (*mpore*), perimeter and total area of *mpore* were determined.

Although several methods can be employed in the study of the morphometry of soil macroporosity (Sampaio & Sampaio 2010), the population of *mpore* was classified after Pagliai et al. (1983; 1984) using a form factor ($FF = area/(perimeter)^2$) in three classes: rounded pores ($FF > 0.04$), irregular pores ($0.04 > FF > 0.015$) and elongated pores ($0.015 > FF$). Equivalent pore diameter (EPD) was calculated for each class using $EPD = 2(area/\pi)^{0.5}$ (for rounded and irregular pores) and EPD = (perimeter-$((perimeter^2)\text{-}16area)^{0.5}/4$ (for elongated pores). *mpore* were classified in three classes: $EPD > 0.5$, $0.5 > EPD > 0.05$ and $EPD < 0.05$. Finally, *mpore* were distributed by EPD using pore size distribution (PSD).

Statistical analyses were carried out in order to obtain and compare the distributions of the different groups of data (Minitab 2007). The following statistics were calculated: standard deviation (STD), skewness, Q1 (median for the first half of the data), Q2 (median for the entire set of data) and Q3 (median for the second half of the data).

Results and discussion

A rather low crop yield was obtained over the whole experiment, when compared with reference values for local dry-land farming (about 4,000 kg/ha; G. Gorchs, personal communication). As presented in Table 1, productivity of NT was significantly different from CT ($\alpha = 0.05$) in 3 of the 6 years of study (5^{th} year was severely damaged). Grain production varied consider-

Table 2. ~~Macro- and meso pore~~ classification as percentage of the whole pool of measured pores. Classification according to factor form (FF) and equivalent pore diameter (EPD) (Pagliai et al. 1983, 1984)

FF	EPD (mm)	CT (%)	NT (%)
Elongated	EPD > 0.5	0.11	0.12
	0.5 > EPD > 0.05	0.54	0.73
	0.05 > EPD	4.18	4.29
Irregular	EPD > 0.5	0	0
	0.5 > EPD > 0.05	10.08	10.54
	0.05 > EPD	28.47	31.21
Rounded	EPD > 0.5	0	0
	0.5 > EPD > 0.05	3.09	3.98
	0.05 > EPD	53.54	49.14

CT: Conventional tillage; NT: No tillage; EPD: Equivalent pore diameter

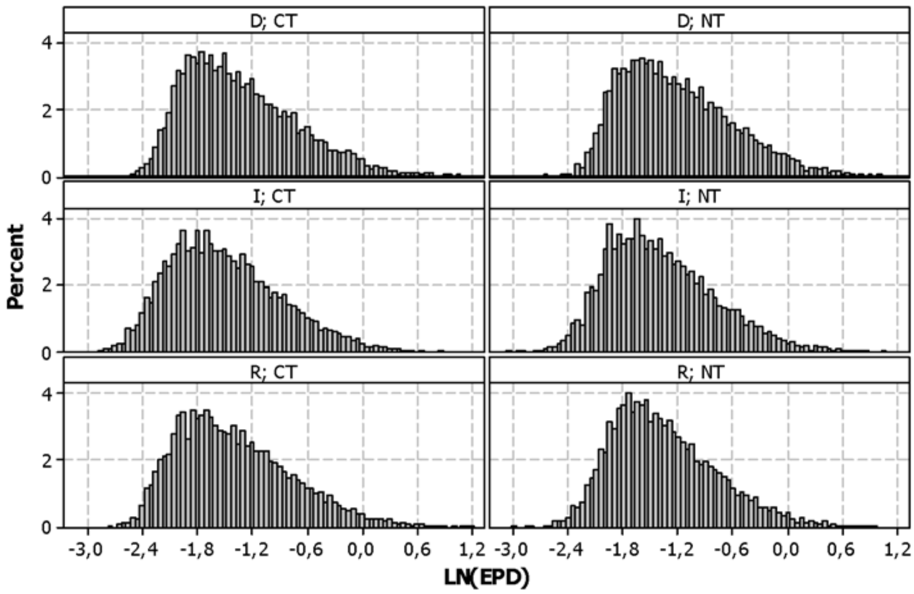

Fig. 1. Pore size distribution (PSD) of topsoil macropores from CT (conventional tillage) and NT (no-tillage) plots in three different topsoil positions (D, 60 to 110 mm depth; I, drilling interrow; R, drilling-row, 0 to 60 mm).

ably between years. The ratio of annual yields between treatments (CT:NT) was closest to 1 on the 3rd year and corresponded to the most favourable conditions. Also, no significant differences were found on the 6th year. These two cycles showed that both systems could have a similar yield potential. In contrast, data from the other three years of the experiment show significant differences between treatments, with the CT:NT ratio reaching a value close to 2 (4th year, barley). This different response might be related with different factors such as irregular rain distribution (both within and between years), variability of local conditions of soil preparation, or soil moisture content at the time of seeding (Griffith et al. 1988). The number of pores classified was 65890, of which 36304 corresponded to the CT treatment ($0.005 < EPD < 7.395$ mm, average = 0.3073 mm and STD = 0.2794, Q1 = 0.1518, Q2 = 0.2228, Q3 = 0.3604, skewness = 5.23). The other 29586 pores corresponded to the NT treatment ($0.006 < EPD < 11.206$ mm, average = 0.3284 mm and STD = 0.3009, Q1 = 0.1687, Q2 = 0.2420, Q3 = 0.3836, skewness = 7.27). For each tillage system, *mpore* were classified according to the described method, regardless of their position relative to the seeding line (Table 2). In the case of CT, the application of pore classification yielded very similar results, either when pores were analysed as a whole or when they were analysed according to their relative positions in the topsoil (data not shown). As shown in Table 2, more than 90% of *mpore* fell into just three classes (out of nine), and less than 1% of *mpore* corresponded to four of the classes. According to the EPD classification, the number of *mpore* in each class decreased as follows: rounded (0.05–0.5) > irregular (0.05–0.5) > irregular (> 0.5 mm) > elongated (0.05–0.5). The form factor classified most pores as irregular (nearly 40%) and rounded (nearly 50%). Taken together, the results show a strong predominance of "small rounded" *mpore*. Similar results were obtained after soil *mpore* classification of NT data. In both cases, the percentage of *mpore* in the most represented classes was similar between CT and NT. The cumulative effect (six cycles) of NT application to a clay-loamy soil

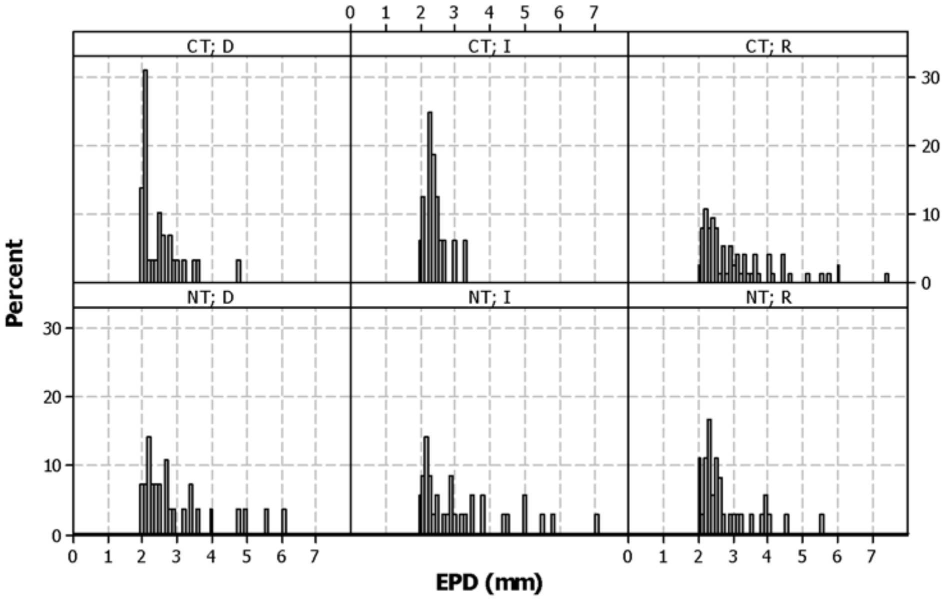

Fig. 2. Pore size distribution (PSD) of pores (equivalent pore diameter in the range 2 > EPD > 7.5 mm) of CT (conventional tillage) and NT (no-tillage) treatments, in different topsoil positions (D, 60 to 110 mm depth; I, drilling interrow; R, drilling-row, 0 to 60 mm).

on its topsoil structure did not seem relevant in comparison with CT, particularly for the class distribution of macro- and mesopores according to shape and size, although the average values of 2D macro-porosity differed by more than 10% (Josa et al. 2011). However, the effect of drying (natural or during preparation) on samples and on their vertic characteristics should be taken into account. *mpore* PSD was obtained for each treatment (Fig. 1) separating the relative positions of samples in the topsoil. In all cases, although the natural log was applied to the skewed EPD data, this transformation was not enough to obtain a normal distribution. Only slight differences were recognised, in central values. Other differences were observed in the relative frequency of maximum values, which were slightly higher in NT than in CT. The tails in the analysis of frequency distribution show differences that affected a much smaller population of *mpore* (0.33% of all measured pores). As shown in Fig. 2, considerable differences in PSD are detected in the 2–7.5 mm range in the lower position of topsoil (D) and interrow (I) position of the CT treatment (more specifically between 2.05 mm and 2.35 mm). The upper part of the tilled layer of CT showed increased variability of macropores slightly larger than 2 mm in both row and interrow positions (R vs. I) and vertically (R, D). This kind of distribution is not seen in NT, where macropores appear evenly distributed in the three positions. This behaviour may be linked to the normal aggregate breakdown and regrouping processes, which take place every year as a result of meteorological conditions, farming machinery and cropping intensities (Farkas et al. 2009).

The quantity of organic matter was the same in both treatments, or slightly lower in NT. For this reason, this result was attributed to tillage, either the farming system itself or the work team, or the way tools were used. CT tillage contributed to create this greater number of macropores slightly larger than 2 mm in topsoil, as well as their discontinuous distribution. R, I and D positions are spaced a few centimetres and a larger diversity of aeration and drying conditions occurs in CT than NT under similar meteorological conditions. Therefore, the CT plot as a whole became more adaptable to the daily and seasonal variations of humidity and aeration conditions in the topsoil. This is particularly important during the critical periods of germination and tillering, and this large diversity of drying conditions may contribute to explain why the conditions prevailing at seeding time were so important for crop yield, especially in NT.

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