Hydraulic conductivity, residue cover and soil surface roughness under different tillage and crop management systems in a semiarid environment

Abstract

The objective of this study was to investigate the effect of tillage and cropping system (fallow versus continuous cropping) on some soil properties related to soil water storage and to obtain data to be used in soil water simulation models. The measurements were made in an experiment comparing three tillage systems (Subsoil Tillage, Minimum Tillage and No-Tillage), and three field situations (Continuous Crop, Fallow and Crop After Fallow) in two soils (Soil A, a Fluventic Xerochrept of 120 cm depth, and Soil B, a Lithic Xeric Torriorthent of 30 cm depth). In Soil B subsoil tillage was not used. Hydraulic conductivity was measured with a tension infiltrometer set at 0, 1, 3, 5, 10, 15, and 20 cm H_2O tension. The percentage of soil surface covered by residues was estimated by the line-transect method. Random and perpendicular roughness were determined by the chain method. Soil water content data were also available. Most differences between tillage and cropping systems were found for tensions greater than 5 cm H_2O (pores greater than 0.6 mm in diameter). No-tillage showed lower hydraulic conductivity (mean of 5.0 cm day^{-1}) than subsoil (15.5 cm day^{-1}) or minimum tillage (14.3 cm day^{-1}) in continuous crop. During fallow, hydraulic conductivity was high soon after tillage but was progressively reduced by the effect of rains. In the crop after fallow no differences were found between tillage systems. Residue cover at sowing was greater under no-tillage (60%) than under subsoil or minimum tillage (below 10%) in continuous crop. During fallow, residue cover decreased, leading to values below 10% at sowing of the following crop for all tillage systems in both soils. Surface roughness increased with tillage, reaching mean values near to 16 (with a maximum near to 30 after subsoiling), and fell with rainfall. In non-tilled plots surface roughness was relatively low (3-4). In the first years of no-tillage hydraulic conductivity decreases as a consequence of a reduction in soil porosity. The negative effect of this on infiltration is counteracted by the presence of residues over the soil, resulting in greater water storage in non-tilled than in tilled plots. If cut straw is removed after harvest, residue cover under no-tillage falls during fallow to values below 30%. Therefore, when no-till fallow is used, more residues must be left over the soil at harvest, or a surface tillage must be performed in spring to increase infiltration and reduce evaporation.

Keywords: Hydraulic conductivity, residue cover, surface roughness, subsoil tillage, no-tillage, fallow, tension infiltrometer, disc permeameter, soil water.

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Introduction

In rainfed agriculture the ability of soil to store water plays an important role in the success of crops, especially in arid and semiarid environments. Infiltration and evaporation are the most significant soil-controlled processes determining soil water storage.

Surface conditions play a major role in determining the rates of water infiltration and evaporation from soil. Tillage is the most effective way to modify soil surface characteristics due to its effect on pore space (shape, volume and continuity of pores), structure, residue cover and surface roughness. The soil management system that optimises soil water storage is dependent on soil and climate (Godwin, 1990), because the soil characteristics that define surface conditions can have contradictory effects on the soil processes involved in water balance (infiltration, redistribution and evaporation).

For example, high porosity and pore continuity are good characteristics for increasing soil water storage capacity and deep infiltration, but they also favour water evaporation from deeper soil layers. Residue cover increases infiltration and reduces evaporation but under extended dry conditions there are no differences from bare soil (Godwin, 1990). Surface roughness produced by tillage increases surface ponding, reducing surface runoff, but also increases the soil surface area exposed to evaporation. A soil mulch produced by tillage reduces evaporation from deep layers, but moist soil is drawn to the soil surface, producing water losses. Therefore, the final result of a defined soil management system will depend on the soil characteristics and the meteorological conditions.

A number of works try to evaluate the impact of different tillage systems on soil water dynamics by studying the infiltration behaviour. This is accomplished by the use of rainfall simulators and ponded or tension infiltrometers. In general, infiltration is reported to be greater under no-tillage than in tilled soils (Ehlers and van der Ploeg, 1976; Radclifee *et al.*, 1988; Chan and Heenan, 1993; Azooz *et al.*, 1996; McGarry *et al.*, 2000) due to the large number of macropores conserved under this system (Moran *et al.*, 1988; Logsdon *et al.*, 1990; Chan and Heenan, 1993; McGarry *et al.*, 2000), increased fauna activity, which is responsible for many of these macropores (Blevins *et al.*, 1983, Moreno *et al.*, 1997, Logsdon and Kaspar, 1995; Suwardji and Eberbach, 1998), and accumulated organic matter forming a litter of residues (Radclifee *et al.*, 1988; Pikul and Zuzel, 1994; Golabi *et al.*, 1995; Logsdon and Kaspar, 1995; Arshad *et al.*, 1999). Disruption of macropore continuity by tillage is reported to reduce infiltration and hydraulic conductivity in tilled soils (Ehlers and van der Ploeg, 1976; Godwin, 1990; Logsdon *et al.*, 1990).

In other studies, infiltration and/or hydraulic conductivity is found to be lower under no-tillage (Pelegrin *et al.*, 1988; Ferreras *et al.*, 2000). The cause of this seems to be the great bulk density (small porosity) found in no-till soils and the increase in porosity produced by tillage (Pelegrin *et al.*, 1990; Hubbard *et al.*, 1994; Pelegrin and Moreno, 1994), which affects in particular coarse pores (Tebrügge and Düring, 1999).

Hydraulic conductivity was found to decrease during the growing season in tilled soils (Messing and Jarvis, 1993; Mwendera and Feyen, 1993; Logsdon *et al.*, 1993) due to soil structural breakdown and surface sealing, and root growth that progressively blocks the pores (Ankeny *et al.*, 1990; Suwardji and Eberbach, 1998). For these reasons, in some studies saturated hydraulic conductivity was found to be greater for tilled soils at the beginning of the growing season due to increased porosity caused by tillage (Radclifee *et al.*, 1988; Hill, 1990; Suwardji and Eberbach, 1998), whereas it was greater for no-tillage at the end of the season (López and Arrúe, 1997; Suwardji and Eberbach, 1998).

The use of residues to conserve soil and water in arid and semiarid areas is becoming more and more important. In fact, the decisive criterion for classifying tillage as conservation tillage is that 30% of soil is covered by residues after sowing (Unger *et al.*, 1991; Blevins and Frye, 1993; Gilley, 1995). Residues protect the soil from raindrop impact (Unger and McCalla, 1980; Smika and Unger, 1986; Unger *et al.*, 1991; Blevins and Frye, 1993; Gilley, 1995), reducing slaking of surface aggregates and preventing pore sealing and crust formation. Residues also increase soil aggregation and structural stability (Cannell and Hawes, 1994; Singh *et al.*, 1994). Residues left over the soil slow the flow of surface runoff (Smika and Unger, 1986; Blevins and Frye, 1993; Gilley, 1995), increasing the opportunity of water to infiltrate (Godwin, 1990). The result of these factors is an increase in infiltration (McCalla and Army, 1961; Unger and McCalla, 1980; Potter *et al.*, 1995). Residues also slow the rate of evaporation during the first stage (Bond and Willis, 1971; Smika and Unger, 1986; Godwin, 1990; Unger *et al.*, 1991; Blevins and Frye, 1993) by isolating the soil from sun heating and air temperature, and increasing resistance to water vapour flux by reducing wind speed (Smika and Unger, 1986; Blevins and Frye, 1993). The increase in infiltration and the decrease in evaporation generally results in greater soil water storage, depending on the amount of residues left on the soil surface (Unger and McCalla, 1980; Smika and Unger, 1986) and the duration of the dry period (residues give only short-term protection) (McCalla and Army, 1961; Bond and Willis, 1971; Unger and McCalla, 1980; Godwin, 1990; Unger *et al.*, 1991; Blevins and Frye, 1993).

The quantity of residues on the soil surface undergoes great variation over time (Ghidey and Alberts, 1993; Singh *et al.*, 1994). The most important reasons for this variation are tillage and residue decay. Tillage modifies residue cover instantaneously, and some authors provide data about the percentage of residues left or buried after tillage according to tillage system and intensity (Blevins and Frye, 1993; Kok and Thien, 1994; Gilley, 1995). Residues decay in time following an exponential function (Steiner *et al.*, 1994; Schomberg and Steiner, 1999). Residue decay is controlled basically by temperature and moisture (McCalla and Army, 1961; Steiner *et al.*, 1994; Schomberg and Steiner, 1999; Steiner *et al.*, 1999), but also depends on the residue properties (McCalla and Army, 1961; Schomberg and Steiner, 1999) and the number and kind of micro-organisms in the soil (McCalla and Army, 1961). In summer, a rapid loss of residues was observed by Stroo *et al.* (1989). Standing biomass seems to decompose more slowly than flat residues (Steiner *et al.*, 1999).

Soil surface roughness increases the depression storage capacity of the soil (Mwendera and Feyen, 1993; Hansen *et al.*, 1999), extending the time in which infiltration can take place before runoff starts (Blevins and Frye, 1993). On agricultural land, surface roughness is mainly influenced by tillage, vegetation, soil type and the previous amount and intensity of rainfall (Hansen *et al.*, 1999). Tillage influences two of the four types of surface roughness stated by Römkens and Wang (1986): random roughness (non-directional surface variations due to cloddiness as a result of soil break-up by tillage implements), and oriented roughness (one-directional systematic differences in elevation due to farm implements). Though in general tillage increases surface roughness (Unger *et al.*, 1991; Singh *et al.*, 1994; Gilley, 1995), repeated tillage operations can also reduce it (Römkens and Wang, 1986).

Rainfall reduces surface roughness (Singh *et al.*, 1994; Gilley, 1995), especially the first rains after tillage, owing to the breakdown and sloughing of soil clods upon wetting during rainstorms, the consolidation of the loosely tilled soil upon drying, and soil erosion by drop impact and deposition into depressions (Römkens and Wang, 1986). Hyperbolic (Römkens and Wang, 1987) and exponential functions (Römkens and Wang, 1987; Foletto and Norton, 1997) have been used to model the decrease of surface roughness with cumulative rainfall. A large variation in surface roughness with time is observed, especially in tilled soils. Under no-tillage, surface roughness is low and runoff control depends on surface residues (Singh *et al.*, 1994).

The objective of this work was to investigate the effect of different tillage and cropping systems on the soil properties related to soil water storage: hydraulic conductivity, residue cover and surface roughness. A secondary objective was to obtain data to be used in simulation models of water in soil in order to simulate the effect of tillage over a long series of years.

Materials and methods

The data used for this paper were obtained from a tillage experiment located in El Canos, a semiarid area in the north-east Ebro Valley, Spain (mean annual precipitation of 440 mm). This experiment was repeated in two soils of contrasting depth. The deep soil (Soil A) was a fine-loamy, mixed, mesic Fluventic Xerochrept (Villar, 1989) of 120 cm depth, with a water holding capacity of 266 mm. The shallow soil (Soil B) was a loamy, mixed, calcareous, mesic, shallow Lithic Xeric Torriorthent of 30 cm depth, with a water holding capacity of 56 mm. The stone content in the surface was appreciable in the two soils (≈15%), especially in Soil B. Some selected properties of these soils are shown in Table 1.

Table 1
Selected soil properties for the different soil layers (from Villar, 1989 in Soil A).

Depth (cm)	Organic Matter (%)	Equivalent CO_3Ca (%)	Texture USDA (%)		
			Sand	Silt	Clay
Soil A					
0-12	2.4	24	25.1	52.0	22.9
12-32	1.0	25	24.6	53.2	22.2
32-47	0.6	16	23.4	51.4	25.2
47-117	0.7	7	21.0	51.5	27.5
Soil B					
0-10	2.9	26	23.5	55.6	20.9
10-30	2.5	26	22.6	55.9	21.5

We designed the tillage experiment as a randomised complete block with four replications. The plots (10 by 6 m in area) were arranged in three contiguous strips. In the central strip, barley (*Hordeum vulgare* L.) was cropped every year. Lateral strips were alternatively under fallow or cropped with barley each year.

Three tillage systems were compared in Soil A (subsoil tillage, minimum tillage and no-tillage), and two in Soil B (minimum tillage and no-tillage). Subsoil tillage (ST) consisted of a subsoiler worked at 40 cm depth in August and a field cultivator at 15 cm depth in October (a cultivator also in May in the fallow strip). Minimum tillage (MT) consisted of a field cultivator working to a depth of 15 cm before sowing (and in May on the fallow strip). No-tillage (NT) consisted of maintaining the soil free of weeds by total herbicide spraying (2 l of 36% glyphosate [N-(phosphonomethyl)glycine] ha^{-1}) in October. The dates on which tillage operations were performed are shown in Table 2. More details on crop operations can be found in Lampurlanés *et al.* (2000a and 2000b).

Rainfall and temperature were monitored at a weather station situated 250 m from the experimental field.

Table 2
Dates of tillage operations and measurements of Surface Covered by Residues (SCR), Surface Roughness (SR), and Hydraulic conductivity (K) in the Continuous Crop (CC), Crop After Fallow (CAF) and Fallow (F) strips of Soil A and Soil B, and days and accumulated rainfall from last tillage operation (in parenthesis when different for fallow plots).

Date	Tillage operation	Variable sampled	From last tillage	
			Days	Rainfall (mm)
Soil A				
01.09.94	Subsoiling of ST plots			
26.10.94	Cultivator in ST and MT plots			
01.11.94	Sowing			
07.02.95	Resowing			
29.03.95	Cultivator in ST and MT fallow plots			
02.05.95		SCR (F plots)	(34)	(23)
09.05.95		SR(F plots)	(41)	(28)
15.08.95	Subsoiling of ST plots			
15.09.95		SR (F plots)	30	39
16.10.95	Cultivator in ST and MT plots			
23.10.95	Sowing			
08.11.95		SR	23	5
09.11.95		SCR	24	6
13-23.11.95		K (F plots)	34	14
23.02.96		SCR	130	212
26.02.96		SR (F and CC plots)	133	212
4-28.03.96		K (F plots)	151	223
08.05.96	Cultivator in ST and MT fallow plots			
28.05.96		SCR (F plots)	(20)	(61)
07.06.96		SR (F plots)	(30)	(109)
24.07.96		SCR (F and CC plots)	282 (77)	473 (180)
23-31.7.96		K	283 (78)	473 (180)
10.09.96		SCR	330 (125)	576 (284)
16.09.96	Subsoiling of ST plots			
24.10.96	Cultivator in ST and MT plots			
25.10.96	Sowing			
04.11.96	Compactor roller in ST and MT plots			
3-7.11.96		K (F plots)	12	1
06.11.96		SCR	13	1
07.11.96		SR	14	1
28.02.97	Resowing continuous crop plots			
11.03.97		SR, SCR (F plots)	138	274
6-14.8.97		K	290	481
Soil B				
26.10.94	Cultivator in MT plots			
01.11.94	Sowing			
24.11.94	Resowing			
29.03.95	Cultivator in MT fallow plots			
02.05.95		SCR (F plots)	(34)	(23)
26.09.95		SR	338 (181)	263 (194)
06.10.95		SCR (F plots)	(191)	(195)
16.10.95	Cultivator and compactor roller in MT plots			
23.10.95	Sowing			
08.11.95		SR	23	5
09.11.95		SCR	24	6
12.02.96		SCR	119	212
22.02.96		SR (F and CC plots)	129	212
08.05.96	Cultivator in MT fallow plots			
28.05.96		SCR (F plots)	225 (20)	354 (61)
07.06.96		SR (F plots)	(30)	(109)
02.08.96		SCR	291 (86)	483 (190)
16.09.96	Cultivator in MT plots			
24.10.96	Cultivator in MT plots			
25.10.96	Sowing			
04.11.96	Compactor roller			
07.11.96		SCR	14	1
11.03.97		SR, SCR (F plots)	138	274

Unsaturated hydraulic conductivity was measured in Soil A at different times during the experiment, especially in the fallow strip (Table 2). We used a tension infiltrometer similar to that of Perroux and White (1988). The infiltration disk was 250 mm in diameter and the water reservoir 32 mm id. We adopted some of the modifications introduced by Ankeny (1992) to facilitate calibration in the lab and refilling in the field without removing the disk: a base valve and a tripod. Calibration was done in the laboratory following the indications of Ankeny (1992) and Reynolds (1993), to measure unsaturated hydraulic conductivity at seven different tensions: 0, 1, 3, 5, 10, 15 and 20 cm H_2O.

In the field, the first step was to locate a nearly flat place in the plot and then to remove straw and free stones to ensure good contact between the soil and the disk without modifying the soil surface. Then a retaining ring was inserted about 0.5 cm into the soil, and a nylon cloth and contact sand was placed inside and levelled (Ankeny, 1992; Reynolds, 1993). Following Reynolds (1993), measurements were made from the largest to the lowest tension (20 to 0 cm H_2O). No measurements were taken in Soil B because the greater stone content in the surface prevented us from installing the infiltrometer without significant soil surface disturbance.

The residue-covered surface was determined with the line-transect (Dickey *et al.*, 1986) or meterstick method (Morrison *et al.*, 1993). We extended a 10 m tape diagonally over each plot and checked every 0.1 m if that point touched a piece of residue. The percentage of residue cover was directly the number of times residues touched the points checked.

To measure surface roughness we used the chain method proposed by Saleh (1993). This method consists in measuring the horizontal distance between the tops of a roller chain laid out on the soil surface following the irregularities (roughness) of the soil. The roughness is calculated as (1-L1/L2)*100, where L1 is the horizontal distance and L2 is the actual length of the chain (we use a chain of 100 cm length). We measure the roughness parallel to the tillage direction to obtain the random roughness (Crr), and perpendicular to the tillage to obtain the perpendicular roughness (Cpr).

Soil water content was also available from simultaneous studies (Lampurlanés *et al.*, 2000a; Lampurlanés *et al.*, 2000b).

Statistical analyses were accomplished using SAS® software, grouping the plots by their condition: continuous crop, crop after fallow or fallow. Data were analysed as repeated measures over time (Steel and Torrie, 1980; Gómez and Gómez, 1984). Due to unequal cell size, this analysis was done as a split-split plot (Littell *et al.*, 1991) with tillage (TILL) as a main plot and sampling time (DATE) and tension (TENSION), in the case of hydraulic conductivity analysis, as successive sub-plots. Most of the variables had to be transformed to meet the assumptions of the ANOVA model. Mean separations were done for significant effects with the LSD test at $P = 0.05$ (Montgomery, 1991).

Results

1. Rainfall

Total rainfall was below the mean (441 mm) in 1994-95 (430 mm) and above it in 1995-96 (551 mm) and 1996-97 (603 mm). Rainfall distribution was different in 1994-95 from 1995-96 and 1996-97 (Table 3). In 1994-95, rainfall was higher between the primary and secondary tillage than between secondary and spring tillage. On the other hand, in 1995-96 and in 1996-97 the highest rainfall was found between the secondary and spring tillage. 1994-95 was characterised by high autumn rains and low winter precipitation (Fig. 1), and 1995-96 by the heavy winter and spring rains. 1996-97 was similar to 1995-96 but with lower precipitation.

Table 3
Accumulated rainfall (in mm) between tillage events.

Year	Primary-Secondary	Secondary-Spring tillage	Spring-Primary next year
1994-95	142	69	122
1995-96	74	294	193
1996-97	52	275	-

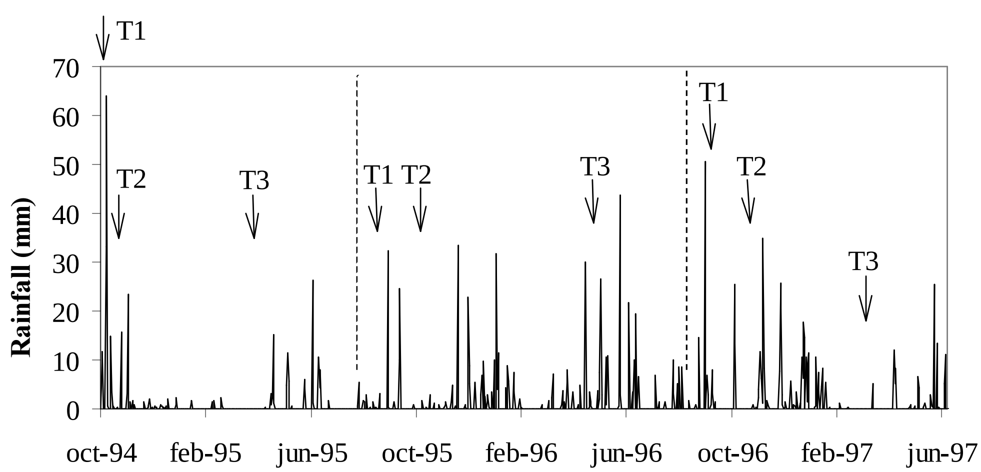

Fig. 1. Daily rainfall and tillage operations during the experiment. (T1: Subsoiling in subsoil tillage plots; T2: Cultivator in subsoil and minimum tillage plots; T3: Cultivation in subsoil and minimum tilled fallow plots).

2. Hydraulic conductivity (K)

Observed values of K ranged from 5 to 300 cm day^{-1} at 0 cm H_2O tension, and from 0.03 to 1 cm day^{-1} at 20 cm H_2O tension. In the ANOVA (Table 4) no effect of tillage as a main factor was observed. TILLxDATE interaction was significant in the CC strip ($P<0.05$), where differences between tillage systems varied with time. In July 1996 (Fig. 2), K was about 3 times smaller for NT than for ST or MT at all tensions, whereas in August 1997 no differences were found between tillage systems. Compared with July 1996, K decreased at 0 and 1 cm H_2O tensions for ST and MT, and increased at 3, 5, 10 and 20 cm H_2O tensions for NT. In the CAF strip, K was unaffected by the tillage system, but the decrease in K from July 1996 to August 1997 at 0 and 1 cm H_2O tensions was similar to the CC strip (significant DATExTENSION interaction for both strips with $P<0.0001$, Table 4). The general decrease in K found in 1996-97 was a consequence of the flood that occurred in January 1997 due to high winter rainfall.

In the F strip, the general pattern of K showed a significant decrease with time (Fig. 3). TILLxDATExTENSION interaction was significant in this strip ($P<0.003$, Table 4). For low tensions, from 0 to 5 cm H_2O (we show, as more representative, tensions 1 and 3 cm H_2O in Fig. 3), NT showed a lower K than ST or MT in 1995-96 and no significant differences in 1996-97. For tensions from 10 to 20 cm H_2O (see tension 10 in Fig. 3), no significant differences were found in 1995-96. In 1996-97, NT had a smaller K in November than ST or MT, though these differences disappeared in August.

No differences were found in mean K between strips in July 1996 or in August 1997. Higher K was measured in F strips, where additional measurements were made soon after tillage operations. Mean K was similar on CC and CAF strips for ST and MT (Table 4). For NT, mean K was 3 times lower on CC than on CAF strips.

Table 4
Hydraulic conductivity (K, cm day^{-1}) ANOVA and mean separation for the different crop sequences. Soil A.

Source of Variation	Continuous crop (CC)	Crop after fallow (CAF)	Fallow (F)
TILL	NS	NS	NS
DATE	NS	NS	0.0001
TILLxDATE	0.05	NS	NS
TENSION	0.0001	0.0001	0.0001
TILLxTENSION	NS	NS	NS
DATExTENSION	0.0001	0.0001	0.0001
TILLxDATExTENSION	NS	NS	0.003
Model Pr>F	0.0001	0.0001	0.0001
MSE	0.096	0.081	0.405
D.F.	54	53	186
R-square	0.98	0.99	0.98
C.V.	28.6	22.6	34.0
Transformation	$Log_{10}(K)$	$Log_{10}(K)$	$Log_{10}(K)$
TILL			
ST	15.5	13.7	21.8
MT	14.3	14.2	27.5
NT	5.0	14.7	11.5
$LSD_{0.05}$	15.4	5.8	11.1
DATE			
Nov 95	-	-	26.0 a
Mar 96	-	-	28.3 a
Jul 96	13.8	17.7	13.0 b
Nov 96	-	-	17.5 ab
Aug 97	6.1	5.8	5.7 b
$LSD_{0.05}$	4.8	4.5	11.8
TENSION			
0	37.4 a	46.5 a	73.9 a
1	21.2 b	25.7 b	40.5 b
3	3.6 c	3.5 c	6.4 c
5	1.7 c	1.6 c	2.0 c
10	0.6 c	0.7 c	0.7 c
15	0.4 c	-	0.4 c
20	0.3 c	0.3 c	0.3 c
$LSD_{0.05}$	14.1	7.7	8.7

TILL Tillage system: Subsoil Tillage (ST), Minimum Tillage (MT), and No-Tillage (NT)
DATE Date on which measurements were made.
TENSION Tension at which water was applied to soil in cm H_2O.
MSE Mean Square Error.
D.F. Degrees of Freedom.
C.V. Coefficient of Variation.
$LSD_{0.05}$ Least Significant Difference ($P<0.05$).

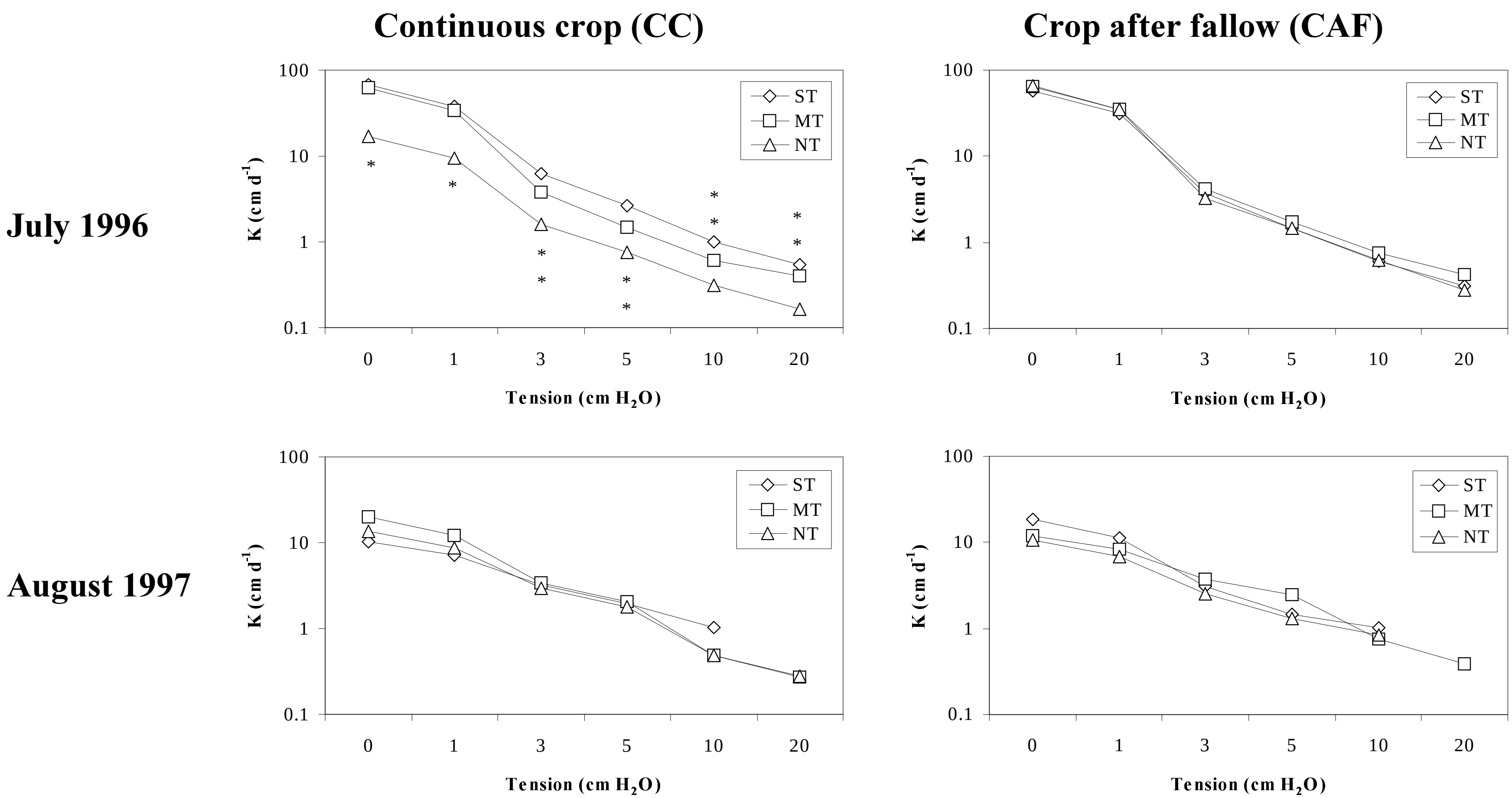

Fig. 2. Hydraulic conductivity (K) vs. water tension curves in 1996 and 1997 on continuous crop and crop after fallow strips under different tillage systems: Subsoil Tillage (ST), Minimum Tillage (MT) and No-Tillage (NT). Soil A. (Asterisks indicates significant differences: * $P<0.05$, ** $P<0.001$).

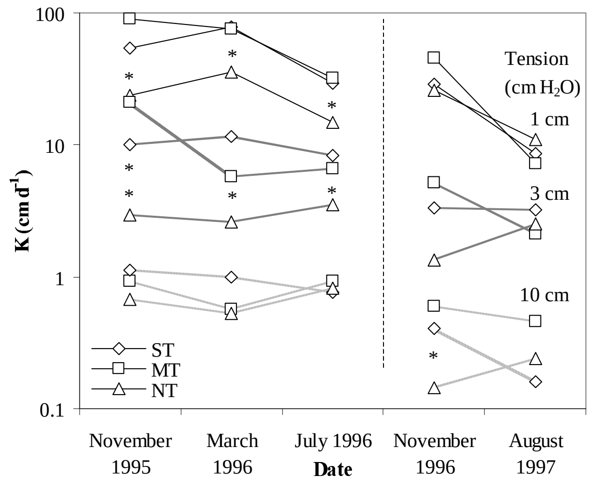

Fig. 3. Hydraulic conductivity (K) trends over time for three representative tensions on the fallow strip under different tillage systems: Subsoil Tillage (ST), Minimum Tillage (MT) and No-Tillage (NT). Soil A. (Asterisks indicate significant differences: * P<0.05, ** P<0.001).

3. Surface covered by residues (SCR)

The percentage of soil covered by residues (SCR) ranged from 0 to 97% in Soil A, and from 0 to 85% in Soil B. In Soil A both the TILL and TILLxDATE terms of ANOVA were highly significant (P<0.0001, Table 5). In Soil B, only the TILL term was significant because NT showed a larger SCR than ST or MT, especially in the F strip. SCR trends were similar in the CC and the CAF strip for the two soils, though at sowing SCR was below 10% for all tillage systems in the CAF strip. Fig. 4-A and 4-B present the results for the CC strip, in which more differences were found. After tillage operations (October 1995 and October 1996), SCR under ST or MT was lower than 10% in both soils. Under NT, SCR was significantly greater (P<0.01), up to 55% in Soil A (Fig. 4-A) and much lower (about 30%) in Soil B (Fig. 4-B). From October to February, SCR decreased mainly under NT. This decrease continued at a lower rate until the harvest. At harvest, SCR increased up to 90% in Soil A and 70% in Soil B. After harvest, SCR started to decrease at a similar rate in all tillage systems (Fig. 4-A) until October. In October, tillage operations reduced SCR in tilled plots in comparison with NT (by about 30% in Soil A and 20% in Soil B).

In the F strip, the differences between NT and ST or MT were greater than in the CC or CAF strips, and were maintained throughout the fallow period (Fig. 5-A and 5-B). SCR in ST and MT was around 10% for both soils throughout the fallow period. However, after tillage operations (October 1995), SCR was about 60% for NT on Soil A (Fig. 5-A), decreasing slowly to 30% in October 1996. In Soil B (Fig. 5-B), SCR was 40% for NT in November 1995, decreasing to 25% in February 1996. This level of residues was maintained until the end of the fallow period. Higher residue levels were reached in October-November 1996 than in 1995 under NT: 90% for Soil A and 60% for Soil B. In Soil B this level of residues was maintained until March 1997, but in Soil A it fell to 40% in the same period of time.

Table 5
Surface covered by residues (SCR,%) ANOVA and mean separation for the different crop sequences. Soils A and B.

Source of Variation		Continuous crop (CC)	Crop after fallow (CAF)	Fallow (F)
Soil A				
TILL		0.0001	0.0001	0.0001
DATE		0.0001	0.0001	0.0001
TILLxDATE		0.0001	0.0001	0.0016
Model Pr>F		0.0001	0.0001	0.0001
MSE		0.018	0.016	0.064
D.F.		36	18	54
R-square		0.98	0.99	0.87
C.V.		10.3	12.2	23.7
Transformation		Log_{10}(SCR+1)	Log_{10}(SCR+1)	Log_{10}(SCR+1)
TILL	ST	31.8 c	21.8 b	5.1 b
	MT	36.5 b	23.0 b	9.0 b
	NT	59.9 a	45.2 a	54.4 a
	$LSD_{0.05}$	4.5	5.0	9.7
DATE				
	May 95	-	-	21.8 bcd
	Nov 95	20.2 d	17.2 b	25.2 b
	Feb 96	5.8 e	-	24.0 bc
	May 96	-	-	17.0 d
	Jul 96	82.6 a	-	-
	Sep 96	75.6 b	66.5 a	18.4 cd
	Nov 96	29.4 c	6.3 c	36.0 a
	Mar 97	-	-	17.5 d
	$LSD_{0.05}$	5.9	5.8	5.2
Soil B				
TILL		0.08	0.09	0.006
DATE		0.0001	0.0001	0.0001
TILLxDATE		NS	NS	NS
Model Pr>F		0.0006	0.0001	0.0001
MSE		0.088	0.069	0.068
D.F.		18	18	42
R-square		0.80	0.93	0.78
C.V.		23.2	33.1	20.0
Transformation		$(SCR+1)^{0.3}$	$(SCR+1)^{0.3}$	$(SCR+1)^{0.3}$
TILL	MT	23.4 b	20.9	15.8 b
	NT	36.5 a	23.1	44.1 a
	$LSD_{0.05}$	10.6	5.0	10.1
DATE				
	May 95	-	-	49.2 a
	Nov 95	-	-	48.1 ab
	Feb 96	19.9 b	0.9 b	25.2 de
	May 96	11.9 b	3.8 b	16.2 ef
	Jul 96	-	-	13.4 f
	Sep 96	66.2 a	77.6 a	15.8 ef
	Nov 96	21.8 b	5.6 b	34.2 cd
	Mar 97	-	-	37.0 bc
	$LSD_{0.05}$	11.7	6.3	9.6

TILL Tillage system: Subsoil Tillage (ST), Minimum Tillage (MT), and No-Tillage (NT)
DATE Date on which measurements were made.
MSE Mean Square Error.
D.F. Degrees of Freedom.
C.V. Coefficient of Variation.
$LSD_{0.05}$ Least Significant Difference (P<0.05).

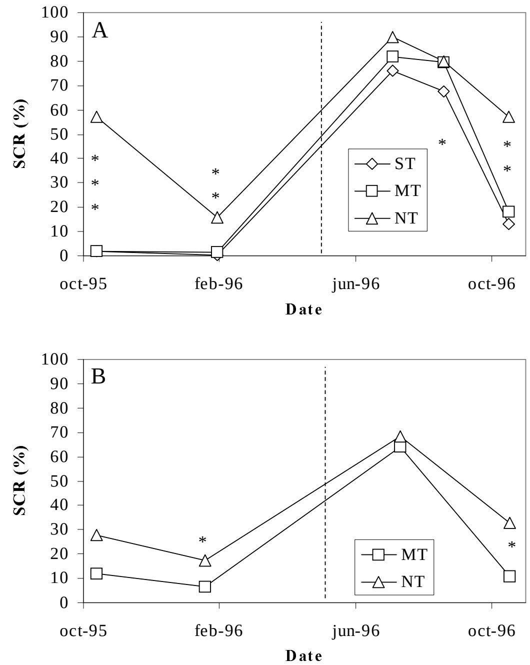

Fig. 4. Surface covered by residues (SCR) trends in the continuous crop strip under different tillage systems: Subsoil Tillage (ST), Minimum Tillage (MT) and No-Tillage (NT). Soils A (A) and Soil B (B). (Asterisks indicate significant differences: * P<0.05, ** P<0.001, *** P<0.0001).

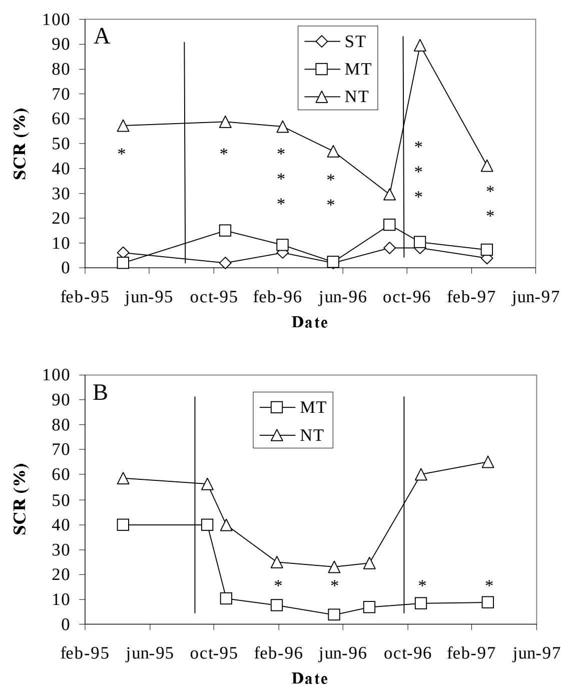

Fig. 5. Surface covered by residues (SCR) trends in the fallow strip under different tillage systems: Subsoil Tillage (ST), Minimum Tillage (MT) and No-Tillage (NT). Soils A (A) and Soil B (B). (Asterisks indicate significant differences: * P<0.05, ** P<0.001, *** P<0.0001).

4. Surface roughness

Random roughness (Crr) ranged from 0.1 to 25 in Soil A, and from 1 to 14 in Soil B. Perpendicular roughness (Cpr) ranged from 0.5 to 27 in Soil A, and from 1 to 20 in Soil B. In general then, the values of Cpr were greater than those of Crr. Lower and more homogeneous values were obtained in Soil B than in Soil A.

TILL factor had a significant effect on Crr and Cpr for both CC and F strips on Soil A (Table 6) and F strip on Soil B (Table 7). In general NT showed less roughness than ST or MT; the differences depended on DATE, as indicated by the significant TILLxDATE interaction (Table 6 and Table 7).

Greater surface roughness was found in the CAF and F strips than in the CC strip. However, temporal trends were similar in the three strips. Fig. 6 shows the results of the fallow strip in which most samples were taken. NT plots maintained Crr and Cpr values around 3 to 4, whereas ST and MT plots underwent great variations with time. Greater differences were detected with Cpr than with Crr, though temporal trends were similar.

In Soil A, the greatest roughness was observed under ST and MT during the first fallow period, in May 1995 (about 13, Fig. 6-A and 6-B), 41 days and 28 mm of rain after the last tillage operation. In September 1995 (second fallow period, Fig. 6-A), Crr was similar for ST and MT but Cpr was greater for ST owing to a recent subsoiling operation (30 days before), which affected more perpendicular than random roughness. After a cultivator pass in October 1995, Crr and Cpr were similar for ST and MT, though Cpr was about 3 points greater than Crr. In February 1996, after 110 days and 207 mm of rain, Crr decreased to 4 for ST and MT. The Cpr reduction was greater for MT (6 points) than for ST (4 points). Due to a cultivator pass in May 1996, roughness under ST and MT increased to 6 for Crr and to 10 for Cpr. In the third fallow period the pass of the compactor roller in ST and MT plots reduced its roughness to levels similar to those of the NT plots (3 to 4). In these conditions, 276 days and 206 mm of rainfall produced a small decrease in surface roughness of only 1 point.

In Soil B, Crr and Cpr trends were similar to those of Soil A (Fig. 6-C and 6-D), with increases after tillage operations of about 2 points in autumn Crr, and up to 5 in spring Cpr. In the third fallow period, no differences were found between tillage systems because the compactor roller was passed after sowing.

Table 6
Random roughness (Crr) and perpendicular roughness (Cpr) ANOVA and mean separation for the different crop sequences. Soil A.

Source of Variation		Continuous crop (CC)	Crop after fallow (CAF)	Fallow (F)
Random roughness (Crr)				
TILL		0.001	NS	0.0009
DATE		0.0001	0.0001	0.0001
TILLxDATE		0.01	0.0022	0.0001
Model Pr>F		0.0001	0.0001	0.0001
MSE		0.026	0.03	0.038
D.F.		78	57	234
R-square		0.58	0.79	0.69
C.V.		30.3	23.4	31.4
Transformation		Log_{10}(Crr)	Log_{10}(Crr)	Log_{10}(Crr)
TILL	ST	5.2 a	8.8	6.9 a
	MT	4.0 b	7.7	6.4 b
	NT	2.7 c	4.2	2.8 c
	$LSD_{0.05}$	0.7	3.7	0.4
DATE				
	May 95	-	-	9.0 a
	Sep 95	-	-	5.7 bc
	Nov 95	4.8 a	9.0 a	6.5 b
	Feb 96	3.2 b	-	3.6 d
	Jun 96	-	-	4.8 c
	Nov 96	3.1 b	2.8 b	3.0 d
	Mar 97	-	-	1.9 e
	$LSD_{0.05}$	1.0	1.5	1.1
Perpendicular roughness (Cpr)				
TILL		0.044	NS	0.0004
DATE		0.0001	0.0001	0.0001
TILLxDATE		0.06	0.0003	0.0001
Model Pr>F		0.0001	0.0001	0.0001
MSE		0.024	0.04	0.03
D.F.		78	57	234
R-square		0.67	0.75	0.81
C.V.		23.1	23.0	25.2
Transformation		Log_{10}(Cpr)	Log_{10}(Cpr)	Log_{10}(Cpr)
TILL	ST	6.3 a	11.4	9.2 a
	MT	5.9 a	10.2	8.5 a
	NT	4.3 b	5.8	2.6 b
	$LSD_{0.05}$	1.3	3.9	1.1
DATE				
	May 95	-	-	9.7 a
	Sep 95	-	-	8.0 bc
	Nov 95	7.6 a	12.0 a	8.7 ab
	Feb 96	3.4 b	-	4.6 d
	Jun 96	-	-	7.4 c
	Nov 96	3.3 b	3.4 b	3.2 e
	Mar 97	-	-	2.0 f
	$LSD_{0.05}$	1.1	1.7	1.1

TILL Tillage system: Subsoil Tillage (ST), Minimum Tillage (MT), and No-Tillage (NT)
DATE Date on which measurements were made.
MSE Mean Square Error.
D.F. Degrees of Freedom.
C.V. Coefficient of Variation.
$LSD_{0.05}$ Least Significant Difference (P<0.05).

Table 7
Random roughness (Crr) and perpendicular roughness (Cpr) ANOVA and mean separation for the different crop sequences. Soil B.

Source of Variation	Continuous crop (CC)	Crop after fallow (CAF)	Fallow (F)
Random roughness (Crr)			
TILL	NS	NS	0.008
DATE	0.0001	NS	0.003
TILLxDATE	0.075	0.0055	0.003
Model Pr>F	0.0001	0.005	0.0001
MSE	0.01	0.011	0.01
D.F.	84	54	111
R-square	0.47	0.34	0.37
C.V.	7.7	8.3	8.0
Transformation	Log_{10}(Crr)	Log_{10}(Cpr)	Log_{10}(Crr)
TILL			
MT	5.1	5.1	6.3 a
NT	5.0	3.6	3.8 b
$LSD_{0.05}$	2.8	2.1	0.9
DATE			
Sep 95	3.1 b	4.3	4.9 a
Nov 95	5.6 a	4.4	5.6 a
Feb 96	6.4 a	-	5.4 a
Jun 96	-	-	5.6 a
Mar 97	-	-	3.0 b
$LSD_{0.05}$	1.1	1.2	1.4
Perpendicular roughness (Cpr)			
TILL	NS	0.065	0.012
DATE	0.0001	0.0001	0.0001
TILLxDATE	0.0001	0.0001	0.0001
Model Pr>F	0.0001	0.0001	0.0001
MSE	0.026	0.015	0.035
D.F.	84	54	111
R-square	0.60	0.71	0.63
C.V.	20.7	15.1	25.5
Transformation	Log_{10}(Cpr)	Log_{10}(Cpr)	Log_{10}(Cpr)
TILL			
MT	7.0	8.4	9.4 a
NT	6.8	5.6	4.1 b
$LSD_{0.05}$	2.2	3.8	2.8
DATE			
Sep 95	4.7 b	6.2 b	7.3 b
Nov 95	8.3 a	7.8 a	7.3 ab
Feb 96	7.7 a	-	5.8 b
Jun 96	-	-	8.9 a
Mar 97	-	-	3.9 c
$LSD_{0.05}$	1.3	1.0	1.6

TILL Tillage system: Subsoil Tillage (ST), Minimum Tillage (MT), and No-Tillage (NT)
DATE Date on which measurements were made.
MSE Mean Square Error.
D.F. Degrees of Freedom.
C.V. Coefficient of Variation.
$LSD_{0.05}$ Least Significant Difference ($P<0.05$).

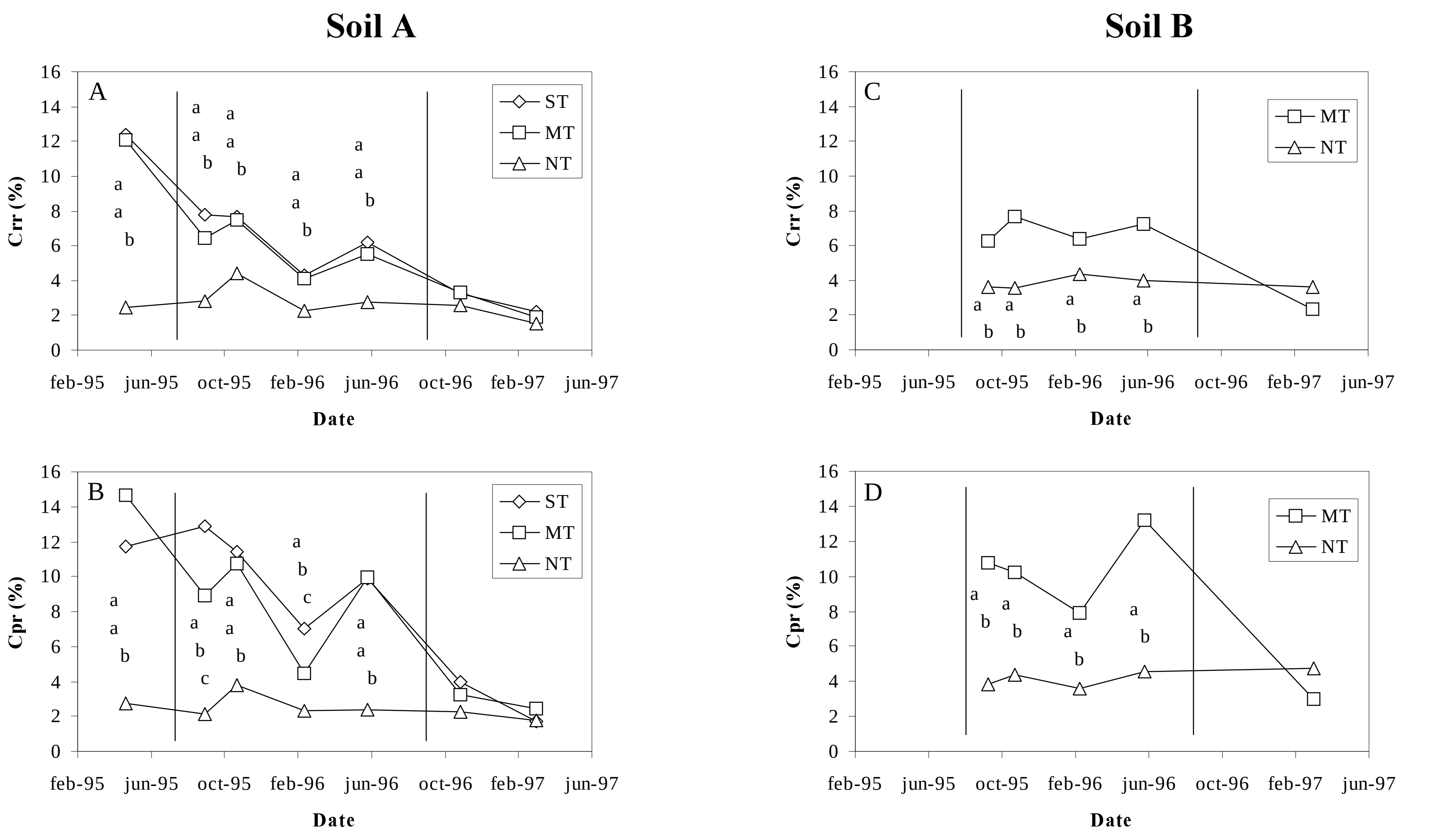

Fig. 6. Random roughness (Crr) and perpendicular roughness (Cpr) coefficient trends during three fallow periods (separated by vertical lines) under different tillage systems: Subsoil Tillage (ST), Minimum Tillage (MT) and No-Tillage (NT). Soil A and Soil B. (Different letters indicate significant differences between means).

Discussion

1. Hydraulic conductivity

Worse conditions for water movement were found under no-till, as indicated by the hydraulic conductivity differences encountered in the CC strip (July 1996, Fig. 2), far from tillage operations. This is an effect of the increase in bulk density (decrease in soil porosity) observed in this soil (Lampurlanés and Cantero-Martínez, 2000), which usually occurs in the first years after introduction of no-tillage (Kinsella, 1995). It seems that, as Linsdrom stated in 1981 (cited by Logsdon *et al.*, 1993), the consolidation of the soil surface during the first year of no-till, produced by raindrop impact before residue cover was established, was not reduced by the ameliorating factors (freeze-thaw, wetting-drying, fauna activity) in subsequent years.

The top layer of litter and organic matter that generally develops under NT, which is decisive for maintaining high infiltration rates (Golabi *et al.*, 1995), was not observed in NT, probably because cut straw was baled and removed every year. It is likely that more years and greater quantities of residues left over the soil are needed to appreciate changes under NT (López and Arrúe, 1997).

Similar soil surface conditions developed under ST and MT after the cultivator pass. For this reason, no significant differences in K were found between ST or MT in either the CC, CAF or F strips. Perhaps if K measurements had been made deeper in the soil profile some differences would have been found, though Messing and Jarvis (1993) found no differences between ploughed and unploughed soil from 15 to 25 cm depth.

Fallow was not as effective in increasing K as it was in reducing soil strength (Lampurlanés and Cantero-Martínez, 2000), because no differences in K were observed between the CC and CAF strips in August 1997 (Fig. 2). However, it seems that fallow favoured the amelioration process on NT because in July 1996 a greater K was observed for NT in the CAF strip than in the CC strip (Fig. 2).

Differences in soil porosity can explain the differences in K found between tillage systems and between sampling times. These differences were more evident at tensions lower than 5 cm H_2O (pores greater than 0.6 mm), which indicates that tillage operations and settling processes affected mainly macropores.

2. Residue cover

As expected, tillage (both ST and MT) reduced SCR drastically to levels below 10%. Regarding residues left, both tillage systems had the same effect as a mouldboard plough (Gilley, 1995) working at more than 20 cm (Kok and Thien, 1994), or as a chisel + disk twice (Griffith *et al.*, 1986, cited by Blevins and Frye, 1993).

On the other hand, in general NT maintained a greater SCR than ST or MT. In the CC plots of Soil A, SCR at sowing (about 60%, Fig. 4-A) was quite far from the 30% limit considered for conservation tillage. In Soil B, only 30% of SCR was obtained at sowing because straw production was lower than in Soil A, according to grain yield (Lampurlanés *et al.* 2000a). In years of lower than mean rainfall, SCR will probably be below 30% at sowing in this soil.

In CAF plots, SCR at sowing was below 10% in Soil A, and near to 0% in Soil B (data not shown). Residue breakdown due to biological and physical factors during the long fallow period reduced the SCR progressively (Fig. 5-A and 5-B), leading to these low values at sowing.

In these two situations, when fallow is used or in the shallow, less productive Soil B, more straw should be left over the soil after harvest if one wishes to meet the condition of 30% residue cover at sowing.

3. Surface roughness

Tillage was very effective in increasing surface roughness, and rainfall and compactor roller in reducing it. Surface roughness was greater on ST than on MT (before the cultivator pass) because ST produced greater clods than MT.

In ST or MT fallows, where residues are not left on the soil, surface roughness produced by tillage may play an important role in maintaining infiltrability by increasing surface storage capacity. Therefore, the use of the compactor roller, which drastically reduces surface roughness, may have deleterious effects on infiltration.

The chain method proved to be a fast, easy-to-use and reliable method for measuring roughness in tillage studies. Both the Crr and Cpr soil roughness parameters were very sensitive to tillage operations and soil settling by rainfall. Cpr was the most sensitive of the two.

4. Effect on soil water

In general, greater water content was found under NT than under ST or MT in continuous crop (Lampurlanés *et al.*, 2000a). During fallow, water storage was greater under NT in the July to February period, and greater under ST or MT in the February to October period, resulting in a similar water accumulation in the complete fallow period (Lampurlanés *et al.* 2000b). As a consequence, no differences between tillage systems in soil water were found in the following crop.

Surface covered by residues is the only factor that could explain the greater soil water content that is sometimes found under NT in comparison with ST or MT, since K was equal or lower, and surface roughness lower on NT than on ST or MT. It therefore seems very important to not remove residues after harvest if NT is used, in order to favour their beneficial effect on water storage. This increase in residue cover will also accelerate the formation of a surface layer of litter and organic matter that will further improve infiltration (Golabi *et al.* 1995).

The cultivator pass performed during fallow in spring on the ST and MT plots improved water storage in different ways. Firstly, it reduced evaporation by eliminating weeds and creating a soil mulch. Secondly, it increased infiltration due to the loosening action of tillage and also increased soil surface roughness. This spring tillage may also be a way to improve soil water storage when the surface covered by residues falls below 30% in non-tilled fallows.

The effect of residue on infiltration was not measured directly in this study because a tension infiltrometer was used. If a rainfall simulator had been used, greater infiltration rates would probably have been found on NT, because residues play a role similar to that of surface roughness: increasing the time for infiltration to take place.

Conclusions

After the introduction of no-tillage there is a decrease in hydraulic conductivity due to the reduction in soil porosity. This negative effect of no-tillage on infiltration is counteracted by the presence of residues over the soil surface, resulting in greater water storage. It also seems that fallow accelerates the amelioration process in non-tilled soils.

If cut straw is removed after harvest, residue cover during fallow on no-tillage plots falls to levels below 30% at sowing of the following crop. Thus, when no-tilled fallow is used, more straw should be left on the soil to obtain at least 30% of soil surface covered by residues at sowing. If this is not possible, some kind of surface tillage that creates a soil mulch and increases surface roughness may help to increase infiltration and reduce evaporation.

Similar soil surface conditions developed under subsoil and minimum tillage because in both tillage systems secondary tillage consisted in a pass of the cultivator. As a result, water storage was similar with both tillage systems.

If minimum tillage is used, a reduction to only one pass of cultivator will produce greater surface roughness and more residues will remain on the surface, resulting in better conditions for water storage.

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