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Effect of tillage and water pressure head on the hydraulic properties of a loamy soil surface

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Abstract

The effect of different tillage practices on soil hydraulic properties was studied in a mature, drip irrigated apricot orchard with a 7% slope, in Murcia (SE Spain). The soil had a loamy texture. Three soil tillage treatments were applied between the rows of trees: 1) control treatment (non-tilled, although weeds were cut to ground level using a blade attached to a tractor following the common practice of the area), 2) perforation treatment, in which soil surface was mechanically perforated with an adapted plough, and 3) mini-catchment treatment, in which small banks were manually raised perpendicular to the line of emitters. The perforation and mini-catchment treatments increased the infiltration of water into the soil surface: the hydraulic conductivity and sorptivity values were higher than those of the control treatment. Both tillage treatments were designed to prevent runoff and both increased rainwater penetration of the soil. They may therefore be useful as part of water management strategies in semiarid areas with scarce water resources, such as Mediterranean countries. The process of infiltration appears to be controlled more by gravity than by capillary forces since the values for time related to gravity were small.

Additional key words: disk infiltrometers, hydraulic conductivity, infiltration, pore size, sorptivity, time related to gravity.

Resumen

Efecto del laboreo y la carga hidráulica sobre las propiedades hidráulicas de la superficie de un suelo franco

Se estudió la variación de las propiedades hidráulicas del suelo en una parcela situada en Murcia (SE de España), con un suelo franco y una pendiente del 7%, que soporta un cultivo adulto de albaricoque en riego por goteo, en función de diferentes labores practicadas en el mismo. Se realizaron tres tratamientos de suelo entre filas de árboles: tratamiento control (sin labor), siguiendo la práctica normal de la zona, eliminando la flora arvense mediante el paso de cuchillas arrastradas por un tractor; tratamiento ahoyado, por el cual se perforó el suelo mediante un apero diseñado a tal efecto; y tratamiento minicuencas, que consiste en levantar caballones perpendicularmente a las líneas de goteros. Los tratamientos minicuencas y ahoyado fueron realizados con el fin de mejorar las condiciones de infiltración del agua en los momentos en que se produjeran eventos de lluvia. Ambos tratamientos incrementaron la infiltración del suelo, tal y como indican los mayores valores de conductividad hidráulica y sorptividad con respecto al tratamiento control. Por otro lado, el proceso de infiltración está controlado en mayor medida por la fuerza de gravedad que por las fuerzas capilares, dado que los tiempos gravimétricos hallados son pequeños.

Palabras clave adicionales: conductividad hidráulica, infiltración, infiltrómetros de disco, sorptividad, tamaño de poro, tiempo gravimétrico.

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Introduction

The widespread use of tractors and agricultural machinery in intensive agriculture causes soil compaction, one of the leading causes of soil degradation threatening future productivity (Yavuzcan, 2000). A major effect of soil compaction on irrigated soils is a reduction in the infiltration rate (Goldhamer and Peterson, 1984). Under given climatic conditions and soil-plant systems, tillage and irrigation can, however, alter the soil structure (Messing and Jarvis, 1993; Somaratne and Smetem, 1993), improving this problem. Although several soil management strategies are available, currently the most widely used is mechanical tillage. Recent findings suggest, however, that interest in mechanical tillage is warranted only because of the enhanced water infiltration rate it helps achieve (Hernández *et al.,* 2005). When a soil is tilled, the infiltration rate can be increased because of a reduction in the bulk density of the soil, but it can also be decreased if large-pore continuity is disrupted. The relative importance of these two factors depends on the degree of soil compaction (Kooistra *et al.,* 1984). The proper use of tillage should, however, allow growers to maintain adequate infiltration rates and thus allow appropriate amounts of irrigation water to be used (Meek *et al.,* 1992).

One of the biggest problems in determining the hydraulic conductivity of cultivated soils is its sensitivity to changes in soil structure; great care must be taken to minimise alterations in soil structure when taking measurements (Vieira *et al.,* 1981; Wilson and Luxmoore, 1988; Reynolds and Zebchuk, 1996; Bosch and West, 1998; Zavattaro *et al.,* 1999). Further, in modelling water transport through unsaturated soils, it is assumed that the characteristics of the soil remain temporally invariant, which can lead to discrepancies between expected and observed results.

The tension disk infiltrometer is a simple device which is widely used to determine *in situ* hydraulic conductivity and the sorptivity of undisturbed soil in circular source infiltration experiments (Perroux and White, 1988; Smettem and Clothier, 1989; Thony *et al.,* 1991; Vauclin and Chopart, 1992). The size range of the pores and cracks participating in the flow of water is determined by the tension on the infiltrometer disk membrane. Tension infiltrometers are useful for characterizing differences in soil structure resulting from tillage operations (Sauer *et al.,* 1990; Ankeny *et al.,* 1991), root growth (Sully and White, 1987), sediment erosion/deposition, and soil shrink-swell (White *et al.,* 1992). Tension infiltrometers are also potentially useful for revealing the saturated and near-saturated hydraulic properties of soils required as inputs in water and solute transport models.

The accuracy of *in situ* tension infiltrometer measurements is affected primarily by soil heterogeneity and macrostructure collapse under the infiltrometer during infiltration. Although all measuring procedures are affected by soil heterogeneity to varying extents, those that employ multiple infiltrometers of different radius (Smettem and Clothier, 1989) and those requiring analyses based on the combined transient steady state flow (White *et al.,* 1992) appear to be the most susceptible. In addition, good and consistent hydraulic contact between the infiltrometer membrane and the soil must be maintained at all times if reliable results are to be obtained (Reynolds and Zebchuk, 1996). This is best achieved by placing a layer of contact sand between the infiltrometer membrane and the soil surface. Perroux and White (1988) indicate that a 3-5 mm single grain thickness for this contact material (which should have a fine sand texture) is adequate for most agricultural soils. Smettem and Clothier (1989) used contact material layers of 5-15 mm in thickness which were not successful.

The aim of this paper was to assess the effect of different soil surface tillage practices on the hydraulic properties of a loamy soil, based on tension disk infiltrometer measurements. The test area was a commercial apricot orchard cultivated on a hillside under semiarid conditions. Hydraulic conductivity, sorptivity, mean pore size, and the time related to gravity were estimated from the different tensions recorded during the infiltration process.

Material and Methods

This experiment was performed in 2002 in a 2 ha plot in a commercial orchard in the Mula valley, Murcia (SE Spain). The plot had a highly calcareous (65% total calcium carbonate), loamy textured soil (Table 1) with a pH of 7.8, a low organic matter content (1.07%), and a low cationic exchange capacity (97 mmol kg^{-1}). The soil was classified as a Xeric torriorthent. The plot had a 7% slope. The volumetric water content at field

Table 1. Particle-size distribution and dry bulk density of surface soil in the different tillage treatments

Particle size (mm)	%, in weight[1]		
Clay (< 0.002)	27.21		
Silt (0.002 – 0.02)	42.92		
Fine sand (0.02 – 0.2)	26.76		
Coarse sand (0.2 – 2)	3.09		
Texture	Loam		
	Control	**Mini-catchments**	**Perforated**
Dry bulk density of soil surface, ρ_d (g cm^{-3})	1.42 c	1.36 b	1.32 a

[1] Values are the mean of 4 replications. Means followed by different letters are significantly different according to Duncan's multiple range test (significance was set at $P > 0.05$).

capacity and wilting point (measured by Richard's pressure plate) was 26 and 11% respectively. The plant material consisted of adult apricot trees *(Prunus armeniaca* L., cv. Búlida, grafted onto Real Fino apricot rootstocks) spaced 8 × 8 m and under drip irrigation (Pérez-Pastor *et al.,* 2004).

The test plot was divided into three subplots (each consisting of four rows of 16 trees). In each, a different soil surface tillage practice was used between rows of trees. In the first subplot (control, non-tillage treatment) weeds were cut back to ground level by a blade attached to a tractor (following the common practice of the area), leading to high soil compaction. In the second subplot (perforated treatment) the soil was mechanically perforated with an adapted plough. The perforation imprint was 20 holes per m^2; each hole had a depth of 10 cm and a volume of 130 cm^3. The third subplot (mini-catchment treatment) consisted of producing mini-catchments with banks 20 cm in height and 2 m long, manually raised at 1 m intervals perpendicular to the line of the emitters and runoff. No organic amendments were added to the soil and the weeds were controlled with applications of 18% MCPA [(4-chloro-2-methylphenoxy) acetic acid] + 18% glyfosate.

Soil surface hydraulic characterizations were performed using tension disk infiltrometers of radius 40 and 125 mm (Vauclin and Chopart, 1992). The base of each disk was covered with a 20 μm pore nylon mesh. A thin layer (2-3 mm) of contact sand was used between the soil and the infiltrometers. The pressure heads used *(h)* were -90, -60, -30, and 0 mm; water infiltration was measured with each infiltrometer for each *h.* The volumetric soil water contents (θ_o) at the different *h,* were calculated from the water content of shallow samples scraped from the soil surface under the disk. These samples were taken immediately after removing the disk infiltrometer and contact material. Measurements were made at four sites with average textural characteristics for each tillage treatment, as indicated by Plana *et al.* (2002).

The hydraulic conductivity, $K = K(h)$, and sorptivity, $S = S(h)$, were obtained using the multidisk approach (Smettem and Clothier, 1989; Thony *et al.,* 1991; Angulo-Jaramillo *et al.,* 1997). This method is based on Wooding's (1968) equation for steady-state asymptotic flux.

$$K = \frac{q_1 r_1 - q_2 r_2}{r_1 - r_2}$$

where q is the steady-state water flux, r is the radius, and 1 and 2 correspond to the 40 and 125 mm radius infiltrometers respectively.

Sorptivity was calculated according to White and Sully (1987):

$$S = \sqrt{\frac{\Phi \cdot (\theta_o - \theta_n)}{0.55}}$$

where Φ is the matrix flux potential, θ_o is the volumetric soil water content at the imposed water pressure heads, and θ_n is the initial water content.

Additionally, a soil structure index was defined by the frame-weighted mean pore size λ_m (White and Sully, 1987):

$$\lambda_m = \frac{\sigma}{\rho \cdot g} \frac{(\theta_o - \theta_n) \cdot K}{b \cdot S^2}$$

where σ is the surface tension of water (0.073 N m^{-1}), ρ the density of water (1000 kg m^{-3}), and g the acceleration due to gravity (9.8 m s^{-2}). Usually the value of b for a field soil is 0.55 (Warrick and Broadbridge, 1992).

The three dimensional flow emanating from a disk is composed of a combination of gravity and capillary and geometry effects. Philip (1969) defined the characteristic time related to gravity (t_{grav}), as:

$$t_{grav} = \left[\frac{S}{K}\right]^2$$

This indicates the time after which gravity should dominate the capillary effect during the infiltration process.

At the same sampled sites (four replicates), the initial volumetric water content (θ_o) and dry bulk density (ρ_d) of the soil surface were determined in undisturbed cores of 100 cm^3 using Eijkelkamp's soil sample ring kit (Table 1).

Results and Discussion

The hydraulic conductivity *(K)* values were significantly affected ($P < 0.0001$) by both the soil tillage practice and the pressure head (Table 2). K decreased with the pressure head; the lowest K values were associated with the lowest pressure heads in all three treatments (Table 2).

Fig. 1 shows the mathematical equations for the three soil tillage treatments when the relationship between K and h is exponential (Philip, 1986).

Fig. 1 and Table 2 show that the highest K values corresponded to the mini-catchment and perforation treatments; this was the case for all the water pressure heads applied. The differences in the K values between the three soil treatments exactly reproduced the differences in the dry bulk densities of the soil surfaces (Table 1), confirming that both soil tillage treatments increased the infiltration capacity of the soil. Compared with an untilled soil, Allmaras *et al.* (1977) found a fourfold increase in unsaturated hydraulic conductivity by chiselling to a depth of 0.43 m. Lai (1978) reported infiltration rates of 0.13 mm s^{-1} for non-tilled soil and 0.04 mm s^{-1} for a ploughed treatment in a field that had been planted with maize for five years. They also found that surface residues prevented surface sealing in the non-tilled treatments. Meek *et al.* (1989) recorded a 17% increase in the infiltration rate when the soil was packed lightly (compared with no packing) before the first flood irrigation.

It is important to note that the low hydraulic conductivity values measured in the control treatment (Table 2), together with the slope of the orchard (≈ 7%), could be a cause of notable runoff under non-tilled conditions (Ruiz-Sánchez *et al.,* 2005).

Angulo-Jaramillo *et al.* (1997) reported similar hydraulic conductivity in sandy-loam and sandy soils

Table 2. Hydraulic conductivity and sorptivity values achieved with the different tillage treatments and pressure heads.

Soil tillage	Hydraulic conductivity ($K \times 10^{-2}$, mm s^{-1})			
	0 mm	**–30 mm**	**–60 mm**	**–90 mm**
Control	2.24 a D	1.10 a C	0.34 a AB	0.22 a A
Mini-catchments	2.32 ab D	1.15 a C	0.65 b AB	0.40 b AB
Perforation	2.70 b D	1.24 b BC	1.10 c B	0.55 c B
	Sorptivity (S, mm $s^{-1/2}$)			
Control	0.569 a D	0.357 a C	0.100 a AB	0.071 a A
Mini-catchments	0.728 b D	0.330 a C	0.190 b AB	0.174 b A
Perforation	0.832 c D	0.391 a C	0.239 b B	0.146 b A

Means followed by different letters in the same row (upper case) or column (lower case) are significantly different according to Duncan's multiple range test (significance was set at $P > 0.05$).

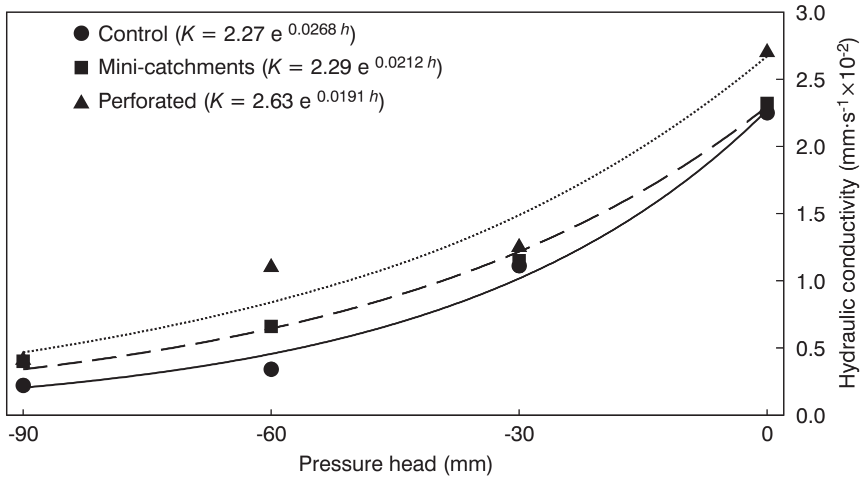

Figure 1. Hydraulic conductivity *vs.* pressure head in the three soil tillage treatments (control, mini-catchment, and mechanical perforation treatments). Data points are the average of four measurements.

with gravel (≈ 5.4 × 10^{-2} mm s^{-1}) at saturated pressure head values. These values are higher than those found in the present experimental conditions (≈ 2.4 × 10^{-2} mm s^{-1}, Table 2). Moreno *et al.* (1993) found that hydraulic conductivity fell significantly as the pressure head decreased in clay soils, but not in sandy soils, due to the much more uniform pore size of the latter.

The sorptivity values *(S)* showed the same tendency as *K,* increasing with pressure head in both tillage treatments (Table 2). Significantly higher *S* values were seen in the perforation treatment than in the control (at h = 0 mm), probably because breakage of the soil surface structure allows clay to occupy the macropores, creating a degree of microporosity that increases sorptivity. The pore radius values (λ_m) showed a similar tendency (Table 3), defining a mean width for hydraulically functioning pores at each pressure head imposed. Therefore, λ_m is directly proportional to both *K* and *S,* and is useful in the analysis of the porous network dynamics.

Fine textured soils generally show higher sorptivity values than coarser soils. For clayey (Moreno *et al.,*

Table 3. Pore radius and time related to gravity for the different soil tillage treatments and pressure heads (0, –30, –60 and –90 mm)

Soil tillage	Pore radius (λ_m, mm)			
	0 mm	–30 mm	–60 mm	–90 mm
Control	232.78 a B	135.29 a AB	127.12 a A	70.22 a A
Mini-catchments	219.74 a B	155.11 a AB	156.68 a AB	70.63 a A
Perforation	223.06 a B	200.73 a B	157.73 a AB	82.40 a A
	Time related to gravity (t_{grav}, mm)			
Control	11.43 A	18.49 AB	16.92 AB	22.99 B
Mini-catchments	17.08 A	15.18 AB	22.39 AB	33.14 B
Perforation	16.74 A	21.57 AB	23.40 AB	27.55 B

Means followed by different letters in the same row (upper case) or column (lower case) are significantly different according to Duncan's multiple range test (significance was set at P > 0.05).

1993) and sandy-loam (Angulo-Jaramillo *et al.,* 1997) soils at saturation or near-saturation pressure head values, sorptivity values similar to those found in the present loamy textured soil (control treatment) (Table 2) have been reported. The sorptivity values of sandy soils are reported to be considerably lower (Smettem and Clothier, 1989).

No significant differences were seen in t_{grav} for the different soil treatments (Table 3), although those of the mini-catchment and perforation treatments were slightly higher than those recorded for the control. The t_{grav} values decreased when water pressure head increased, although this effect was statistically significant only for the extreme values (0 and –90 mm).

The soil surface was rapidly saturated (a t_{grav} mean value of 15 min was observed at h = 0 mm, Table 3). Therefore, sorptivity acts for only a very short time period; any subsequent water movement would obey gravity rather than capillary forces. This shows that hydraulic conductivity was more important than sorptivity in explaining the infiltration process in the experimental plot.

In saturated clayey soils, Moreno *et al.* (1993) found higher t_{grav} values (> 500 min) than those of the present study, indicating a strong influence of capillary forces over gravity in fine textured soils. In this particular case, sorptivity was more important with respect to explaining the infiltration process.

In conclusion, the steady-state flow reached at the base of the infiltrometers in the mini-catchment and perforation treatments was greater than in the non-tilled soil. This led to an increase in infiltration due of the increase in hydraulic conductivity. Thus, soil surface tillage treatments might facilitate infiltration during rainfall events, reducing runoff (Ruiz-Sánchez *et al.,* 2005). Under the present experimental conditions, the flux of water entry into the soil was characterised by the relative dominance of gravity over the capillary forces, independent of the water pressure head imposed. Given the low t_{grav} values (≈ 15 min at h = 0 mm), hydraulic conductivity would appear to have the greatest influence on the infiltration process.

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