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Effect of various cultivation methods on the structure and hydraulic properties of a soil in a semi-arid climate

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Abstract

In the absence of irrigation, the cultivation of cereals in semi-arid zones provides a poor yield. To study the consequences of fallow tillage on the soil structure and hydraulic properties, we conducted an experiment from 1991/1992 to 1997/1998 using various techniques (chisel or disc plough, early or late tillage) on a calcisol of the high plateaus of eastern Algeria. In the middle of the tilled horizon (between 8 and 25 cm depth), we measured the near-saturated hydraulic conductivity at four soil water tensions (or potentials) using multidisc infiltrometers, and quantified the morphology of the macropore space using image analysis. Results indicated that tillage increased soil conductivity mainly at low water potential (0.06 and 0.3 kPa). This increase was more significant with the chisel (1.84×10^{-5} m s^{-1} at 0.06 kPa) than with the disc plough (1.25×10^{-5} m s^{-1}), but was attenuated during the crop cycle. Significant differences appeared between tillage treatments for surface macroporosity (5.1% for chisel, 1.1% for disc), pore-space morphology (thin cracks separating compact aggregates under disc, loose fine soil assemblage separating smaller aggregates under chisel) and porosity distribution pattern (equivalent diameter of the macropores varied from 1 mm under disc to more than 2–3 mm under chisel). Analyses of porosity distributions indicate a possible relationship between the structure of the surface horizon and soil hydraulic properties. Durum wheat grain yield varied from 1.08 to 2.85 t ha^{-1} during the 7-year trial. Grain yield under shallow tillage was significantly higher than under disc plough treatment during wet years. Tillage-date varied across seasons and early tillage effect was more apparent when the fallow season was less rainy.

Keywords: Semi-arid; Tillage; Hydraulic conductivity; Water potential; Image analysis; Pore morphology; Durum wheat yield

1. Introduction

The Algerian high plateaus are characterised by a semi-arid climate with a pattern of scarce and variable rainfall. The farming system widely used here is based on cereal/sheep production in a fallow/cereal rotation. This cultivation system degrades the soil structure of the tilled horizon and reduces its organic matter content (Batouche and Labiode, 1990; Kribaa, 1992). These conditions make it difficult to improve soil water use and thereby boost crop grain yield levels that are among the lowest in the region. In a comparative study, Belaid and Moussaoui (2000) reported that durum grain yield of the North African region varied from 0.6 t ha^{-1} in Algeria to 1.2 t ha^{-1} in Tunisia and

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1.4 t ha^{-1} in Morocco. Cannolly (1998) reported that soil structure degradation was a major constraint on water infiltration, redistribution and storage in the profile. Structural degradation is the result of the interaction of tillage-tool effects on soil disturbance, soil biological activity and variability of climatic factors (Pagliai et al., 1983; Guerif, 1987).

Fallow management aims to bury cereal residues, to control weeds, to improve soil porosity and hydraulic conductivity, to increase soil water storage for the succeeding crop and to reduce soil erosion (Lyon et al., 1998). Several investigations have been conducted to study the effect of fallow tillage on soil physical properties, particularly on infiltration. However, the results are controversial when compared with untilled conditions (Heard et al., 1988; Arshad et al., 1999; McGarry et al., 2000).

Most agronomic studies carried out so far in Algeria have been restricted to understand crop behaviour under the harsh conditions of the semi-arid region of the high plateaus. Few studies have investigated soil structural evolution using different tillage implements in a fallow–wheat system. The aim of the present trial is to evaluate the effect of different fallow–tillage practices on soil hydraulic conductivity, soil macropore space and the grain yield of a winter-sown durum wheat crop (*Triticum durum* Desf. cultivar Mohammed Ben Bachir).

2. Materials and methods

2.1. Site description and experimental design

The experiment was carried out at the Agricultural Experimental Station of the Institut Technique des Grandes Cultures (ITGC) during the period from 1991/1992 to 1997/1998. The experimental site is located in the eastern part of the Algerian high plateaus (latitude 36°9′N, longitude 5°21′E). The soil is a calcisol (WRB), of fine-grained texture (38.4% clay, 42.7% silt, 18.7% sand) and carbonate-bearing (26.6% $CaCO_3$). The soil profile often contains a thin calcareous crust that limits deep-rooting growth (Lahmar et al., 1993).

The climate is of a semi-arid type, with long-term average annual precipitation of 380 mm. Average precipitation during the 7 years of the experiment (1991/1992–1997/1998) was 397 mm (Table 1). Most of the precipitation occurred during the winter months. Wheat seasonal precipitation (November–June) varied from a minimum of 163 mm for the 1996/1997 cropping season to a maximum of 395 mm for the 1995/1996 growing season. Monthly mean temperatures ranged from a high of 35.8°C observed in August 1994 to a low of 0.4°C noted in January.

The trial was made up of five unreplicated strips, each 6 m wide and 60 m long, that were managed as follows: chisel-tilled fallow, 8 months before sowing (C1) and just before sowing in November (C2), disc-ploughed fallow at the same periods (D1), (D2), and an untilled fallow (Z). Treatments C1, C2, D1 and D2 were sown in November of the following year with a treated seed of the local durum wheat variety Mohammed Ben Bachir at a rate of 250 seeds m^{-2}. Growing wheat received 100 kg ha^{-1} of superphosphate 46% just before sowing, and 100 kg ha^{-1} of ammonium nitrate 33.5% at the tillering stage. Weeds were controlled by application of 2,4-dichlorophenoxy acetic acid (2,4-D) at a level of 1 l ha^{-1} mixed with 250 l of water. Treatment Z was continuously fallowed and kept uncropped. Four stations of

Table 1
Monthly precipitations and temperatures

	S	O	N	D	J	F	M	A	M	J	J	A	Total
Precipitation (mm)													
Mean	49.9	36.4	32.4	37.0	40.6	39.1	29.9	40.9	47.5	20.8	9.8	11.9	397.0
Dry year	18.8	9.2	10.7	29.7	32.4	7.7	4.5	37.3	20.3	20.8	10.5	16.2	228.1
Wet year	44.5	37.1	22.3	25.4	62.0	92.4	47.9	52.9	69.2	22.9	9.1	18.1	503.8
Temperature (°C)													
Mean	20.0	14.9	10.1	6.5	5.7	8.8	9.1	11.0	19.1	22.2	25.1	25.0	
Hot year	26.3	22.1	13.5	11.2	9.6	12.2	16.9	15.2	27.8	29.9	34.6	35.8	
Cold year	15.8	10.3	4.6	1.0	0.4	1.4	3.4	5.2	9.7	12.0	16.3	19.0	

3 m × 3 m were taken as replications for each strip and served for notations and data collection. Randomized complete block analysis of variance was performed with the STAT-ITCF software. Main effects were tested using the contrast method (Steel and Torrie, 1982). Soil data were collected during the wheat cropping season at the tillering (January) and heading stages (April). Crop measurements were carried out at maturity.

2.2. Near-saturated hydraulic conductivity measurements

Near-saturated hydraulic conductivity $K(h)$ was measured in situ, at between 8 and 25 cm soil depth, using a triple-ring infiltrometer with multiple suctions (Ankeny et al., 1990; Vauclin and Chopart, 1992). Four water potentials were applied (0.06, 0.3, 0.6 and 1.5 kPa) during each sampling run, from the highest down to the lowest value. An 80 mm-diameter disc with a thin sand layer was used to create a uniform surface and to improve soil contact. $K(h)$ was estimated during the steady state according to the method reported by Ankeny et al. (1991).

2.3. Pore space description

Pore space description was carried out on an undisturbed soil sample taken from the 8–25 cm ploughed layer in each treatment, in January and April. Soil samples were taken from the most representative zone, determined by mapping the given ploughed soil layer (Manichon and Roger-Estrade, 1990; Curmi et al., 1996). Soil samples were dried and impregnated with a polyester resin containing fluorescent dye (Murphy et al., 1977). Each soil block was cut vertically allowing observations and image analysis to be performed on five polished sections. Image analysis was carried out on a SUN Sparc IPC workstation with Visilog software. Images were captured under reflected ultraviolet light on each section with a CCD camera. Each individual image (77 mm × 58 mm) was digitized in a rectangular grid of 768 × 576 pixels with a spectral resolution of 256 grey levels and a spatial resolution of 100 μm per pixel, so that only macropores were analysed. Grey level images were then thresholded according to the method described by Hallaire (1994).

We quantified macroporosity on the binary images using

- The *specific surface porosity*: expressing the proportion of pixels belonging to the macropore space.
- The *pore typology*: classifying the macropores after they are grouped into 'poroids' (Moran et al., 1988). The typology was determined according to pore size and shape. Pore size was measured by its area a on the binary image, and pore shape by the elongation index e with $e = (\text{perimeter})^2/4\pi a$ (Coster and Chermant, 1989). Three size classes ((1) $a < 0.5 \times 10^6\ \mu\text{m}^2$; (2) $a = 0.5–5 \times 10^6\ \mu\text{m}^2$; (3) $a > 5 \times 10^6\ \mu\text{m}^2$) and three shape classes (T: tubules, $e < 5$; C: cracks, $e = 5–20$; P: packing voids, $e > 20$) were defined, allowing classification of macropores into nine morphological types (Hallaire and Cointepas, 1993).
- The *porosity distribution*: which gives the proportion of porosity in terms of pore equivalent diameter (Hallaire et al., 1998). It was obtained by filling the macropore binary image with hexagonal structural elements, using the 'opening' morphology mathematical operation (Serra, 1982).

2.4. Crop measurements

Crop measurements concerned the determination of number of heads per square meter, the biomass above ground, grain yield and number of kernels per unit area. The area harvested was 3 m × 3 m per replicate. In the present report, only grain yield and number of heads produced per unit area were analysed.

3. Results and discussion

3.1. Hydraulic conductivity changes

At a water potential of 1.5 kPa, hydraulic conductivity shows significant differences between tillage treatments and between sampling dates. $K(h)$ values range from 1 to $2 \times 10^{-6}\ \text{m s}^{-1}$ (Fig. 1). At other water potentials, $K(h)$ values are significantly different between treatments. Fallow tilled with the chisel shows higher $K(h)$ values than disc-ploughed fallow, and both treatments yield higher values than untilled fallow. Within each cultivation method, early tillage

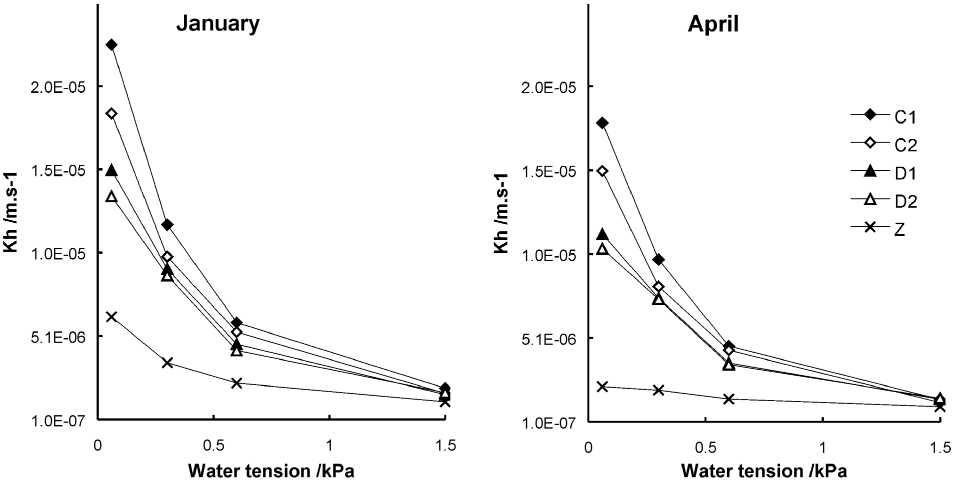

Fig. 1. Hydraulic conductivity *K*(*h*) of the 8–25 cm layer in one of the five treatments in January and April as a function of the water potential (mean values).

shows higher hydraulic conductivity than late tillage. The main tool effect is larger than the main tillage-date effect (Table 2). Tillage treatment differences become larger as conditions approach saturation. These results are in agreement with those reported by Miller et al. (1998).

On the first two axes of the principal components analysis carried out on the *K*(*h*) values of the second sampling date, three groups appear that clearly represent chisel, disc and untilled-fallow treatments (Fig. 2). Hydraulic conductivity showed a temporal evolution from early to late sampling date. *K*(*h*) took significantly lower values by the end of this period, loosing 20% of their initial values, averaged over the three water potentials (0.06, 0.3 and 0.6 kPa). These results are in agreement with the observations made by Cassel and Nelson (1985), who found large variations in conductivity at three sampling depths and dates. They are also compatible with the results of Starr (1990), who reported a significant decrease in *K*(*h*) with time under ploughed and no change under untilled conditions. The results of the present study disagree,

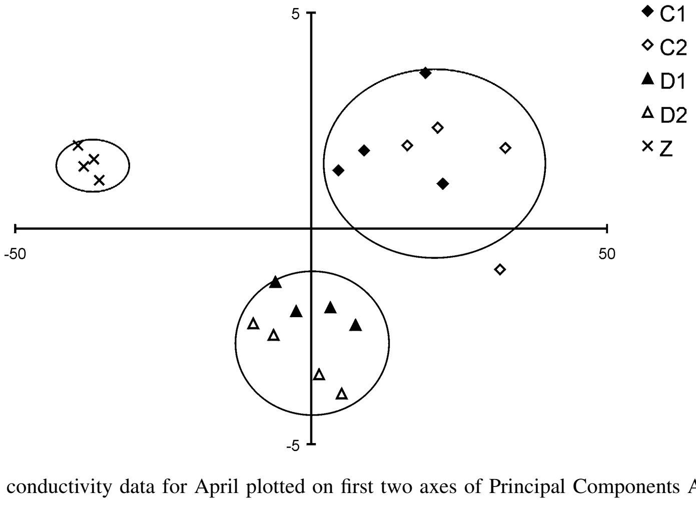

Fig. 2. Hydraulic conductivity data for April plotted on first two axes of Principal Components Analysis diagram.

Table 2

Summary statistics of hydraulic conductivity, porosity, pore space morphology and porosity spectra[a]

Treatment	Hydraulic conductivity				Porosity	Pore morphology classes						Porosity spectra classes								
	$K(0.06)$	$K(0.3)$	$K(0.6)$	$K(1.5)$	P	T1	T2	T3	C2	C3	P3	G1	G2	G3	G4	G5	G6	G7	G8	G9
Tillage	3738.2*	936.8*	178.7*	6.00*	42.09*	0.53*	1.94*	0.13*	0.57*	4.24*	3.19	0.86*	1.25*	1.06*	0.59*	0.21*	0.12*	0.07*	0.05	0.03*
Tilled vs fallow	10595*	3269*	595.4*	20.31*	11.22	0.26*	0.94*	0.00	0.12	0.53	1.39	0.10*	0.49*	0.31*	0.12*	0.06	0.04	0.03	0.02	0.01
Chisel vs disc	3648.3*	313.2*	118.1*	0.03	128.36*	1.26*	4.62*	0.38*	2.16*	16.06*	3.82	2.80*	3.63*	3.27*	2.04*	0.66*	0.38*	0.28*	0.19*	0.08*
Date	1860.0*	355.2*	120.7*	11.11*	1.63	0.77*	0.72*	0.23*	0.17*	0.22	3.52	0.23*	0.69*	0.50*	0.08	0.00	0.00	0.00	0.02	0.00
Tillage vs date	9.53	1.14	1.19	0.79*	19.67*	0.09	0.19	0.18*	0.46*	3.06*	2.58*	0.28*	0.38*	0.32*	0.19*	0.07	0.06*	0.06*	0.03	0.03*
Early vs late	576.0*	109.1*	10.63*	0.76*	25.19*	0.58*	2.16*	0.04	0.02	0.27	5.10	0.49*	0.83*	0.62*	0.19*	0.13	0.06	0.06	0	0.02
Error	16.3	4.06	0.95	0.11	3.43	0.04	0.07	0.03	0.04	0.84	1.41	0.02	0.04	0.04	0.03	0.04	0.02	0.02	0.02	0.01

[a] $K(0.06)$, $K(0.3)$, $K(0.6)$, $K(1.5)$: hydraulic conductivity at soil water tensions of 0.06, 0.3, 0.6 and 1.5 kPa; P: surface macroporosity; T1, T2, T3: small, medium and large tubules; C2, C3: medium and large cracks; P3: large packing voids; G1 to G9: porosity spectra classes.

[*] Significant at $P = 0.05$.

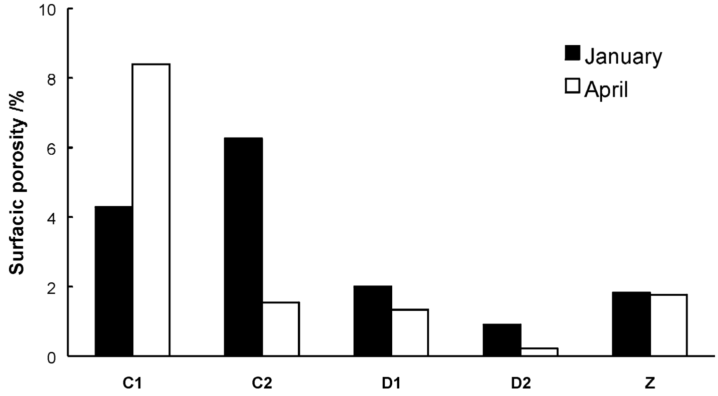

Fig. 3. Specific surface macroporosity of the five treatments in January and April (mean values).

however, with those reported by Prieksat et al. (1994) who observed an increase in the hydraulic conductivity with time under chiselled plots.

3.2. Macroporosity changes

Macroporosity measured under untilled uncropped fallow plots shows slightly scattered values around 2%, changing little from January to April (Fig. 3). Among the tillage treatments, D1 displayed similar behaviour as untilled fallow. Macroporosity under early shallow tillage (chisel) was more persistent over time, allowing earthworm activity as indicated by the increased biopore number. It reaches a value more than twice that measured under late chiselling. Aura (1999) found that shallow tillage leads to increased number of biopores with equivalent diameters of 0.2–1 and >1 mm at 20 cm soil depth.

Porosity under late tillage is equivalent to that measured under untilled fallow. By April, only the C1 treatment led to an increased porosity (of more than 8%), while the porosity of C2 remained unchanged. Macroporosity under late-discing treatment decreased from January onward and fell to almost zero by the April sampling. Mata et al. (1998) found that conventional tillage reduced macroporosity and shallow tillage improved soil hydraulic properties and root growth. Mielke and Wilhelm (1998) have also reported differences in macroporosity between conventional tillage and sub-tillage.

Macropore morphology provides information on the pore classes affected by these changes (Fig. 4). The different pore classes are illustrated in Fig. 5, which presents an example of each treatment. Compared with untilled fallow, disc treatments produced a closing up of the inter-aggregate pores (cracks and packing voids in small quantity) in January, intra-aggregate pores underwent a significant increase in D1 treatment only. Chisel treatments showed an increase in macroporosity for the whole range of morphological pore types, including pores external to the aggregates, whatever their size. From January to April, we observed a closing up of cracks and an overall reduction in packing voids in treatments C2, D1 and D2. Meanwhile, C1 treatment showed a significant increase in macropores including the largest (Table 2).

As far as soil structural modifications are concerned, the present study indicates that untilled fallow has a compact structure, without any well-defined structural elements. Shallow tillage (chisel) results in soil aggregates separated by cracks. This type of structure is more apparent with early than with late tillage. Late-chisel fallow, like untilled fallow, leads to a closing up of inter-aggregate spaces, resulting in a compact structure. Disc-ploughed treatment results in the formation of tightly spaced clods that are compact under late tillage and porous under early tillage. However, under this treatment, the soil structure returned to a compact state by the April sampling date, because of alternating periods of desiccation–dampening.

3.3. Conductivity–structure relationships

Infiltrometers with controlled suction made it possible to separate water flow in inter-aggregates and

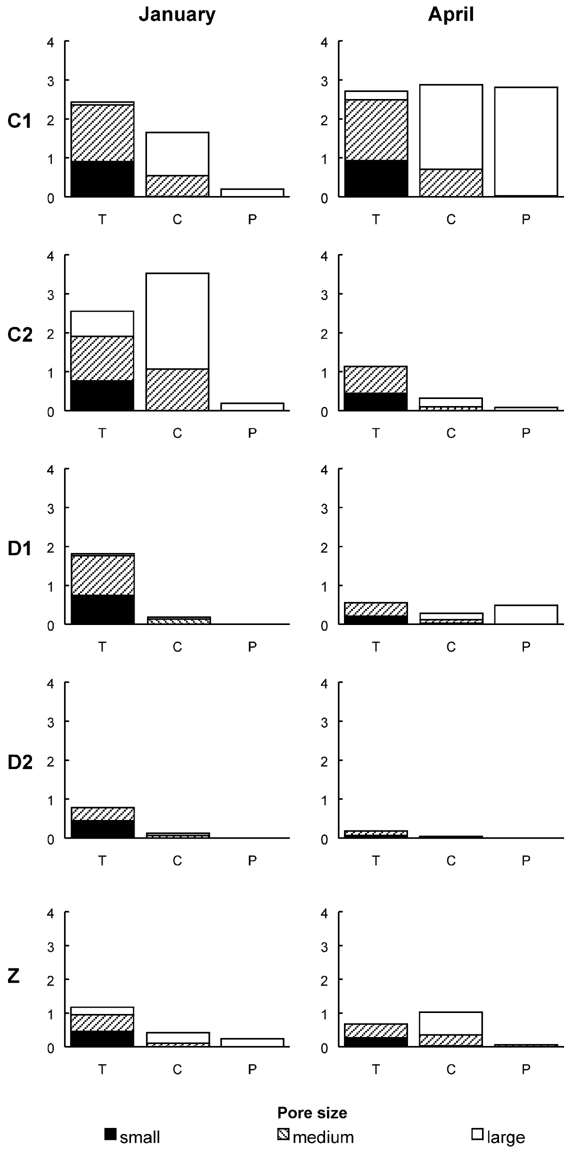

Fig. 4. Macropore typology according to shape (T: tubules; C: cracks; P: packing voids) and size, on the five treatments in January and April (mean values).

biological pores from water flow in soil matrix pores (Ankeny et al., 1988). It also enables us to quantify the contribution of the various pore-space compartments to water infiltration (Lin et al., 1997). Suction values of 0.06, 0.3, 0.6 and 1.5 kPa correspond to the participation of pores having equivalent diameters smaller than 5, 1, 0.5 and 0.2 mm, respectively. Macropore equivalent diameters can be measured by image analysis. The method used here for determining the porosity distribution proved to be crucial in establishing the relationships between soil porosity and conductivity, $K(h)$, since pore typology alone could not achieve this objective (Beaudet-Vidal et al., 1998).

The selected observation scale allowed us to describe a full range of equivalent diameters, from 0.3 to 7.5 mm. The porosity distributions show significant differences between tillage methods over all the investigated range of pore sizes (Table 2). The differences in macroporosity could thus explain differences in water conductivity potentials closest to saturation state. Apart from treatment C1, whose spectrum increased between January and April (Fig. 6), the other treatments produced a reduction in the porosity spectrum and in $K(h)$. These results are corroborated Azevedo et al. (1998), who noted a reduction in infiltration via macroporosity during the crop cycle. The data of the present study indicate that chisel tillage yielded the most favourable soil structure and conductivity conditions, in particular at water potentials of 0.06 and 0.3 kPa. This was due to the presence of numerous pores with an equivalent diameter larger than 1 mm, which were recorded in the April sampling.

Disc plough resulted in an intermediate condition between chisel and untilled fallow treatments, as measured in January. However, parameters measured on disc plough do not differ from those of untilled fallow in the April sampling. Selvaraju and Ramaswami (1997) noted that fallow tillage improved soil porosity and hydraulic conductivity as compared to untilled fallow. Results from this study demonstrated that this effect was primarily due to the porosity between soil aggregates, consisting of strongly inter-connected packing voids with large equivalent diameters. These favourable soil structural conditions were more developed under chiselling than under discing.

3.4. Crop yield

Durum wheat grain yield varied from 1.081 to 2.850 t ha^{-1} during the 7-year trial. Wheat grain yield under shallow tillage was significantly higher ($P = 0.05$) than grain yield under disc plough treatment during wet years (Table 3). Grain yield differ-

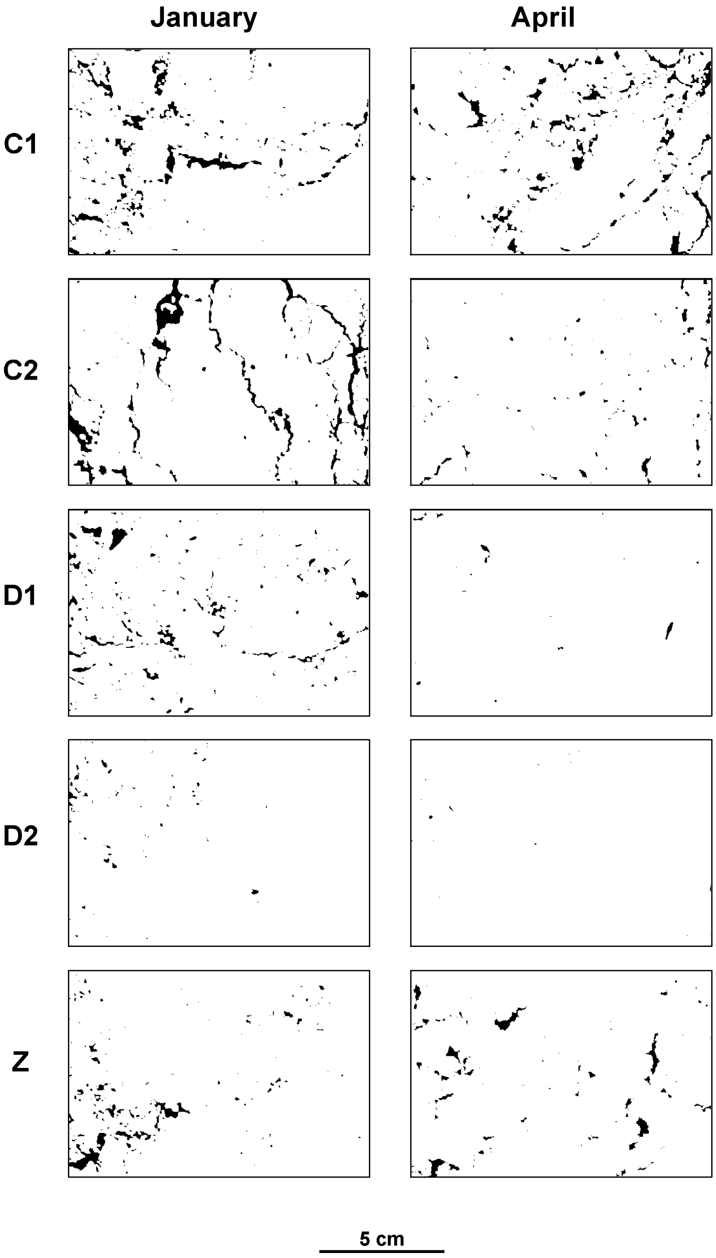

Fig. 5. Binary images illustrating the soil structures of the five treatments in January and April (macropores in black).

ences varied from 0.2 to 0.6 t ha^{-1}. Differences in grain yield due to the effect of tillage-date are statistically significant only during the 1993/1994, 1994/1995, and 1997/1998 cropping seasons. The effect of early tillage is more apparent when the fallowing season is less rainy, and it outperforms late tillage treatment by 0.3–0.75 t ha^{-1}. These data seem to indicate that the effects of tillage and tillage-date are conditioned by the amount of rainfall and are less evident during drought years such as the 1996/1997

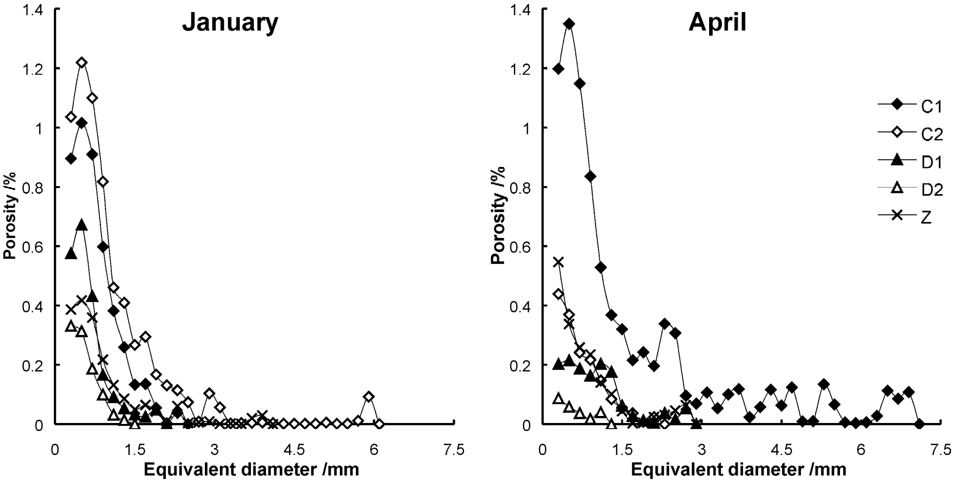

Fig. 6. Porosity distribution pattern according to equivalent diameter of pores (mean values) in the five treatments in January and April.

Table 3
Summary statistics of grain yield

Treatment	1991/1992	1992/1993	1993/1994	1994/1995	1995/1996	1996/1997	1997/1998
Tillage	54.18*	5.25	87.71*	69.04*	44.35	0.33	44.30*
Chisel vs disc	150.18*	14.82*	34.63*	8.81	96.04*	0.02	93.12*
Early vs late	11.94	0.72	221.86*	198.04*	36.00	0.44	39.06*
Error	2.82	2.81	2.14	2.28	15.60	1.09	3.07

[*] Significant at $P = 0.05$.

cropping season. These results do not corroborate those reported by Aura (1999) and Arshad et al. (1999), who found that wheat grain yield was improved under shallow compared to conventional tillage, especially during hot and dry years.

Crop grain yield depends partially on soil physical properties created by tillage. Structure and soil hydraulic properties such as those characterizing the 1997/1998 cropping season show significant differences between tillage treatments (Table 2). The differences were more marked in January, during wheat ear initiation. A regression analysis of durum wheat grain yield and number of heads per unit area gives the following relationships which indicates that grain yield is strongly determined by the number of ears produced per unit area

$$\text{Yield} = 0.1208\,\text{heads m}^{-2} - 3.43$$
$$(R^2 = 0.96^*, \text{significant at } P = 0.05)$$

The number of heads appears as the main yield component which needs to be well established under semi-arid environments (Kribaa, 1992).

4. Conclusion

The results of this study indicate that tillage increases soil conductivity, especially at water potentials close to saturation. This increase is more significant under shallow (chisel) compared to disc-plough treatments. We find significant quantitative and qualitative differences in macroporosity between treatments. Disking creates coarse and compact aggregates, while chiselling causes crumbling of aggregates, leaving a loose fine soil assemblage with pores having an equivalent diameter larger than 1 mm. Soil structure created under early chisel treatment is more lasting. A close relationship exists between soil structure created by the various tillage operations and soil water conductivity. Durum wheat grain yield varied from 1.081 to 2.850 t ha^{-1} and was significantly higher under shallow tillage than under disc plough treatment, but only during wet years. The effect of tillage-date varies across cropping seasons, and the effect of early tillage is more apparent when the fallowing season is less rainy. We conclude that early shallow tillage is the best-suited cultivation method for establishing and maintaining a favourable soil structure state under cereal–fallow rotation.

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