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Effects of two tillage techniques on soil macroporosity in sub-humid environment**

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Abstract. In an experiment conducted in NE Spain, cereals and legumes were rotated for seven cycles using two different tillage techniques – conventional tillage and direct drilling (no-tillage: NT). Straw was removed after harvesting in both tillage systems. With NT, more than 30% of the soil surface was still covered by residues (stubble) at sowing. The soil was Calcic Cambisol and the climate aridity index was 0.76. The climatic water balance was negative, at -187 mm y^{-1} from 1950 to 1980. The aims of the study were to determine the effect of tillage system on 2-D macroporosity by micromorphology, and bulk density (excavation method) of the upper layer of the ploughed horizon. To identify differences, either parametric or nonparametric statistical tests were performed depending on sample size. Direct drilling with residue removal affected bulk density, macroporosity and mean macropore area in the top 10 cm of the profile. The same effects were observed under conventional tillage. The upper layer of the studied horizon had higher total porosity than the layer beneath with both treatments. The upper layer of the horizon showed unfavourable physical conditions with direct drilling.

Keywords: leguminous-cereal rotation, row and inter-row macroporosity, 2-D macroporosity, mean macropore area, bulk density

INTRODUCTION

In the Mediterranean region, water available for crops is restricted by irrigation and/or rainfall patterns despite the technological advances and improvements in water distribution and availability for crops. Approximately 77.6% of the arable surface in Spain is dryland (INE, 2007, data for 2003). Specifically in Catalonia (NE Spain), 72% of arable land is dryland (data for 1999). The main crops in this area are cereals (wheat, barley, rye) and, to a lesser extent, legumes (IEC, 2005).

Direct drilling or no-tillage (NT) is a very widespread practice used in several ways. Both stubble and straw may be left in place, and all crop residues burnt (Bescansa *et al*., 2006), or straw may be removed (either for weed control or for sale), and stubble left in place. When crop residues return to the soil they help maintain soil porosity and tilth (Larson, 1979).

Conventional tillage (CT) is used to prepare the seedbed (improving seed-soil contact), facilitating regular, unvarying early plant emergence. However, in the long-term, CT (primary and secondary tillage operations for preparing seedbeds) causes intense alteration of the top centimetres of the soil directly affected by tillage and might contribute to negative physical fertility of soils. These effects may vary at different depths. CT decreases organic matter content in Ap horizons and reduces structural stability in the surface horizon. It also compacts the soil at some depth (plough pan) and increases resistance to root penetration (Micucci and Taboada, 2006). It alters the soil pore system (Sasal *et al*., 2006) and total porosity, especially in subsurface horizons, changing the infiltration rate and affecting the soil water storage capacity (Lipiec *et al*., 2006).

Infiltration is essential to ensure soil water recharge for dryland farming. Parameters such as sorptivity regulate the initial stages of infiltration and depend on management

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practices (Scott, 2000). An increase in residual biomass incorporated into the soil enhances micro-aggregation in the top 2.5 cm as well as effective porosity (Shaver *et al*., 2003). Conservation tillage has been shown to improve the physical properties of the soil, particularly by allowing higher soil water content (Unger *et al*., 1991; Lampurlanés and Cantero-Martínez, 2006). Farkas *et al*. (2009) compared the range of total soil water in different tillage systems and found mouldboard ploughing < loosening + disking < NT < disking. Furthermore, NT soil retained more water in the upper 0.20 m layer and less in the 0.80 m layer than with disking, which indicates that NT provided more balanced soil water distribution within the profile because root distribution was more uniform due to the absence of tillage-induced subsoil compaction. Tóth *et al*. (2009) have reported carbon dioxide emission with different soil management systems (NT, ploughing, loosening + disking) and different soil water content ranges. In general, the rate of emission increased with increasing soil water content, and CO_2 emissions were the highest and lowest for the NT and CT treatments, respectively. This could be explained by organic carbon being more accessible for microbes in less disturbed soil.

The results of a study conducted on two experimental sites in Poland to determine the effect of two tillage systems (conventional and reduced) on changes in some soil microbiological activity parameters showed that the reduced tillage system created a more friendly environment for the growth and activity of soil microorganisms than CT (Gajda, 2008), and also improved soil physical properties (Czyż and Dexter, 2008). The soil physical properties assessed at those sites indicated that bulk density and aggregate stability were higher for reduced tillage than for CT, whereas reduced tillage increased water content throughout the profile in silt loam soil (Site 1), and only at the top in heavy loamy sand (Site 2). There is presently a growing interest in developing conservation tillage systems as an alternative to traditional tillage in some areas, but the success of reduced tillage and direct drilling depends on the crop, soil type and climatic conditions.

Micromorphological techniques have been widely used in the assessment of macroporosity and soil microstructure. Since the pioneering publications of Brewer (1964) and Jongerius (1957) with precise soil microstructure descriptions, and Lafeber (1965) with the first quantitative pore assessments (size and orientation) in polished sections of undisturbed soils, many researchers have actively contributed to the present status of soil micromorphology (Bullock and Murphy, 1976) and soil micromorphometry (Pagliai, 1988; Ringrose-Voase, 1990) as reliable techniques for the morphological characterization of the physical, chemical and biological properties of soil. Pagliai (1988) and Ringrose-Voase (1990) have used this technique to assess many geometric soil pore parameters (size, area, Feret diameter, orientation, *etc.*) in both steady-state and dynamic studies on the physical effects of different uses and types of management on soil.

In research conducted in NE Spain (Josa and Hereter, 2005), cereals and legumes were rotated using two different tillage techniques, conventional and direct drilling (or no-tillage, maximum tillage depth = 0.2 m). For five consecutive years (1995 to 1999), the straw was removed from the fields at the end of each cycle, and water content in the surface horizon (0 top 0.2 m) was monitored during the spring. Throughout this period, the water content was higher with NT than with CT. However, this did not lead to an improvement in yield with NT.

The aims of this paper are:

– to describe the effects of the tillage system on the macropores using soil micromorphological techniques, after seven consecutive years of NT or CT;

– to acquire information on bulk density to find out the effects of tillage at different depths in the soil profile.

The results found can be related to soils in any other semiarid Mediterranean area where direct drilling techniques are applied.

MATERIAL AND METHODS

The study area, located in Vallès Oriental, Barcelona (NE Spain), has a Mediterranean climate, with wet autumns and springs, dry summers, and wide inter-annual variability in precipitation. The annual water balance shows a deficit of 187 mm y^{-1} (P = 605 mm y^{-1} and ET_0 = 792 mm y^{-1} series from 1950 to 1980), with a climate aridity index of 0.76 (UNESCO, 1977), which is quite common in wide areas around the Mediterranean. It is an area of marginal farming (15.5% of the area is occupied by extensive agriculture) amidst woodland and urban areas. There is a high risk of forest fires during the summer, and farmers are advised to remove crop residues. Hence, it is common practice to remove straw and leave stubble in place.

The experiment was carried out on two representative plots with soil developed on arkosics clays and sandstones. The main components are quartz, feldspar, biotite, in a kaolinitic matrix (ITGE, 1993).

The soil was classified as Calcic Cambisol (Commission European Community, 1985) over the whole experimental area, which shows a uniform gentle slope (8%). Soil characteristics were very similar throughout (Josa *et al*., 1998): over 0.80 m deep; rich in $CaCO_3$, and uniform clay loam texture throughout the profile. Their pH in water ranged from 8.2 to 8.4, total organic carbon was 1.03% in the top 8 cm, decreasing with depth. Cation exchange capacity ranged from 15.2 to 12.1 $cmol_{c+}$ kg^{-1} and the electrical conductivity at 25ºC (water extract 1:5) was 0.21 dS m^{-1} or lower.

Four-crop grain legume/cereal rotation consisting of legume (pea/soybean) – cereal (wheat) – cereal (wheat) – cereal (barley) was used for both traditional tillage and direct drilling.

The main features of the tillage experiment, which started in 1994, are described in detail in Josa and Hereter (2005). Soil samples were taken at the end of the experiment in September 2001, after seven complete crop cycles.

The experimental area comprised two plots on the backslope of a generally sloping area, each one measuring 30x90 m.

One plot was subjected to direct drilling in the following farming sequence:
– mineral fertilization,
– weed control (Imazethapyr in pea; chlorsulfuron and tribenuron applied as described by Mas and Verdú, 2003),
– sowing (disk direct drill, with row spacing of 186.6 mm),
– weed control (pendimethalin),
– harvest (Josa and Hereter, 2005).

Seeding and harvesting were carried out with the same agricultural machinery (row spacing: 0.187 m) on both plots at the same time.

The other plot was subjected to conventional tillage as commonly used in the area, in the following farming sequence:
– cultivator plough,
– harrow and roller;
– mineral fertilization,
– weed control (similar to NT),
– sowing,
– harvest.

Organic matter management was identical in the two plots: stalks and straw were removed and stubble was left in place. Crop residues were found to cover more than 30% of the surface area of the NT plot (measured after straw removal).

At the end of the seventh consecutive cycle, undisturbed samples were taken from each plot for micromorphological analysis of soil pore space and bulk density measurement. Samples were taken after the barley crop under dry soil conditions.

Two sampling areas were defined (middle backslope and lower backslope) in each plot, and in each area a trench (1 m long by 0.5 m deep) was dug, perpendicular to the direction of tillage-drilling. Samples were taken from each of two layers, upper (0 to 50 mm) and lower (below 50 mm), identified in the ploughed horizon. Undisturbed and oriented samples were taken in Kubiena boxes (50x70x40 mm). In the upper layer, samples were taken a) in the drilling furrow (Row), and b) in the drilling interrow (Interrow). In the lower layer, differences between the positions were not as obvious as in the first and consequently just one set of samples was taken. Three replicates (K boxes) were sampled from each upper layer and two replicates (K boxes) from the lower layer.

Undisturbed samples were stored in dry atmospheric conditions (protected with filter paper) and then impregnated with an unsaturated polyester resin (diffractive index = 1.52) with a fluorescent dye (Uvitex DB, from Ciba-Geigy) in it, under vacuum conditions. Once polymerized, the blocks were cut with a large diamond disk saw into slices approximately 1 cm thick and up to 7 cm long.

From 3 to 5 slices were taken from each block. Polished slices were analyzed separately on both sides. Defective slices (deficient impregnation) were rejected. Table 1 shows the sample distribution pattern and the area analyzed (in mm^2). The polished faces (45 mm x 65 mm) of each slice were illuminated with both tungsten and UV light and scanned (without geometric distortion) at a resolution of nearly 2 megapixels per image. Binary images were processed and analyzed with OPTIMAS 5.2 (Optimas Corp.) software to measure the two-dimensional porosity parameters, following Torrentó and Solé (1992) and Raducu *et al*. (2002). The image pixel size was 35 μm and, therefore, the minimum pore size considered was 50 μm equivalent diameter.

Table 1. Depth of samples from ploughed horizon. Identification of blocks, polished faces and total area analyzed

Tillage	Position	Depth (mm) (±5)	Sample blocks	Polished faces	Surface area analyzed (mm^2)
Conventional tillage	upper layer row	0-60	3	13	22 400
	upper layer interrow	0-60	3	12	16 450
	undifferentiated lower layer	60-110	2	6	13 400
	complete ploughed horizon	0-110	8	31	
No tillage	upper layer row	0-60	3	14	21 850
	interrow upper layer	0-60	3	13	22 525
	undifferentiated lower layer	60-110	2	8	23 250
	complete ploughed horizon	0-110	8	35	
Total				66	322 975

Water flux in soil is usually conditioned by the macroporosity characteristics (total macroporosity, number, form and continuity of macropores). This is relevant for water infiltration, and during drying, because each macropore interacts with its immediate neighbour to allow water transmission and regulate the air-filled porosity (Weiler and Naef, 2003).

With a view to characterising the effects of the CT and NT tillage systems on macroporosity, three measurements were made on every slice analyzed: number of macropores, area of macropores (mm^2), and total surface area analyzed (mm^2), and the following variables were calculated:

– 2-D macroporosity (area of macropores/total surface area analyzed) which is well correlated with total porosity measured by other methods (Edwards, Shipitalo, and Norton, 1988),

– number of macropores per unit area (NMUA), which along with 2-D macroporosity is an indication of how good water transmission fluidity (Mallants *et al.,* 1997),

– mean macropore area (MPA), used as a simple way to characterize the effects of tillage system on soil macroporosity *ie* using CT/CT : NT/CT (noted as "CT/NT ratio").

Bulk density was determined using the excavation method (Blake and Hartge, 1986). Sample volume was from 450 to 650 cm^3 of soil extracted at the same depth as the micromorphological samples. Three replicates were taken of each position (upper and lower layers in row and interrow in CT and NT plots) for a total of 24 samples.

Statistical analysis of bulk density data and porosity parameters from the polished sections were used, first, to compare the two tillage systems (CT and NT), and second, to find any significant differences between the upper and lower parts of the ploughed horizon in each tillage system. Differences between row and interrow were also analyzed for each system, although only for the samples from the upper layer, from field observations, and assuming that observed differences in the lower layer were minimal.

The right test for comparing measurements can present a problem, as a choice must be made between two families of tests, parametric and nonparametric. Whether or not the choice really matters depends on sample size. Large data sets present no problem. The central limit theorem ensures that parametric tests work well even if the population is non-Gaussian, and nonparametric tests are only slightly less powerful than parametric tests. Small samples present a dilemma. In a parametric test with data from non-Gaussian populations, the P-value may be inaccurate, but in a nonparametric test with data from a Gaussian population, the P-value tends to be too high. Although nonparametric tests lack statistical power with small samples, in view of this, they are safer.

For this work, we decided which type of statistical test to use on the basis of sample size. We considered a sample large if there were over 20 data in each group for comparison. Otherwise, nonparametric tests were used for small samples. For the comparison of two means, the usual (parametric) method is the t-test which can be employed either when variances within the two groups are the same (pooled t-test) or when they differ (Welch-Satterthwaite modification). An F-test is used to test whether the variances in two populations are equal. The counterpart nonparametric tests that compare two unpaired groups are the Wilcoxon rank sum test, or the equivalent Wilcoxon-Mann-Whitney test (WMW test) for location, and the Ansari-Badley test for dispersion. In this case, the empirical distribution functions and Kuiper statistic were also calculated to test whether the distributions of the response variables were the same across different groups (Montgomery and Runger, 2003).

Statistical analyzes compared the locations of two groups to determine whether one population was shifted with respect to another, using parametric or nonparametric tests according to the sample size, data distribution and dispersion. SAS/STAT software, which provides parametric and nonparametric tests, was used to perform these statistical analyzes (SAS Institute, 1992). The probability level of significance was set at 0.05.

Table 2. 2-D macroporosity per surface area (mm^2 mm^{-2}) and statistical differences between conventional and no-tillage treatments

Set of samples	Conventional tillage					No tillage					Statistical test and P-value				
	N	Mean	SD	Med	Range	N	Mean	SD	Med	Range	t	F	WMW	AB	K
Ploughed	31	0.363	0.208	0.296	0.793	35	0.264	0.153	0.240	0.663	0.031	0.087			
Upper layer	25	0.357	0.210	0.313	0.793	27	0.288	0.166	0.275	0.663	0.192	0.248			
Lower layer	6	0.387	0.219	0.284	0.505	8	0.184	0.047	0.185	0.117			0.013	0.250	0.146
UL row	13	0.455	0.205	0.469	0.716	14	0.283	0.169	0.270	0.523			0.038	0.775	0.454
UL interrow	12	0.251	0.162	0.229	0.570	13	0.294	0.170	0.302	0.663			0.503	0.873	0.987

N – sample size (number of polished sections), SD – standard deviation, Med – median, t – t-test, WMW – Wilcoxon-Mann-Whitney test, AB – Ansari-Badley test, K – Kuiper test, UL – upper layer of ploughed horizon.

RESULTS AND DISCUSSION

2-D macroporosity findings are shown in Table 2. Averages of different positions and depths ranged from 0.184 to 0.455 mm^2 mm^{-2}. This variable was affected by the tillage system, being significantly lower in NT than in CT in all positions except in the upper layer of the interrow.

Larger porosity in the CT ploughed horizon can be attributed to increased porosity in the row (37.8 %) and lower layer. In this case the mean porosity of CT doubles that of NT. Macroporosity in the upper layer of the interrow, however, is quite similar for both CT and NT.

Tillage (CT) induced a significant difference in the lateral distribution of macroporosity observed in the row and interrow (Table 3). In contrast, no differences were noticed between the depths. NT showed the opposite response. A nearly significant difference was observed between the upper and the lower layers, but there were clearly no differences between the row and interrow.

Following the criteria of Pagliai (1988) and Pagliai *et al.* (2003), macroporosity of polished sections was classified by compaction level. This criterion allows soil macroporosity to be classified in four categories, from compacted soil to extremely porous. The results of this classification are shown in Fig. 1. The most frequent category in NT is moderately compacted (48.5%), whereas for CT, it is extremely porous (41.9%). The frequency of the other two categories (compacted and porous) is quite similar for both tillage systems.

These results agree with those found by Hill *et al.* (1985), who attribute them to annual tillage mixing soil material (Kay and VandenBygaart, 2002).

Macroporosity in the tilled horizon of soil subjected to CT is significantly higher than in NT soil, which mainly contributes to increasing infiltration and water accumulation after extended rainfalls (Lipiec *et al.*, 2006). The importance of macroporosity has been discussed by several authors, especially in connection with the development of soil hydrological models for ponded infiltration into soil with

T a b l e 3. P-values for the inferential test comparing bulk density and porosity parameters in different positions for each tillage system

Tillage	Position	P- values 2-D macroporosity			P-values NMUA			P-values Bulk density		
		WMW	AB	K	WMW	AB	K	WMW	AB	K
Conventional tillage	Upper vs lower layer	0.715	0.846	0.749	0.826	0.056	0.263	<0.001	0.011	<0.001
	Interrow vs row	0.019	0.873	0.375	0.152	0.710	0.440	0.549	0.692	0.521
No tillage	Upper vs lower layer	0.074	0.092	0.016	0.055	0.589	0.473	<0.001	0.185	0.008
	Interrow vs row	0.793	0.999	0.806	0.933	0.363	0.806	0.243	0.999	0.417

NMUA: Number of macropores per unit area. Other explanations as on Table 2.

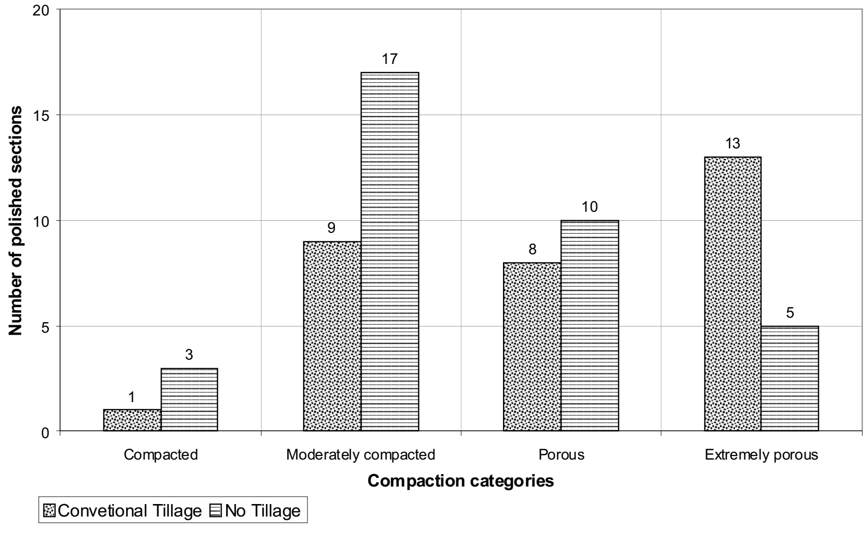

Fig. 1. Absolute frequency distribution of 2-D macroporosity in the polished slices measured. Samples were classified according to Pagliai *et al.* (2003).

preferential movement of water into macropores. According to Dohnal *et al.* (2009), the detailed knowledge of water flow through macropores is of major importance when predicting catchment rainfall-runoff responses. In fact, their water flow simulation, based on measured hydraulic characteristics without consideration of preferential flow effects, does not describe their infiltration experiment adequately. Lin *et al.* (1996) state that porosity of an equivalent diameter over 0.06 mm contributes up to 89% of the total vertical flow of water under these conditions if soil structure is stable enough. The main function of this pore size in the soil is to transmit water and distribute it within the profile (Greenland, 1977; Panini *et al.*, 1997).

In the Mediterranean region this type of porosity is of special interest in periods of intense rainfall (spring and autumn), as it contributes to soil water recharge and reduces surface runoff, as well as diffusion and renewal of the soil gas phase.

NMUA results are shown in Table 4. The CT and NT extremes (only ranges are shown in Table 4), are 1.16 and 0.25 and 0.88 and 0.17 macropores per mm^2, respectively. The highest CT mean (0.808) was found in the upper layer of the interrow. Differences were significant for the ploughed upper layer and upper layer interrow. No differences were observed between row or lower layers, but the level of significance depends on the statistical test applied. The NT lower layer had the lowest value recorded.

The highest NMUA was observed in the CT interrow upper layer and represents cumulative compaction (at the end of the agricultural cycle) by tillage operations, machinery traffic and meteorological conditions (dry-wet and freeze-thaw cycles). As shown in Table 3, there are no differences between the upper and lower layers for the two tillage systems.

Plotting 2-D macroporosity data vs. NMUA, CT and NT behaviour is observed to be different (Fig. 2). Conventional tillage shows a visible tendency to organize the samples in two regions according to their position in the soil:

- slices from the row upper layer have large 2-D macroporosity and a low number of macropores,
- slices from the interrow upper and lower layers are characterized by a large number of macropores but with smaller 2-D macroporosity. No differences are observed in NT slices, which show the most uniform pattern regardless of their position.

A higher NMUA suggests better distribution of the macropore space in the ploughed horizon, suggesting better conditions for air and water transmission within the horizon, although other parameters determine water infiltration or transmission of water (like continuity of pores, their anisotropy and orientation). In spite of that, and under the xeric climate conditions in the area, it also suggests better aeration of the ploughed horizon and, consequently, increased water loss in the upper layer. These results agree with those found by Josa and Hereter (2005), where NT water content in the near-surface soil was higher in late winter.

The mean macropore area (MPA) was calculated, and the CT/NT ratios were compared (Table 5). With NT, the MPA was very similar in all positions and ranged from 0.375 to 0.528 mm^2, whereas with CT the range was wider, from 0.637 to 0.808 mm^2 (Table 4). On comparing the MPA ratio in CT and NT samples (Table 5), ploughed samples and upper layer samples both have a ratio very close to 1, that is, the two tillage systems have a very similar MPA (1:1.04), and the same may be said of the upper layer as a whole.

However, the two different positions in the upper layer show opposite behaviour. The ratio in the row was 1:0.74 (approximately 35% higher in CT than in NT), whereas in the interrow, the ratio was the reverse (1:1.82), and this mean was approximately 82% higher for NT. This result, to be consistent with those in the previous section, indicates that NT produces generally smaller 2D-macroporosity than CT, or CT produces larger macropores than NT, because it is important to note that this variable does not provide absolute macroporosity values. These results can also be explained by the plots in Fig. 2. The two approaches are consistent and coherent. Then the macropore area in the NT interrow (less affected by tillage operations) is larger than with CT. It could also indicate an increase of faunal activity in this position (upper NT layer).

Table 4. Number of macropores per unit area (NMUA) and statistical differences between conventional and no tillage treatments in ploughed horizon

Set of samples	Conventional tillage					No tillage					Statistical test and P-value				
	N	Mean	SD	Med	Range	N	Mean	SD	Med	Range	t	F	WMW	AB	K
Ploughed	31	0.708	0.271	0.628	0.904	35	0.493	0.176	0.501	0.773	<0.001	0.020			
Upper layer	25	0.719	0.294	0.628	0.904	27	0.528	0.159	0.506	0.649	0.007	0.003			
Lower layer	6	0.664	0.150	0.633	0.353	8	0.375	0.119	0.369	0.470			0.029	0.899	0.714
UL row	13	0.637	0.294	0.568	0.900	14	0.535	0.183	0.484	0.642			0.616	0.924	0.979
UL interrow	12	0.808	0.279	0.842	0.880	13	0.520	0.136	0.555	0.442			0.011	0.104	0.187

Explanations as in Table 2.

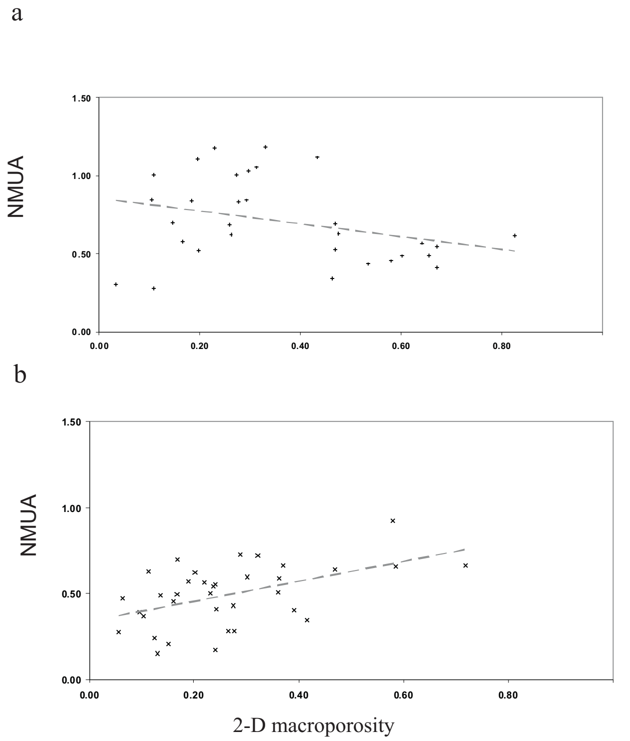

Fig. 2. Scatter plots of the number of macropores per total surface area analyzed (NMUA) vs. 2D-macroporosity (mm^2 macropores mm^{-2} surface area analyzed) for: a – conventional tillage, b – no tillage systems.

Table 5. Mean macropore area ratio

Set of samples	Mean macropore area CT/CT : NT/CT
Ploughed horizon	1: 1.04
Upper layer of ploughed horizon	1:1.10
Upper layer of row	1:0.74
Upper layer of interrow	1:1.82
Lower layer of ploughed horizon	1:0.84

The means were 1.383 and 1.532 Mg m^{-3} for CT and NT, respectively, and the absolute extremes were 1.132 and 1.714 Mg m^{-3} for CT, and 1.219 and 1.816 Mg m^{-3} for NT (total porosity range from 32 to 57%). In all positions and groups of samples, the NT values were higher than their CT counterparts (Table 6). Significant differences were observed in tillage systems and upper layers. The lower bulk density found for CT compared to NT was significant (pooled t-test).

When the nonparametric tests were used, because there were few data, significance was higher in the row and interrow positions (WMW).

The same was true for the upper layer and the interrow with the nonparametric test (WMW). Similar differences between CT and NT have been reported by several authors in connection with the cultivation of maize during the growing season (Katsvairo *et al.*, 2002), soybean (Timlin *et al.*, 2001) and other cereals (Cassel *et al.*, 1995; Hill, 1990). Some of these effects are considered to be transitory in view of the instability of the aggregates and larger pores which collapse from rain and machinery traffic (Hammel, 1998).

This lower bulk density with CT can be attributed to soil behaviour in the upper and lower layers of the interrow. The upper interrow layer behaved differently depending on the tillage system. The bulk density of the interrow position was significantly higher in NT than in CT (Table 6). The disturbance caused by seed drill coulters during drilling was sufficient to attenuate or eliminate this difference within row (growing positions of plants). This effect disappeared when compared independently to the row and interrow positions in each treatment (Table 3).

Similar results were found by Vervoort *et al.* (2001) who report irregular response of soil properties affecting infiltration, runoff, erosion and solute movement between the compacted wheel track and plant growing positions.

With both systems, significant differences were observed between the upper and the lower layer (Table 3). Both systems favour stratification in the top centimetres of the soil. The upper layer was significantly more porous than the lower layer, in which no significant differences were

Table 6. Soil bulk densities (Mg m^{-3}) and statistical differences between conventional and no-tillage treatments

Set of samples	Conventional tillage					No tillage					Statistical test and P-value				
	N	Mean	SD	Med	Range	N	Mean	SD	Med	Range	t	F	WMW	AB	K
Ploughed	31	1.38	0.19	1.36	0.582	35	1.53	0.16	1.54	0.597	<0.001	0.395			
Upper L	25	1.29	0.12	1.25	0.432	27	1.45	0.12	1.46	0.457	<0.001	0.939			
Lower L	6	1.63	0.06	1.64	0.156	8	1.67	0.12	1.69	0.375			0.330	0.063	0.221
Row	13	1.28	0.13	1.23	0.411	14	1.4	0.12	1.37	0.105			0.077	0.434	0.567
Interrow	12	1.32	0.13	1.32	0.419	13	1.46	0.11	1.5	0.321			0.019	0.941	0.339

Explanations as in Table 2.

observed between the two systems (Table 6). The reduction in porosity was more noticeable with CT (reduction of 25% over the upper layer) than with NT (18% reduction).

Horn (2004) reports a significantly lower bulk density in tilled horizons than in horizons under conservation systems or annual chisel ploughing. These differences are maintained up to a depth of 60 cm. Similar results were found by Wiermann *et al*. (2000) in silty soils. In their case, the increase in bulk density started at a depth of 10 cm, whereas in our case it started at approximately 5 to 7 cm, depending on the tillage system.

As undisturbed samples were collected after harvesting, when the soil had been exposed to several intense wetting-drying cycles, these results must be considered as a cumulative effect of tillage. In spite of this, water stress from topsoil, which is typical in this region, recurs annually in most drylands across the Mediterranean region.

CONCLUSIONS

1. Significant differences in the pore system were observed in the ploughed horizon after continuous application (over seven cycles) of two tillage systems in a legume-cereal rotation under dryland farming conditions in NE Spain.

2. Direct drilling with residue removal affects bulk density, macroporosity and mean macropore area in the top 10 cm of the soil. The upper layer has higher total porosity than the layer underneath, with both conventional tillage (CT) and no tillage (NT), though porosity is lower with no tillage (NT) than conventional tillage (CT), and consequently, physical conditions are less favourable (lower 2-D macroporosity, smaller mean macropore area (MPA) and higher bulk density).

3. Lack of tillage and limited residue incorporation are likely to be the main causes of larger 2-D porosity in the row than in the interrow.

4. Higher number of macropores per unit area (NMUA) observed with conventional tillage (CT) suggests better aeration of the ploughed horizon and, consequently, more favourable evaporation conditions in the ploughed horizon with this tillage system. Continual simultaneous application of no-tillage and residue removal may have caused a decrease in the number of macropores per unit area (NMUA) in the ploughed horizon, even though stubble was left in place.

5. As conditions favourable to soil erosion can occur even though stubble is present on the soil surface, it is suggested that detailed studies relating no tillage (NT) to residue removal, crop production and soil erosion over long periods in Mediterranean areas be carried out in order to better understand the effects of this tillage system.

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