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Soil & Tillage Research 52 (1999) 167–175

**Soil &  
Tillage  
Research**

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## Effects of tillage method on soil physical properties, infiltration and yield in an olive orchard

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Received 26 March 1999; received in revised form 27 July 1999; accepted 5 August 1999

### Abstract

The long-term effects of two different tillage systems, conventional (CT) and no tillage (NT), were studied in an olive orchard in Santaella (Southern Spain) for 15 years. In both tillage systems, two distinct zones developed in the orchard in relation to soil physical properties; one underneath the tree canopy, and the other in the rows between trees. Surface soil organic matter content, bulk density, cone index, macroscopic capillary length and hydraulic conductivity showed significant differences between tillage systems and positions. After 15 years, the NT treatment achieved greater bulk density and cone index values than CT. This compaction reduced the infiltration rate of NT soil with respect to CT, particularly in the rows between trees. Despite that reduction, the NT soil retained a moderate infiltration potential. That may be explained by the high infiltration rates and macroporosity of the zone beneath the tree, the temporary effects of tillage on infiltration and probably by the self-repair of soil structure in the Vertisol studied. Yield was not affected by tillage except in one year with very low precipitation, where NT significantly yielded more than CT. The reduction in infiltration in NT must have been compensated by unknown factors that improve the tree water supply in drought years. © 1999 Elsevier Science B.V. All rights reserved.

**Keywords:** Tillage; Olive tree; Yield; Soil compaction; Infiltration

### 1. Introduction

Tillage modifies the soil physical properties. Usually, the bulk density of tilled soils decreases while the tillage implement compacts the soil underneath, creating, after repeated tillage operations, a plough

layer that restricts water flow and root penetration (Carter and Colwick, 1971). When tillage is reduced, soil porosity tends to increase (Voorhees and Lindstrom, 1984), and often, surface sealing occurs, reducing the infiltration rate (Lindstrom and Onstad, 1984). The above describes the general responses observed, which vary significantly with soil type. For instance, Chan and Mead (1989) noted that untilled soils had greater hydraulic conductivity than tilled soils. Other authors have not found differences in

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infiltration rates between tilled and untilled soils (e.g. Ankeny et al., 1990), or have found lower infiltration rates in untilled soils (Heard et al., 1988). The development of surface sealing (Zuzel et al., 1990), and the occurrence of macroporosity (Meek et al., 1990) in some situations may explain the different results described above. An additional source of variation is the time of measurement since last tillage operation, due to the temporary effect of soil modification by tillage (Henderson, 1979). It is therefore difficult to predict soil responses to changes in tillage methods without the help of long-term experimentation.

Olive trees are grown in Spain primarily under rainfed conditions. In the study area, located in south-western Spain, annual precipitation is 606 mm, olive evapotranspiration is estimated as 760 mm (Orgaz and Fereres, 1999) and direct evaporation from the soil of an intensive olive orchard was calculated to be about 260 mm (Bonachela et al., 1999). Conventional tillage (CT) has long been used in olive orchards with the primary goal of reducing weed competition for scarce water. Several decades ago, tractors were introduced and tillage passes increased in frequency, leading to severe erosion in areas of hilly topography. Alternatives to CT have been sought since the appearance of residual herbicides, and many experiments were established around 20 years ago to test the viability of bare soil, NT systems using herbicides. The tests were initially positive because of reduced production costs (Humanes, 1992) and the NT system was adopted in the eighties over 30,000 ha in Andalucía (Southern Spain). There has not been further expansion of NT in the last decade for various reasons, even though many farm trials reported increased yields under NT, particularly in years with below-average rainfall (Pastor, 1988).

We report here the results of a long-term experiment in an olive orchard comparing CT to NT for over 15 years. We emphasise the differential effects of both tillage systems on the physical properties of the soil and on the infiltration rate.

## 2. Materials and methods

### 2.1. Site characteristics and soil

Measurements were conducted in an experimental olive orchard of 8 m × 8 m tree spacing under the two

tillage methods; CT and NT. The orchard is located in Santaella (Cordoba, Spain; 35° 50' 40" N and 4° 51' 02" W), on a Xerochrept Calcixeroll Vertic soil (Soil Survey Staff, 1975) of clay-loam texture, with a slope of 2–7%.

### 2.2. Tillage treatments and sampling

Two different tillage treatments, CT and NT have been applied for the last 15 years. CT is carried out by discing to about 20 cm several times in the spring and autumn as needed for weed control and for harvest preparation. The tillage covers all soil areas, including the area around the trunk base. In the NT treatment, weed control is performed by spraying with the herbicide Simazine. Tillage treatments are replicated five times in a complete randomised design; each individual plot is 24 m × 24 m and the yield from the four trees in the centre of each plot is recorded annually. All measurements described below were always done in two different locations within each plot and tillage treatment; below the tree canopy, and in the rows between trees. We refer to the four different locations as no-till row (NTR), no-till tree (NTT), conventional tillage row (CTR) and conventional tillage tree (CTT). Except when noted, below tree canopy measurements were taken at 0.5–0.8 m from the tree trunk. Measurements in the rows were located 3.0–4.0 m away from the tree trunk.

### 2.3. Characterisation of soil properties

Soil samples were taken at 3 cm intervals starting from the surface downwards to 9 cm for determination of organic carbon content and particle size distribution by standard methods (Nelson and Sommers, 1982; Gee and Bauder, 1986).

Bulk density was measured with an undisturbed soil core sampler (9 cm in diameter and 10 cm long) at 10 cm intervals in the top 40 cm. Samples were taken in all four locations in May, 1996, and again in the CT plots in March, 1997, immediately before and 8 days after discing. Only the two uppermost soil layers were measured on the last date. Two points in each of the five replicated plots were sampled, one below the tree canopy and the other in the row.

The resistance to penetration was measured with a recording penetrometer developed according to ASAE

standards by Agüera (1986). The measurements were carried out down to a depth of 30 cm in transects between two trees with individual sampling points located every 40 cm. Cone index values were recorded in a grid that was 0.5 cm depth  $\times$  40 cm length, with 1200 measurements on each transect. The sampling was performed in June, 1997 two days after 73 mm rain had fallen, which ensured homogeneity in soil water content (Bradford, 1986). Each set of measurements included three transects from one tree to three adjacent trees and a total of eight measurements sets were performed in NT and six in CT.

Field measurements of unsaturated hydraulic conductivity were taken in August 1996 using a 25 cm diameter tension infiltrometer (Perroux and White, 1988), 10 days after disking. The initial soil surface volumetric moisture,  $\theta_v$ , was 0.06, 0.05, 0.09 and 0.07  $\text{cm}^3 \text{cm}^{-3}$  for the CTR, CTC, NTR and NTC treatments, respectively. These values were used to calculate the macroscopic capillary length ( $\lambda_c$ ). This parameter is considered to be related to the soil pore structure (White and Sully, 1987), and according to Raats and Gardner (1971) can be thought as a 'mean' height of capillary rise above a water table. The saturated hydraulic conductivity was calculated following the method outlined by Ankeny et al. (1991) at four water tensions;  $-15$ ,  $-10$ ,  $-5$  and  $0$  cm of  $\text{H}_2\text{O}$ .

The macroscopic capillary length was determined from the experimental data by numerical solution of the following equation (White and Sully, 1987):

$$\lambda_c = (K(\psi_0) - K(\psi_n))^{-1} \int_{\psi_n}^{\psi_0} K(\psi) d\psi. \quad (1)$$

## 2.4. Infiltration

A portable rainfall infiltrometer was constructed based on the guidelines of Peterson and Bubenzer (1986). Metal boxes  $0.5 \times 0.5 \times 0.2$  m were placed 10 cm deep into the soil and, after sealing the soil-box boundaries, simulated rainfall was applied to the  $0.25 \text{ m}^2$  area with a spray nozzle. The nozzle used was the 8W wide angle (Spraying System<sup>®</sup>), operating at  $2.1 \text{ kg cm}^{-2}$  pressure, located 1.4 m above soil surface. All the equipment was covered with a plastic sheet during the tests to avoid distortion of the rainfall pattern by wind. Each run lasted for 1.5 h and applied

$90 \text{ mm h}^{-1}$  of simulated rainfall and runoff was collected at 2 min intervals.

Knowledge of the application rate and of the runoff hydrograph allowed for the calculation of the instantaneous and the cumulative infiltration rates. The kinetic energy of the simulated rainfall was calculated following Kincaid (1996) based on an average drop diameter of 1 mm within a range of 0.75–4 mm. The calculated kinetic energy of  $1000 \text{ J m}^{-2} \text{h}^{-1}$  is about half of that estimated by Peterson and Bubenzer (1986) for a rainfall intensity of 90 mm/h. Thus, the small drop diameter used in our infiltrometer caused hardly any erosion nor did it contribute to degrading the effects of tillage.

A preliminary test was conducted in four locations within the orchard, on recently tilled areas, by running the test on three consecutive days on the same spot without removing the metal box. The final infiltration rates did not vary significantly between the three tests at each point.

Infiltration measurements were performed in February and March, 1997 in both the below-canopy and the in-row locations within the CT and NT treatments, while the last tillage operation had been performed in October of 1996 and harvest performed in January, 1997. Soil surface  $\theta_v$  were 0.18, 0.15, 0.27 and 0.22  $\text{cm}^3 \text{cm}^{-3}$  for the CTR, CTT, NTR and NTT, respectively. Four days after disking, in April, 1997, infiltration was measured in CT following the same procedures, with a surface  $\theta_v$  of 0.14 and 0.13  $\text{cm}^3 \text{cm}^{-3}$  for CTR and CTT. Measurements were repeated again in June, 1997 on the same spots, without having removed the soil boxes after the April tests. 85 mm of natural rain fell between the two measurements, surface  $\theta_v$  were 0.22 and 0.20  $\text{cm}^3 \text{cm}^{-3}$  for CTR and CTT.

## 3. Results and discussion

### 3.1. Organic matter

Fig. 1 shows the organic matter (OM) content for the four positions and three soil depths. Significant differences were detected only in the first soil layer and were associated with position (Fig. 1). The surface soil beneath the canopy had higher OM content in both tillage systems, particularly under NT. The tillage method did not affect the OM content of the soil

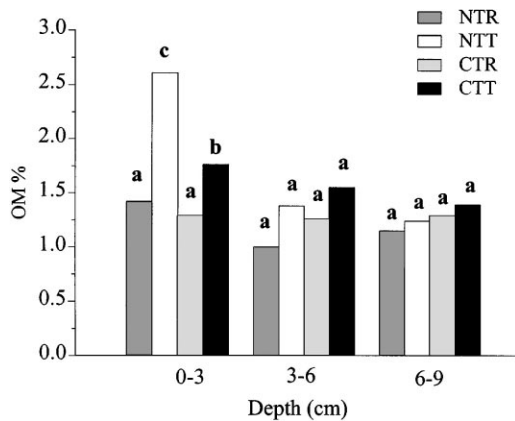


Fig. 1. Soil organic content by depth, tillage treatment and position (T, below-tree; R, in-row).

Table 1  
Summary of three-way completely randomized factors ANOVA for soil organic content<sup>a</sup>

Source	Probability
Soil management (SM)	NS
Position (Po)	**
SM × Po	NS
Depth (D)	**
D × Po	**
D × SM	**
D × Po × SM	NS

<sup>a</sup> NS, non-significant at the 0.05 level; \*\*, significantly different at the 0.01 level.

(Table 1) while the position beneath the tree or in the tree row was important, but only for the first depth increment. This difference in OM beneath and between the trees has been described for natural

(Davenport et al., 1996) and agricultural systems (Gras and Trocmé, 1977), and has been explained by the accumulation of tree litter on the soil surface. The magnitude of the observed differences in OM may have important implications for the structural stability of this soil (Watts and Dexter, 1997), affecting the infiltration rate of the area beneath the tree (Vanderlinden et al., 1998).

### 3.2. Bulk density

Treatment differences in bulk density appeared in the 0–10 and 10–20 cm soil layers; below 20 cm there were no detectable differences in soil bulk density in all samples (Table 2). The highest compaction was detected in NTR followed by NTT and CTR prior to tillage. No till management increases soil bulk density, especially between trees, which is due to both natural compaction and also to the heavy traffic related to agricultural operations. The effect of tillage on reducing bulk density was evident in the measurements taken in CTR after tillage. Soil consolidation in the tillage treatments was evident only in the row position, where bulk density achieved a maximum value of  $1.21 \text{ Mg m}^{-3}$  before tillage. Rainfall interception protected the soil below the canopy, which maintained the low bulk density values produced by tillage; some differences in soil stability due to higher surface OM content under the canopy may be expected, as mentioned previously.

### 3.3. Cone index

The spatial distribution of the cone index (CI) across two trees and with depth is presented for both

Table 2  
Bulk density ( $\text{Mg m}^{-3}$ ) by depth, tillage treatment and position<sup>a</sup>

	0–10 cm	10–20 cm	20–30 cm	30–40 cm
CTR March, 1997 after tillage	1.03a	1.15a		
CTR March, 1997 before tillage	1.21ab	1.23bc	1.40a	1.41a
CTR May, 1996	1.17ab	1.36bc	1.48a	1.56a
CTT March, 1997 after tillage	1.04a	1.14a		
CTT March, 1997 before tillage	1.06a	1.16a	1.35a	1.40a
CTT May, 1996	1.06a	1.17a	1.31a	1.44a
NTR May 1996	1.57c	1.48c	1.38a	1.44a
NTT May 1996	1.23bc	1.29ab	1.41a	1.38a

<sup>a</sup> Values within one depth followed by the same letter are not significantly different (Student–Newman–Keuls's test, 0.05 level).

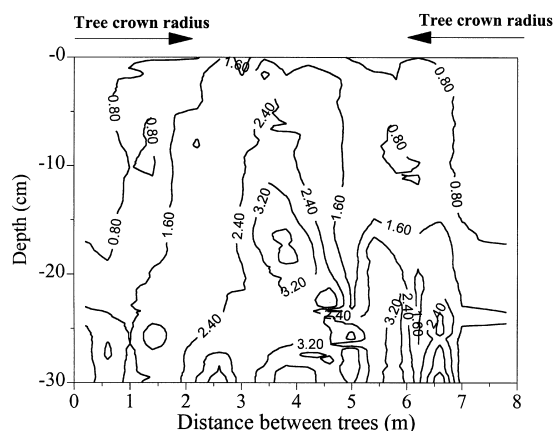


Fig. 2. Cone index (MPa) spatial pattern in NT.

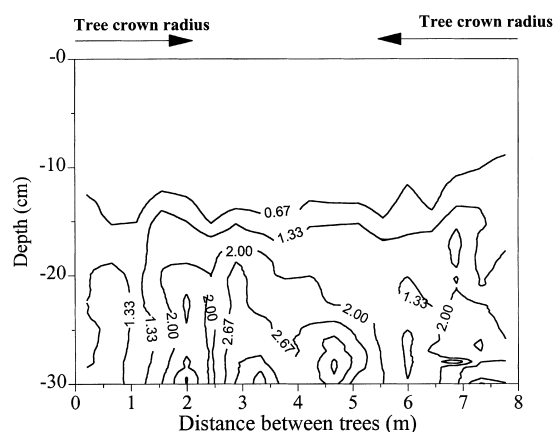


Fig. 3. Cone index (MPa) spatial pattern in CT.

tillage treatments in Figs. 2 and 3. Maximum resistance near the surface was observed in the row of NT where the cone index reached values of 1.6 MPa, while it decreased to values of less than half of this maximum near the tree base (Fig. 2). Values as high as 3.2 MPa were observed between the 10–20 cm depth in NT while CT had lower CI values, which varied between 0.67 and 1.3 regardless of the position (Fig. 3). Nevertheless, CI in CT increased sharply to values above 2 MPa, when the penetrometer approached the plough pan just below the 20 cm depth in that treatment.

It is well known (Ehlers et al., 1983) that CI measurements are very sensitive to variations in soil water content. Concurrent measurements of soil water

content taken at various depths and positions indicated that soil water content did not differ significantly (at the 95% level) among depths and positions, with the exception of the 0–10 cm depth in NTR which had the highest water content (Gómez, 1998).

The CI data obtained in the transects were summarized for the four positions and for the three depths. They are presented in Fig. 4 and the ANOVA in Tables 3 and 4. There was a significant interaction between tillage system and position in the NT system, where the average cone index in the row was always higher than beneath the canopy.

### 3.4. Macroscopic capillary length

Fig. 5 shows the important differences in macroscopic capillary length measured at three suctions in

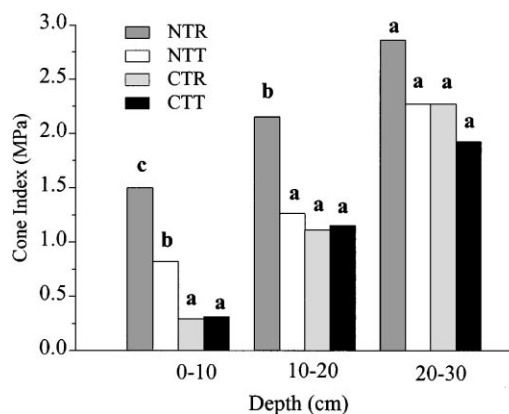


Fig. 4. Cone index (MPa) values by depth, tillage treatment and position. Values within one depth followed by the same letter are not significantly different (Student–Newman–Keuls's test, 0.05 level).

Table 3  
Summary of three-way completely randomized factors ANOVA for bulk density<sup>a</sup>

Source	Probability
Soil management (SM)	**
Position (Po)	*
SM × Po	*
Depth (D)	**
D × Po	NS
D × SM	NS
D × Po × SM	NS

<sup>a</sup> NS, non-significant at the 0.05 level; \*, significantly different at the 0.05 level; \*\*, significantly different at the 0.01 level.

Table 4

Summary of three-way completely randomized factors ANOVA for cone index<sup>a</sup>

Source	Probability
Soil management (SM)	**
Position (Po)	**
SM × Po	**
Depth (D)	**
D × Po	NS
D × SM	NS
D × Po × SM	NS

<sup>a</sup> NS, non-significant at the 0.05 level; \*\*, significantly different at the 0.01 level.

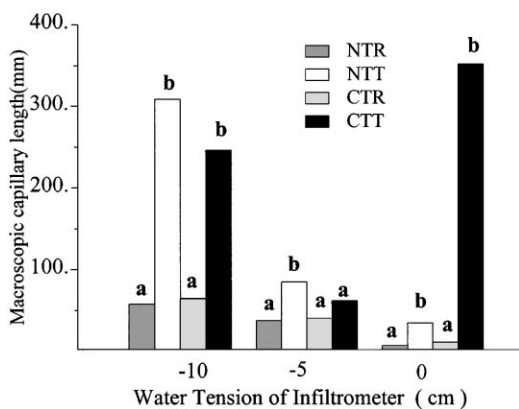


Fig. 5. Macroscopic capillary length (mm) for three tensions of infiltration measurements, tillage treatment and position. Values within one tension followed by the same letter are not significantly different (Student–Newman–Keuls's test, 0.05 level).

the four locations using the tension infiltrometer. These differences in  $\lambda_c$  values should be interpreted resulting from differences in the soil pore system (White and Sully, 1987), which may have been induced by the tillage management. Huang et al. (1996) found differences in this parameter caused by soil traffic and consolidation. The differences in bulk density observed in the two NT locations, together with the greater macroporosity probably induced by root colonisation in the surface layers, could explain the differences observed in the two NT locations in Fig. 5.

The differences observed in CT do not have an obvious explanation. It is possible that differences in OM content (Table 1) may have caused the differences between CTT and CTR.

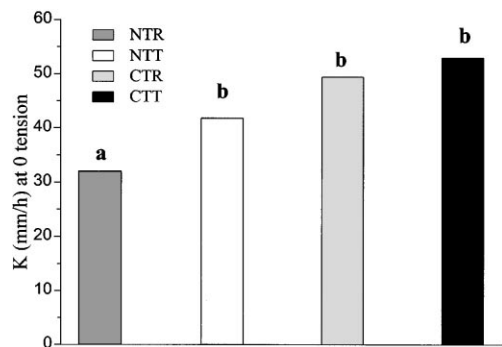


Fig. 6. Hydraulic conductivity (mm/h) at 0 cm water tension. Values within one tension followed by the same letter are not significantly different (Student–Newman–Keuls's test, 0.05 level).

### 3.5. Hydraulic conductivity

Fig. 6 shows the values of hydraulic conductivity measured at 0 cm water tension. They should be considered as approximate values, as the initial soil moisture content was not identical among all treatments. The lowest value hydraulic conductivity values was measured in the more compacted location NTR; there were not significant differences at the 0.05 level among the other three treatments. Recent tillage in CTT and CTC, and lower compaction in NTC with respect to NTT could explain these results. In spite of the expected decrease of the hydraulic conductivity, due to the soil compaction, the soil maintained a moderate infiltration potential according to several classifications: Soil Conservation Service (ASCE, 1996), Soil Survey Staff (Soil Survey Staff, 1975), even for the lowest hydraulic conductivity in NTR. The attenuation of soil compaction by repeated wet/dry cycles, as shown by Sharma et al. (1996) could explain the relative small reduction in hydraulic conductivity in NTR.

### 3.6. Infiltration

Fig. 7 presents the cumulative infiltration in the four positions in February 1997. Infiltration under NTT was less than in CTT, but there was also a difference between the below-tree and in-row locations within both systems. The high compaction in the rows must have been responsible for the low infiltration observed, especially in NTR (Meek et al., 1992).

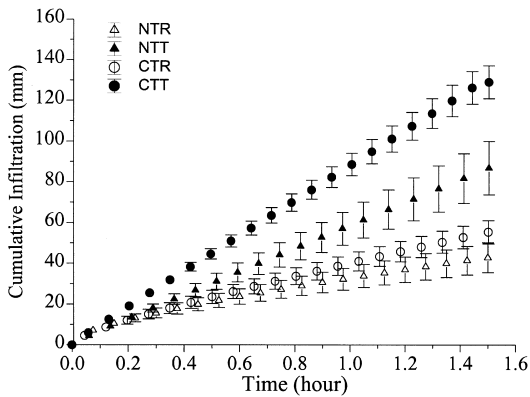


Fig. 7. Cumulative infiltration from rainfall simulation by position and tillage treatment in February–March 1997.

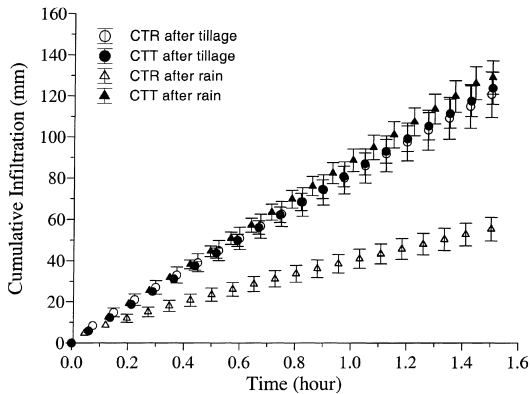


Fig. 8. Cumulative infiltration from rainfall simulation in CT locations, immediately after tillage and 8 weeks later.

Fig. 8 shows the infiltration in CT just after disking and eight weeks later following a total of 85 mm of precipitation. A drastic reduction in infiltration occurred in the rows of CT which had rates similar to those measured in NTR. However, the infiltration beneath the tree in CT remained at about the same level as that observed following tillage which is similar to that observed after harvest. Again, due to the differences in initial water content of the various treatments, the infiltration measurements provide only qualitative differences among treatments.

The improved infiltration caused by tillage had a temporary effect in the row but persisted in the area beneath the canopy. It is well known that the tree canopy redistributes rainfall and increases the average

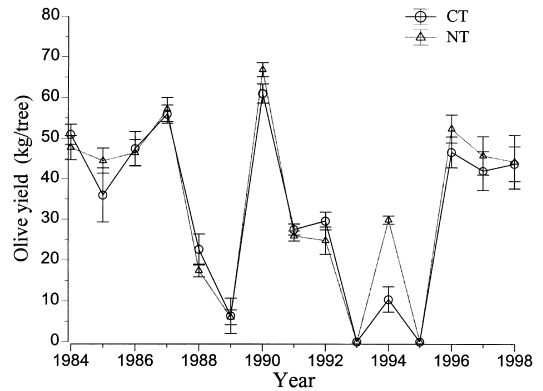


Fig. 9. Average olive yield and error bars for both tillage treatments since 1984.

drop size, increasing the erosive and compaction effects of rainfall (De Luna, 1994). If the high infiltration in the CTT persists it is probably due to the improved structural stability of this zone associated with higher OM content and with the differences in pore structure according to the differences in  $\lambda_c$  shown in Fig. 5.

### 3.7. Yield

Fig. 9 presents the yield recorded for the 15 experimental years in both tillage treatments. Yields varied widely due to rainfall variability and to the alternate bearing behaviour of the olive trees. Tillage caused significant differences in yield only in one of the 15 years. Despite the lower infiltration observed in NT, yields did not differ significantly from those of CT values. The only significant difference was observed in 1994, when NT produced about twice as much as CT (Fig. 9); this occurred in a very dry year, following an 'off year', when both treatments did not produce any commercial yield. It is not known what caused the higher yield of 1994 in NT, but it is possible that root development in the surface layers of NT favours tree water uptake relative to evaporation from the soil, while in the CT, such roots are eliminated periodically by tillage and a higher proportion of surface water content is lost to direct evaporation from the soil over the season. Such differences could be significant in years such as 1994 when rainfall was 67% of average rainfall.

#### 4. Conclusions

Any analysis of the effects of the tillage method on the soil physical properties of an olive orchard must consider the development of the two zones, one beneath the tree and the other in the open rows between trees. Almost all properties examined varied with soil location as much as with the method of tillage used. In the NT treatment, the infiltration rate below trees is four times the infiltration rate in the row between trees, and did not differ significantly from the infiltration rate in recently tilled soil. The positive effects of tillage on infiltration persisted in the areas beneath the canopy, but did not last long in the rows between the trees, where the difference with the non-tillage rows disappeared in a relatively short time, eight weeks.

The differences in soil bulk density explained a good deal of the variation in infiltration observed within both tillage treatments. The differences between the NT below-tree and in-row locations could be attributed to greater consolidation due to traffic in the rows, while between the CT locations it is hypothesised that the differences are likely attributable to differences in structural stability. The intake rate of the soil decreased only moderately in the most compacted areas (NTR), probably due to the self-repair of soil structure as observed in other vertisols (Sharma et al., 1996).

The reduction in infiltration rate observed in NT did not influence the yield of olive trees over a 15-year period. Such a reduction may not have been sufficient to affect the seasonal water supply of the olive in the experimental soil, considering that NTT maintained an adequate infiltration rate in the NT treatment. There is a need to study the effects of NT in soils of inherently low infiltration rate and in those prone to surface sealing. The aim should be to elucidate in what soils the reduction of infiltration rates in NT is severe enough to decrease tree water supply and to increase runoff generation and erosion risk.

#### References

- Agüera, J., 1986. Diseño y aplicación de un penetrómetro registrador para la determinación de la compactación en suelos agrícolas. Ph.D. Thesis, Universidad de Córdoba, Spain.
- ASCE (American Society of Civil Engineers), 1996. Hydrology Handbook, 2nd ed. American Society of Civil Engineers, New York, 784 pp.
- Ankeny, M.D., Kaspar, C.K., Horton, R., 1990. Characterization of tillage effects on unconfined infiltration measurements. *Soil Sci. Soc. Am. J.* 54, 837–840.
- Ankeny, M.D., Ahmed, M., Kaspar, C.K., Horton, R., 1991. Simple field method for determining unsaturated hydraulic conductivity. *Soil Sci. Soc. Am. J.* 55, 467–470.
- Bonachela, S., Orgaz, F., Villalobos, F.J., Fereres, E., 1999. Measurement and simulation of evaporation from soil in olive orchards. *Irrig. Sci.* 18, 205–211.
- Bradford, J.M., 1986. Penetrability. In: Klute, A. (Ed.), *Methods of Soil Analysis, Part 1. Physical and Mineralogical Methods*, 2nd ed. Agron. 9, American Society of Agronomy, Madison, WI, pp. 463–478.
- Carter, L.M., Colwick, R.F., 1971. Evaluation of tillage systems for cotton production systems. *Trans. ASAE* 14, 1116–1121.
- Chan, K.Y., Mead, J.A., 1989. Water movement and macroporosity of an Australian alfisol under different tillage and pasture conditions. *Soil Tillage Res.* 14, 301–310.
- Davenport, D.W., Wilcox, B.P., Breshears, D.D., 1996. Soil morphology of canopy and intercanopy sites in a piñon-juniper woodland. *Soil Sci. Soc. Am. J.* 60, 1881–1887.
- De Luna, E., 1994. Protección del suelo contra la erosión en el cultivo del olivo. Ph.D. Thesis, Universidad de Córdoba, Spain.
- Ehlers, W., Köpke, U., Hesse, F., Böhm, W., 1983. Penetration resistance and root growth of oats in tilled and untilled loess soil. *Soil Tillage Res.* 3, 261–275.
- Gee, G.W., Bauder, J.W., 1986. Particle-size analysis. In: Klute, A. (Ed.), *Methods of Soil Analysis, Part 1. Physical and Mineralogical Methods*, 2nd ed. Agron. 9, American Society of Agronomy, Madison, WI, pp. 383–413.
- Gómez, J.A., 1998. Modelización de los procesos de interceptación de lluvia e infiltración en un olivar. Ph.D. Thesis, Universidad de Córdoba, Spain.
- Gras, R., Trocmé, S., 1977. Un essai d'entretien du sol en verger de pommiers. *Annales Agronomiques* 28, 227–259.
- Heard, J.R., Kladvik, E.J., Mannering, J.V., 1988. Soil macroporosity, hydraulic conductivity, hydraulic conductivity and air permeability of silty soils under long-term conservation tillage in Indiana. *Soil Tillage Res.* 11, 1–18.
- Henderson, D.W., 1979. Soil management in semi-arid environments. In: Hall, A.E., Cannel, G.H., Lawton, L.W. (Eds.), *Agriculture in Semi-arid Environments*. Springer, New York, pp. 224–237.
- Huang, J., Lacey, S.T., Ryan, P.J., 1996. Impact of forest harvesting on the hydraulic properties of surface soil. *Soil Sci.* 161, 79–86.
- Humanes, M.D., 1992. Sistemas de manejo del suelo en olivar: evaluación de técnicas de aplicación de herbicidas. Degree dissertation. Universidad de Córdoba, Spain.
- Kincaid, D.C., 1996. Spraydrop kinetic energy from irrigation sprinklers. *Trans. ASAE* 39, 847–853.
- Lindstrom, M.J., Onstad, C.A., 1984. Influence of tillage systems on soil physical parameters and infiltration after planting. *J. Soil Water Conserv.* 39, 149–152.



- Meek, B.D., De Tar, W.R., Rolph, D., Rechel, E.R., Carter, L.M., 1990. Infiltration rate as affected by an alfalfa and no-till cotton cropping system. *Soil Sci. Soc. Am. J.* 54, 505–508.
- Meek, B.D., Rechel, E.R., Carter, L.M., De Tar, W.R., Urie, A.L., 1992. Infiltration rate of a sandy loamy soil: effects of traffic, tillage, tillage and plant roots. *Soil Sci. Soc. Am. J.* 56, 908–913.
- Nelson, D.W., Sommers, L.E., 1982. Total carbon, organic carbon and organic matter. In: Page, A.L., Miller, R.H., Keeney, D.R. (Eds.), *Methods of Soil Analysis*, 2nd ed. Agron 9, American Society of Agronomy, Madison, WI, pp. 539–580.
- Orgaz, F., Fereres, E., 1999. Riego. In: Barranco, D., Fernández-Escobar, R., Rallo L. (Eds.), *El Cultivo del Olivo*, 3rd ed. Mundi-Prensa, Madrid, pp. 267–288.
- Perroux, K.M., White, I., 1988. Design for disc permeameters. *Soil Sci. Soc. Am. J.* 52, 1205–1215.
- Pastor, M., 1988. *Sistemas de manejo del suelo en el olivar*. Ph.D. Thesis, Universidad de Córdoba, Spain.
- Peterson, A.E., Bubenzer, G.D., 1986. Intake rate: Sprinkler infiltrometer. In: Klute, A. (Ed.), *Methods of Soil Analysis*, Part 1. Physical and Mineralogical Methods, 2nd ed. Agron. 9, American Society of Agronomy, Madison, WI, pp. 845–870.
- Raats, P.A.C., Gardner, W.R., 1971. Comparison of empirical relationship between pressure head and hydraulic conductivity and some observations on radially symmetric flow. *Water Resour. Res.* 7, 921–928.
- Sharma, A.K., Pillai-McGarry, U., McGarry, D., 1996. Repair of the structure of a compacted vertisol via wet/dry cycles. *Soil Tillage Res.* 38, 17–33.
- Soil Survey Staff, 1975. *Soil Taxonomy, A Basic System of Soil Classification for Making and Interpreting Soil Surveys*. USDA-SCS Agricultural Handbook 436, US Government Printing Office, Washington, DC.
- Vanderlinden, K., Gabriels, D., Giráldez, J.V., 1998. Evaluation of infiltration measurements under olive trees in Córdoba. *Soil Tillage Res.* 48, 303–315.
- Watts, C.W., Dexter, A.R., 1997. The influence of organic matter in reducing the destabilization of soil by simulated tillage. *Soil Tillage Res.* 42, 253–275.
- White, I., Sully, M.J., 1987. Macroscopic and microscopic capillary length and time scales from field infiltration. *Water Resour. Res.* 23, 1514–1522.
- Voorhees, W.B., Linstrom, M.J., 1984. Long-term effects of tillage method on soil tilth independent of wheel traffic compaction. *Soil Sci. Soc. Am. J.* 48, 152–156.
- Zuzel, J.F., Pikul, J.L., Rasmussen, P.E., 1990. Tillage and fertilizer effects on water infiltration. *Soil Sci. Soc. Am. J.* 54, 205–208.