Tillage effect on water storage efficiency during fallow, and soil water content, root growth and yield of the following barley crop on two different soils in semiarid conditions

Abstract

In semi-arid areas under rainfed agriculture water is the most limiting factor of crop production. Fallow was a traditional system used in these areas to capture out-of-season rainfall to supplement that of the growing period. To investigate the best way to perform fallow and its possible effect on soil water content and root growth in the crop following fallow, an experiment was conducted on two soils in La Segarra, a semi-arid area in the Ebro valley (Spain). Soil A was a Fluventic Xerochrept of 120 cm depth and Soil B was a Lithic Xeric Torriorthent of 30 cm depth. The experiment was repeated for four fallow-crop cycles in Soil A and two in Soil B. In Soil A three tillage systems were compared: Subsoil Tillage (ST), Minimum Tillage (MT) and No-Tillage (NT). In Soil B only Minimum Tillage and No-Tillage were compared. In the crop fields, Root Length Density (LV), Volumetric Water Content (VWC) and Dry Matter (DM) were measured at important developmental stages of the crop and Yield was determined at harvest. In the fallow fields only Volumetric Water Content was measured at the same time as in cultivated plots. Evaporation (EV), Water Storage (WS) and Water Storage Efficiency (WSE) were calculated from a simplified balance between VWC and rainfall. Values of WSE were in the range of 10 to 18% in the 1992-93, 1993-94 and 1994-95 fallows in Soil A, but fell to 3% in 1995-96. NT showed significantly greater WSE than ST or MT in the June to February period of the 1992-93 and 1993-94 fallows, but significantly lower WSE in the February to October period due to greater evaporation. Consequently, no differences in total WSE were found between tillage systems. In Soil B, WSE was low, about 3-7%, and there were no differences between tillage systems. Only in a few years was VWC at sowing greater after fallow than in continuous crop. During the crop, the differences in VWC, LV and DM between tillage systems were small. Regarding yields, the best tillage system depended on the year. NT is potentially the best system for executing fallow, but residues of the preceding crop must be left spread over the soil. Furthermore, if residue mulch at the end of the spring is insufficient to prevent summer evaporation, a soil mulch should be performed with a shallow pass with the cultivator. The yield increase observed in some years after fallow compared with continuous crop does not compensate for the year without crop.

Keywords: Root length density, soil water, conservation tillage, fallow, barley, semi-arid.

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Introduction

In the semi-arid area of the Ebro Valley (Spain) available water is the most limiting factor of crop production for rainfed agriculture. Traditionally, farmers in the area used fallow to capture out-of-season rainfall to supplement that of the growing season. Recently, interest in fallow has increased because the European Union Agricultural Policy forces a percentage of land to be set-aside in order to receive the subsidy for the cropped land.

Fallow consists in maintaining land free of plant growth prior to sowing a crop, eliminating weeds by tillage (tilled fallow) or by herbicides (chemical fallow) (McDonald and Fischer, 1987). The main aim of this practice is to conserve water to reduce inter-annual variability in grain yield and to increase yield (McDonald and Fischer, 1987; Connor and Loomis, 1991). The effectiveness of fallow for moisture conservation depends on soil type, tillage practices (McDonald and Fischer, 1987), rainfall probability and soil water-storage capacity (French, 1978a; French, 1978b; Connor and Loomis, 1991). For these reason there is a controversy over its value in water conservation in semi-arid regions (McDonald and Fischer, 1987; Godwin, 1990). Thus, while Schultz (1972) and Tennant (1980) found major benefits of fallow in soil water storage at sowing and yield, Kohn *et al.* (1966) indicate that "fallowing in the year before cropping is of little importance for moisture conservation". Also, Papastylianou and Jones (1988) stated that "fallowing improves water availability to a crop only when a relatively dry year follows a relatively wet year" and that "the probability of such a benefit tends to decrease as the climate becomes drier". We can therefore say that fallow efficiency is in general low and variable from year to year (Connor and Loomis, 1991).

In our area, fallow starts in June after the harvest of the preceding crop, and finishes the following year in October, at sowing, about 16 months later. During fallow the soil is maintained free of weeds by harrowing two to four times. Some farmers use subsoilers in August to increase infiltration. Preliminary studies showed significant water accumulation during fallow compared with continuous crop (Cantero-Martínez and Vilardosa, 1996). However, working in a similar area of the Ebro Valley, López and Arrúe (1997) concluded that fallow was an inefficient practice for improving soil water storage and subsequent yield. Using a simulation model, López and Giráldez (1996) also concluded that the low efficiency of fallow does not compensate for a year without crop.

A way to improve storage efficiency of fallow is to retain residues (Schultz, 1972) and to optimise the tillage system (McDonald and Fischer, 1987) in order to improve infiltration and reduce evaporation. Chemical fallows seem to be more efficient for water conservation than cultivated ones (Connor and Loomis, 1991), resulting in greater and more stable yields (Lawrence *et al.*, 1994; Cantero-Martínez *et al.*, 1999). In some experiments, however, negative results have been reported in no-till fallows (Cooke *et al.*, 1985; Samios and Photiades, 1985). On the other hand, no water conservation benefit is obtained with deep tillage unless there is a layer of soil that prevents infiltration (McDonald and Fischer, 1987).

Fallow and tillage affect soil conditions and the root growth environment. Roots acts as a bridge between the impacts of agricultural practices on soil and changes in shoot function and harvested yield (Klepper, 1990). A good tillage system must not only increase the water available to the crop but also allow the root system to grow in zones of the soil profile from which water can be lost by evaporation (shallow layers) or where is stored during the recharge period (deep layers) (Taylor, 1983). Thus, Amir *et al.* (1991) attributed the yield increase after fallow to an increase in the transpiration/evaporation ratio due to a significant increase in root length density.

In this work we try to evaluate the water storage efficiency of different tillage systems during fallow, to investigate its effect on soil water content and root growth in the crop after fallow, and to determine the best way to perform fallow in the set-aside fields forced by the European Union Agricultural Policy.

Materials and methods

The experimental fields used for this study were located in El Canos, a representative location in the semiarid areas of the north-east Ebro Valley, Spain. The mean annual precipitation at the site is 440 mm but there is great variability between and within years. The experimental plots were established on two soils of contrasting depth that are representative of the soils in the area. The deep soil (Soil A) was a loamy fine, 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 two soils showed a high stone content, mainly at the surface (≈15%).

The experiment was designed as a randomised complete block with four replications. The plots were 10 by 6 m in area. To obtain data every year, the experimental design was repeated in two contiguous strips, always over the same plots. In one strip the plots were in fallow and in the other the plots were cultivated. Each year the roles were exchanged. The experiment was repeated for four fallow-crop cycles in Soil A and two in Soil B, always over the same plots. The differential treatment was tillage with three levels for Soil A (Subsoil Tillage, Minimum Tillage and No-Tillage) and two levels for Soil B (Minimum Tillage and No-Tillage). Subsoil Tillage (ST) consisted of a subsoiler tilling at 40 cm depth in August, a field cultivator at 15 cm depth in October, a subsoiler again the following August and a cultivator in October before sowing. Minimum Tillage (MT) consisted of a field cultivator working to a depth of 15 cm three times during fallow: in October, May and again in October before sowing. No-Tillage (NT) consisting of maintaining the soil free of weeds by total herbicide spraying (2 l of 36% glyphosate [N-(phosphonomethyl)glycine] ha^{-1}), in October and again in October before direct-drill sowing.

Before sowing, fertiliser was broadcast at a rate of 50 kg of P (18% superphosphate) ha^{-1} and 50 kg of K (60% potassium chloride) ha^{-1}. Nitrogen fertilisation was performed in February at a rate of 50 kg of N (33.5% ammonium nitrate) ha^{-1}.

In Soil A, barley (*Hordeum vulgare* L., cv. Dobla) was sown in late October or early November in 1993, 1995 and 1996. In 1994 the very high rainfall of September and October waterlogged the experimental field, so sowing was delayed until the beginning of February and another barley cultivar, cv. Garbo, was used. In Soil B, cv. Dobla was sown in late October or early November in 1995 and 1996. For 1993 a no-till disc drill was used but with poor sowing depth uniformity due to surface stones. Therefore, for 1994, 1995 and 1996 a no-till tine drill was used to improve sowing. The sowing rate was 160 kg ha^{-1} (≈450 seeds m^{-2}) in rows spaced 17 cm apart.

After emergence, herbicide was applied as 25 g of 75% tribenuron-methyl [Methyl 2-1 ((((n-3-(4-methoxi-6-methyl-1,3,5-triazin-2-il)methylamino)carbonyl)amino)sulfonyl) benzoate] ha^{-1} to control broadleaf weeds and 2.5 l 50% chlortoluron [N-(3-chloro-4-methylphenyl)-N-N-dimethylurea] ha^{-1} to control *Lolium rigidum* L. In some years, an application of 2.5 l 30% imazametabenz-methyl [2-(4,5-dihydro-4-methyl-4-(1-methylethyl)-5-oxo-1H-imidazol-2-yl)-4(and 5)-methylbenzoic acid (3:2)] ha^{-1} was necessary to control *Avena sterilis* L. in Soil A, and an application of 2% lindane [Gamma 1,2,3,4,5,6-hexaclorociclohexane] to control *Zabrus tenebrioides* L. in Soil B. The harvest was performed with a microcombine. After the harvest, cut straw was removed from all plots.

During the experiment, rainfall and temperature were monitored from a weather station situated 250 m from the experimental field.

In the cultivated strip, root length density and water content profiles were obtained by taking soil cores between rows with Edelman or Riverside augers (EIJKELKAMP®) at major developmental stages of the barley: tillering, stem elongation, anthesis, maturity and harvest. Additional samples were taken at sowing and in winter to determine soil water content. In the fallow strip only volumetric water content (VWC) was determined at the same time as in the cultivated strip. In each plot of Soil A, soil cores were taken from 0-25, 25-50, 50-75 and 75-100 cm depth. In Soil B, the cores sampled the profile from 0 to 10 and 10 to 30 cm depth. Roots in each core were washed out by elutriation (Pearcy *et al.*, 1989) and stained following the procedure of Ward *et al.* (1978), and their length was determined by the line intersection method (Newman, 1966). Soil volumetric water content was obtained by the gravimetric method (Campbell and Mulla, 1990).

Evaporation (EV) during the entire fallow or in subperiods was calculated as $VWC_1+R-VWC_2$, where VWC_1 and VWC_2 are the Volumetric Water Content at the beginning and the end of the fallow or subperiod, and R is the rainfall. Water Storage (WS) was calculated as VWC_2-VWC_1. Water Storage Efficiency (WSE) was calculated as WS/R*100.

In the cultivated strip, above ground biomass was measured by removing plants from two randomly selected half-meter long sections of each plot at various stages of development and determining total dry weight. The development stage was determined with the BBCH scale (Lancashire *et al.*, 1991). Grain yield was obtained by harvesting the entire plot, and corrected to 10% water content to allow comparisons. Water use was calculated as rainfall plus the difference in water content between maturity and sowing.

Statistical analyses were accomplished using SAS® software, pooling the data of all plots in the same situation (cultivated or fallow) irrespective of the strip. When necessary, original data were transformed to meet the assumptions of the ANOVA model. Data were analysed as repeated measures over time and space (Steel and Torrie, 1980; Gómez and Gómez, 1984). Due to unequal cell size, this analysis was done as a split-split-split plot (Littell *et al.*, 1991) with year (YEAR) as a main plot and tillage (TILL), stage of development (BBCH) and depth (DEPTH) as successive sub-plots. Means separation was performed for the significant main effects and interactions with the LSD test at P = 0.05 (Montgomery, 1991).

Results

1. Rainfall

Accumulated rainfall during fallow and the following crop is shown in Table 1. The first two fallow-crop cycles showed lower-than-average accumulated fallow-crop precipitation: 783 mm in 1993-94 and 818 mm in 1994-95, with low precipitation during the growing season, 135 and 114 mm respectively. In the last ones, precipitation was greater than average, 980 mm in 1995-96 and 1154 mm in 1996-97, with greater precipitation during the season, 458 and 465 mm respectively. Rainfall distribution was also different in these two groups of years. In the first group (Fig. 1-A), rainfall showed the typical two maximums (in autumn and in spring) of the Mediterranean climates in the western area of the Mediterranean basin, with little rainfall during winter and summer. In the second group (Fig. 1-B), autumn precipitation continued during the winter months, and June rainfalls were extremely high, breaking the standard rainfall distribution.

Table 1
Precipitation during the fallow and next crop, and difference from the 1951-81 average.

Fallow-crop cycle	Precipitation (mm)			Deviation from mean (mm)
	Fallow	Crop	Total	
1992-94	648	135	783	-99
1993-95	704	114	818	-64
1994-96	522	458	980	98
1995-97	688	465	1154	272
1951-81 average	592	290	882	

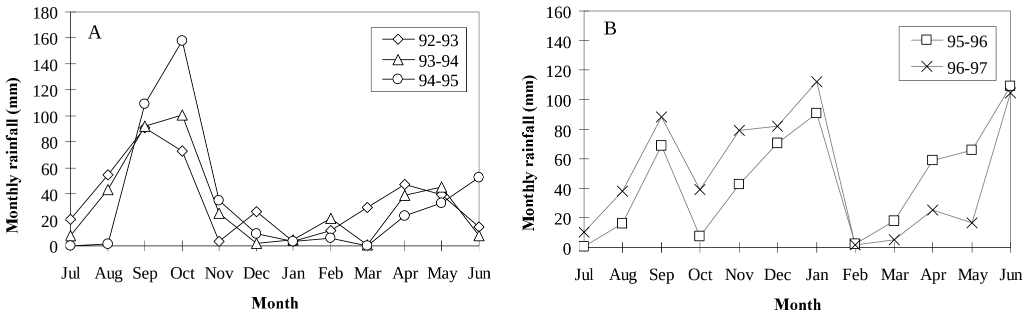

Fig. 1. Monthly rainfall distribution for each season.

2. Soil A

2.1. Fallow period

The VWC trends for each fallow-crop cycle are shown in Fig. 2. In 1992-93 and 1993-94 fallows (Fig. 2-A & 2-B), NT showed greater VWC. In 1992-93 (Fig. 2-A), the great differences observed between tillage systems during the winter fell during the spring and summer, and were insignificant at sowing. In 1993-94 (Fig. 2-B), NT showed greater VWC during practically the entire fallow, but high rainfall in October 1994 and the delay in sowing caused this difference to disappear. During 1994-95 (Fig. 2-C), NT showed a slightly greater VWC at sowing. In 1995-96 (Fig. 2-D), the differences between tillage systems in VWC were negligible.

Table 2 shows the ANOVA and mean separation for Evaporation (EV), Water Storage (WS) and Water Storage Efficiency (WSE) in different periods during fallow: June to February, February to October and the total from June to October. In general, EV was lower in the June to February period, with values ranging from 156 to 274 mm, and greater in the February to October period (263 to 468 mm). WS and WSE followed the same pattern: greater values in the June to February period (27 to 167 mm for WS and 8.8 to 51.7% for WSE), and lower values (even negative) in the February to October period (-82 to 45 mm for WS and -70.4 to 13.2% for WSE). As a rule, the first fallow period (June to February) was a recharge period because storage prevailed over evaporation, mainly during the rainy months (September and October). The second fallow period (February to October) was an evaporation period because evaporation prevailed in the summer months. Total values for the entire fallow period ranged from 429 to 682 mm for EV, 4 to 96 mm for WS, and 0.9 to 18.3% for WSE.

The differences between tillage systems were statistically significant in the first two fallows, 1992-93 and 1993-94 (Table 2). NT showed lower EV, greater WS and then greater WSE during the June to February period. On the other hand, during the February to October period, NT showed greater EV and lower WS and WSE. Therefore, considering the total fallow (June to October), no significant differences were found between tillage systems in EV, WS and WSE because the advantage of NT during the first period was lost during the second one.

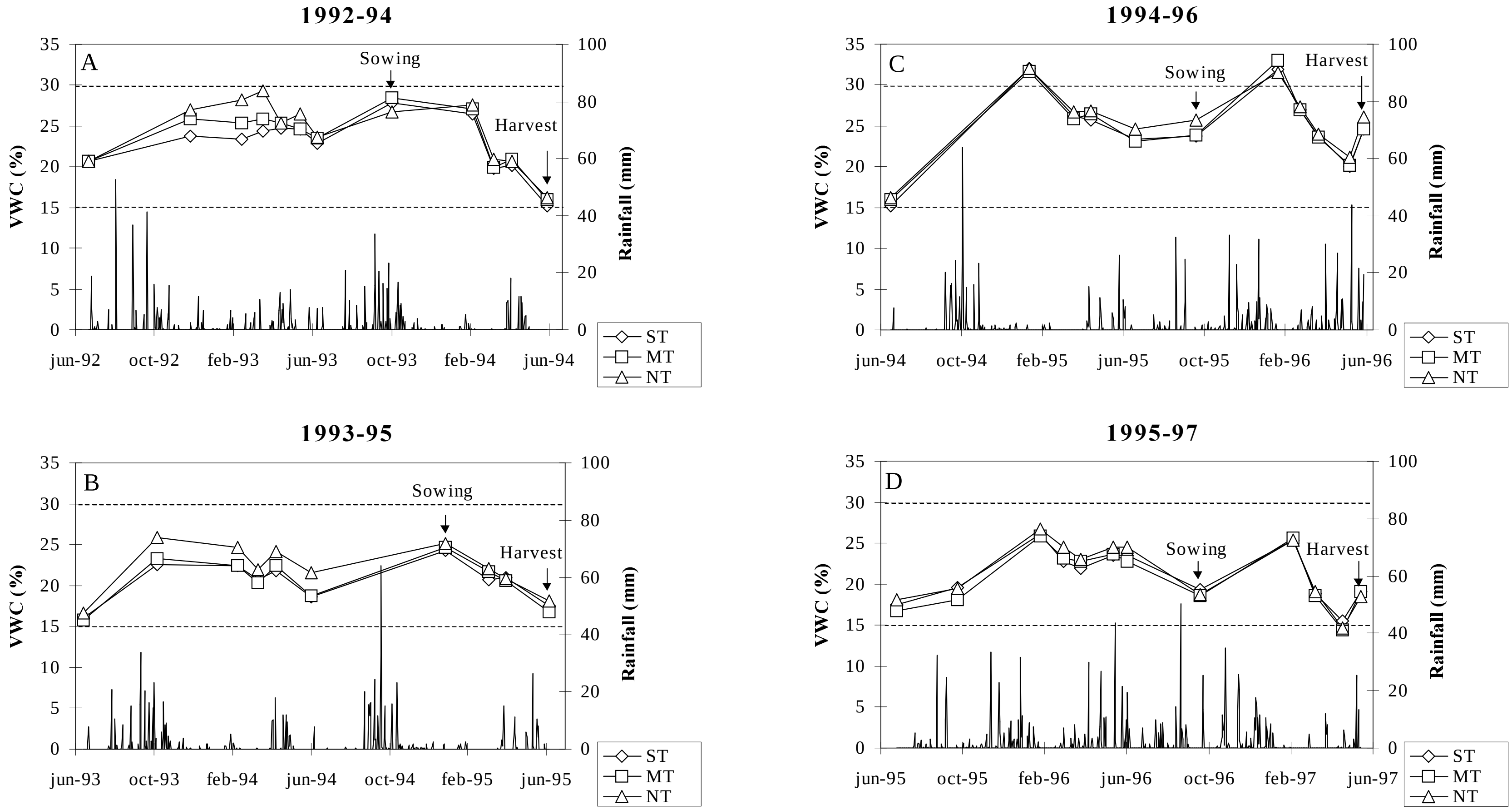

Fig. 2. Mean Volumetric Water Content (VWC) trends and daily rainfall during each fallow-crop period for three tillage systems: Subsoil Tillage (ST), Minimum Tillage (MT) and No-Tillage (NT). Soil A.

Table2
ANOVA and mean separation for Evaporation (EV), Water Storage (WE) and Water Storage Efficiency (WSE) during fallow under three tillage systems: Subsoil Tillage (ST), Minimum Tillage (MT) and No-Tillage (NT). Soil A.

Source of Variation		EV (mm)			WS (mm)			WSE (%)		
		June-February	February-October	**Total**	June-February	February-October	**Total**	June-February	February-October	**Total**
YEAR		0.0001	0.0001	**0.0001**	0.0001	0.0001	**0.0001**	0.0001	0.0001	**0.0001**
TILL		0.02	0.05	**NS**	0.02	0.05	**NS**	0.01	NS	**NS**
TILLxYEAR		0.005	0.02	**NS**	0.005	0.02	**NS**	0.005	0.01	**NS**
Model Pr > F		0.0001	0.0001	**0.0001**	0.0001	0.0001	**0.0001**	0.0001	0.0001	**0.0001**
R-Square		0.94	0.97	**0.98**	0.96	0.93	**0.87**	0.95	0.95	**0.90**
C.V.		6.1	5.3	**3.1**	13.9	-69.2	**27.9**	13.9	-55.3	**26.2**
YEAR	TILL									
1992-93	ST	274 a†	294 b	**568**	27 b	45 a	**71**	9 b	13 a	**11**
	MT	254 ab	307 b	**561**	47 ab	32 a	**78**	16 ab	9 a	**12**
	NT	226 b	353 a	**579**	75 a	-14 b	**61**	25 a	-4 b	**10**
	$LSD_{0.05}$	34	43	**27**	34	43	**27**	11	13	**4**
1993-94	ST	223 a	389 b	**612**	64 b	19 a	**83**	22 b	5 a	**12**
	MT	220 a	386 b	**606**	67 b	22 a	**89**	23 b	5 a	**13**
	NT	208 b	403 a	**611**	79 a	5 b	**84**	28 a	1 b	**12**
	$LSD_{0.05}$	12	10	**13**	12	10	**13**	4	2	**2**
1994-95	ST	156	283	**439**	167	-82	**85**	52	-41	**16**
	MT	166	278	**444**	157	-77	**80**	49	-38	**15**
	NT	166	263	**429**	158	-62	**96**	49	-31	**18**
	$LSD_{0.05}$	23	29	**21**	23	29	**21**	7	14	**4**
1995-96	ST	215	455	**670**	86	-67	**18**	28	-17	**3**
	MT	208	461	**669**	92	-73	**19**	31	-19	**3**
	NT	214	468	**682**	86	-80	**6**	29	-21	**1**
	$LSD_{0.05}$	12	41	**50**	12	41	**50**	4	10	**7**

YEAR Fallow year.
TILL Tillage system.
NS Non-significant at the 0.1 probability level.
C.V. Coefficient of Variation.
† Different letters follow the means that are statistically different (LSD test at 0.05 probability level).

2.2. Crop period

Table 3 shows the results of the overall ANOVA for the crop after fallow. As expected, YEAR, Development stage (BBCH) and DEPTH had a very significant effect on all the variables studied.

VWC trends during the crop were greater for 1993-94 and 1995-96 (Fig. 2-A & 2-B). In 1994-95 and 1996-97 (Fig. 2-C & 2-D), VWC trends were lower, in spite of the greater rainfall, because the high intensity of some rains produced water losses by runoff. Though tillage has no significant effect on mean VWC, the distribution of VWC in the soil profile (Fig. 3) was sometimes different for the different tillage systems (significant TILLxDEPTH interaction, $P<0.005$). NT showed greater values of VWC, especially in the upper part of the soil profile at sowing and maturity in 1995-96 (Fig. 3), but also at the bottom at stem elongation in 1993-94 and at sowing in 1994-95. It is interesting that during the years with least precipitation during fallow (1995-96 with 522 mm, Table 1), NT showed greater VWC values at sowing (Fig. 3) in the first 50 cm of soil.

Table 3
Probability values from ANOVA for the Volumetric Water Content (VWC), Root Length Density (LV), Dry Matter (DM) and Yield (YIELD). Soil A.

Source of Variation	VWC (%)	LV (cm cm^{-3})	DM (g m^{-2})	WU (mm)	YIELD (kg ha^{-1})
YEAR	0.0001	0.0001	0.0001	0.0001	0.0001
TILL	NS	0.001	NS	NS	0.03
TILLxYEAR	NS	0.07	0.05	NS	0.0001
BBCH(YEAR)	0.0001	0.0001	0.0001	-	-
TILLx BBCH(YEAR)	NS	NS	NS	-	-
DEPTH	0.0001	0.0001	-	-	-
DEPTHxYEAR	0.0001	0.0001	-	-	-
TILLxDEPTH	0.005	NS	-	-	-
TILLxDEPTHxYEAR	NS	NS	-	-	-
DEPTHxBBCH(YEAR)	0.0001	0.0001	-	-	-
TILLxDEPTHxBBCH(YEAR)	NS	NS	-	-	-
Model Pr > F	0.0001	0.0001	0.0001	0.0001	0.0001
R-Square	0.94	0.85	0.85	0.99	0.98
C.V.	7.6	18.6	9.5	4.9	4.9
Transformation	Unnecessary	1/(LV+1)	LOG_{10}(DM)	Unnecessary	SQRT(YIELD)

YEAR Crop year.
TILL Tillage system. ST: Subsoil Tillage; MT: Minimum Tillage; NT: No-Tillage.
BBCH Development stage.
DEPTH Depth of soil profile.
NS Non-significant at the 0.1 probability level.
C.V. Coefficient of Variation.

Root Length Density (LV) varied over the years, reaching up to 3 cm cm^{-3} in 1995-96 (Fig. 4), and showing its lowest values in 1994-95 for the reduced growing season. Though significant ($P<0.001$), differences between tillage systems for LV were small. LV was greater under NT than under ST or MT in the upper part of the soil profile at anthesis and maturity in 1993-94, and deeper (25-75 cm) at tillering in 1995-96. In contrast, NT showed the lowest LV from 0 to 25 cm depth at anthesis in 1995-96 and at maturity in 1996-97. MT showed the greatest LV at anthesis in 1995-96 and at tillering in 1996-97.

DM values of the crop at harvest ranged from 428 to 1456 g m^{-2} (Fig. 5). As for LV, 1994-95 showed the lowest values of DM due to the short growing season. Significant TILLxYEAR interaction ($P<0.05$) reflected the lower DM values observed for NT in 1995-96.

Yield ranged between 4473 kg ha^{-1} in 1995-96 and 1137 kg ha^{-1} in 1994-95. Tillage had a significant effect on Yield ($P<0.03$). As a mean of the four years, ST produced 3095 kg ha^{-1}, MT 3346 kg ha^{-1} and NT 3194 kg ha^{-1}. However, the tillage with the best effect on yield depended on the year (significant TILLxYEAR interaction, $P<0.0001$): MT had the greatest yield in 1993-94 and 1994-95, ST in 1995-96 and NT in 1996-97 (Fig. 6).

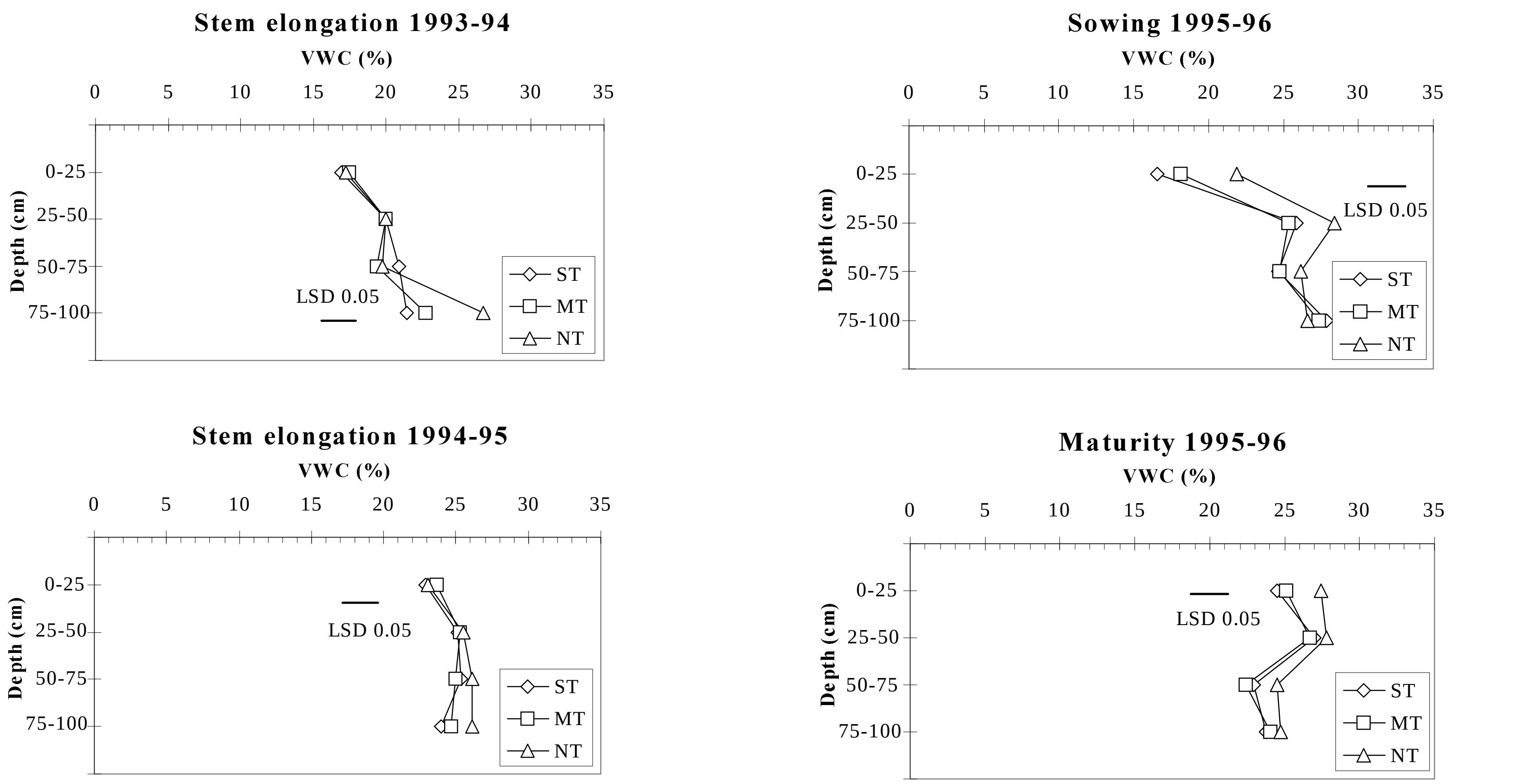

Fig. 3. Volumetric Water Content (VWC) profiles at different development stages for three tillage systems: Subsoil Tillage (ST), Minimum Tillage (MT) and No-Tillage (NT). Soil A.

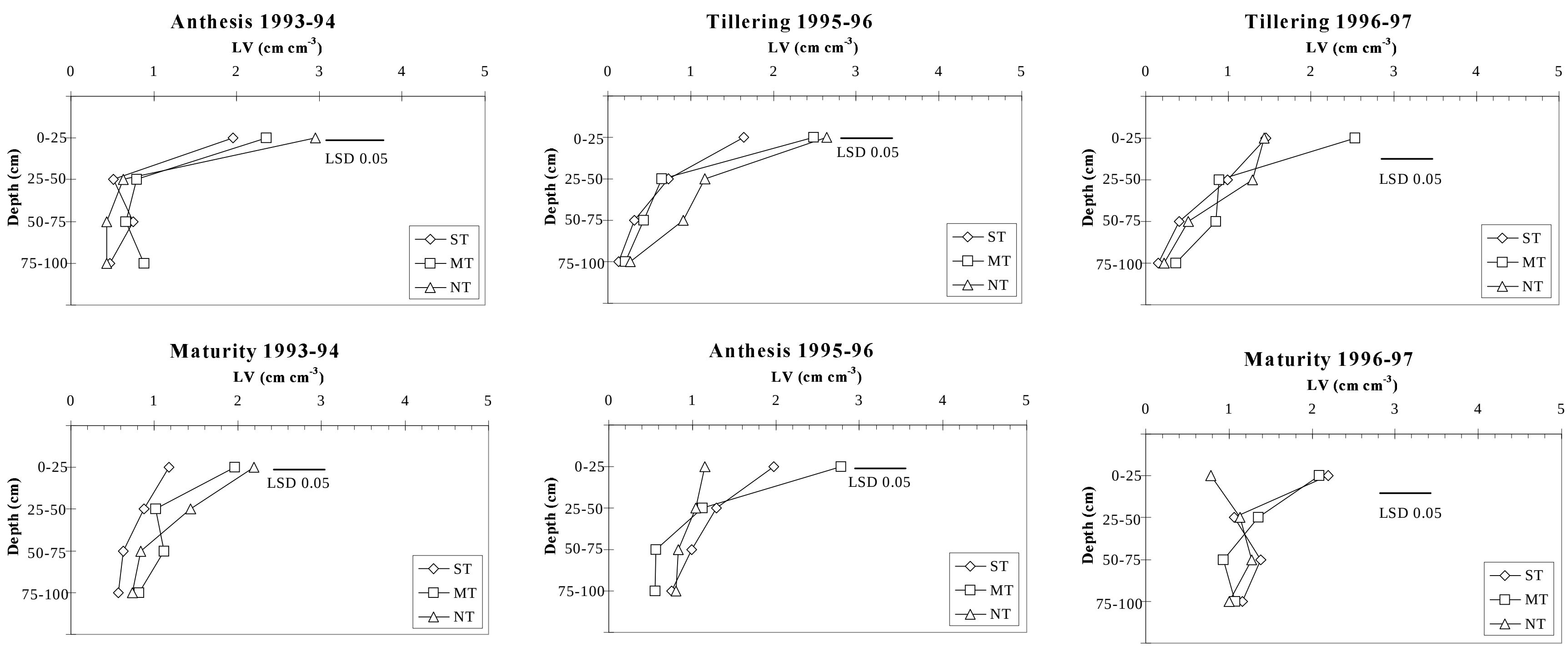

Fig. 4. Root Length Density (LV) profiles at different development stages for three tillage systems: Subsoil Tillage (ST), Minimum Tillage (MT) and No-Tillage (NT). Soil A.

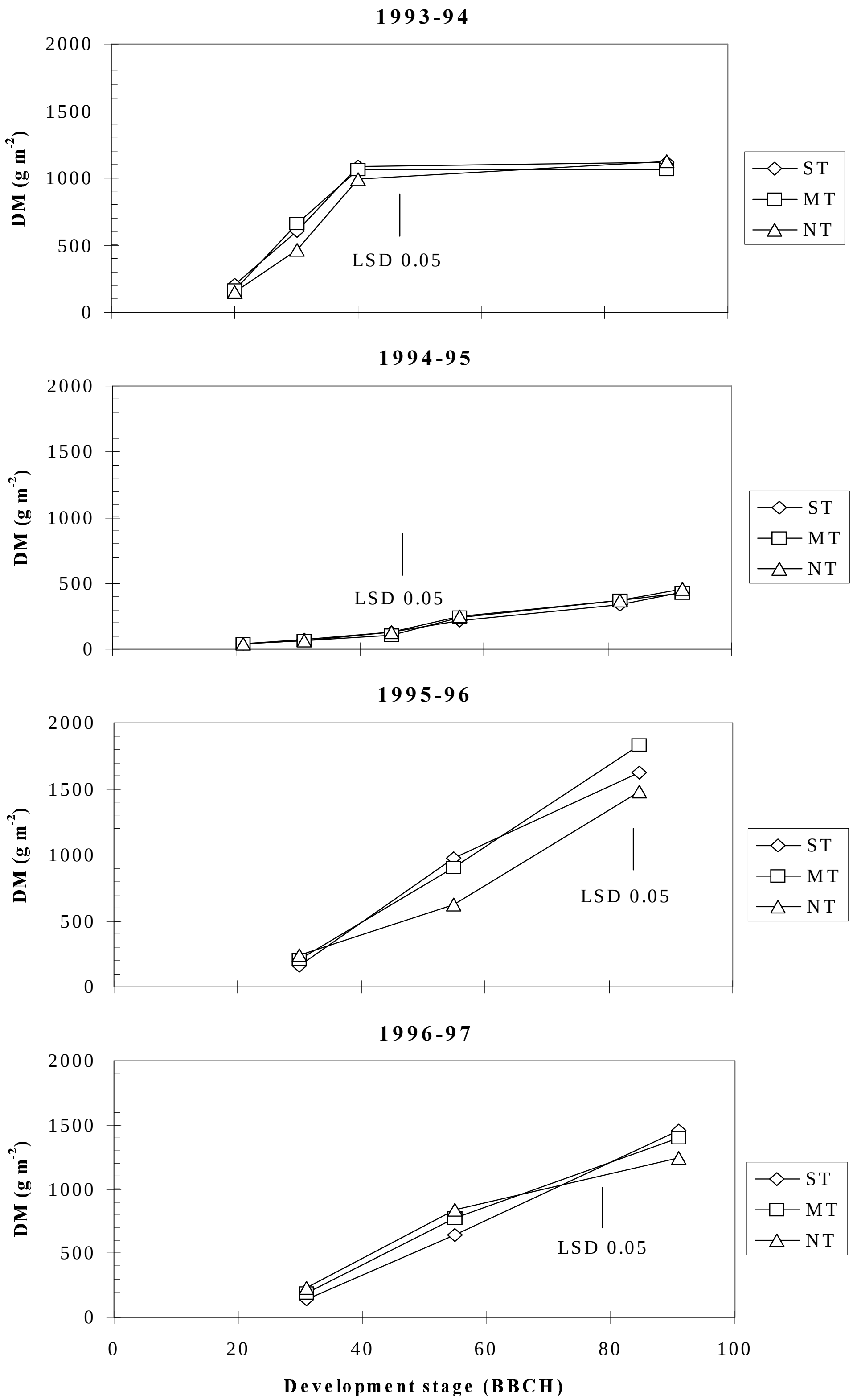

Fig. 5. Dry Matter (DM) trends in each year for three tillage system: Subsoil Tillage (ST), Minimum Tillage (MT) and No-Tillage (NT). Soil A.

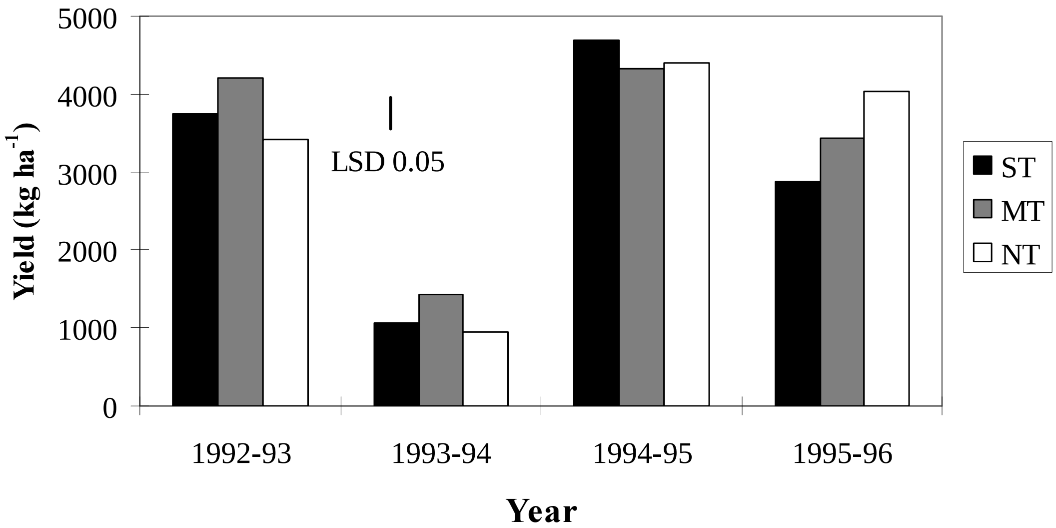

Fig. 6. Yield for each tillage system throughout the experiment: Subsoil Tillage (ST), Minimum Tillage (MT) and No-Tillage (NT). Soil A.

3. Soil B

3.1. Fallow period

Trends of VWC for the fallow and crop cycles are shown in Fig. 7. During fallow, NT showed a slightly higher VWC, especially after the dry 1994-95 winter (Fig. 7-A), and during the spring rainfalls in 1996 (Fig. 7-B) and in 1997 (Fig. 7-C). Nevertheless, at sowing no significant differences were observed in any year.

ANOVA for EV, WS and WSE is shown in Table 4, and only the year had a significant effect on these variables. Total EV was lower for 1994-95 (491 mm) than for 1995-96 (689 mm). No significant differences were observed in WS (33 mm in 1994-95 and 24 mm in 1995-96), but differences were significant ($P<0.05$) in WSE (6.3 and 3.5% respectively). Fallow efficiencies were lower than in Soil A in 1994-95 and similar in 1995-96.

Though tillage does not have a significant effect on fallow parameters, it is interesting that, as in Soil A, EV tended to be lower and WS greater under NT in the June to February period, and EV greater and WS lower in the February to October period (a difference of about 5 mm in 1995-96 fallow).

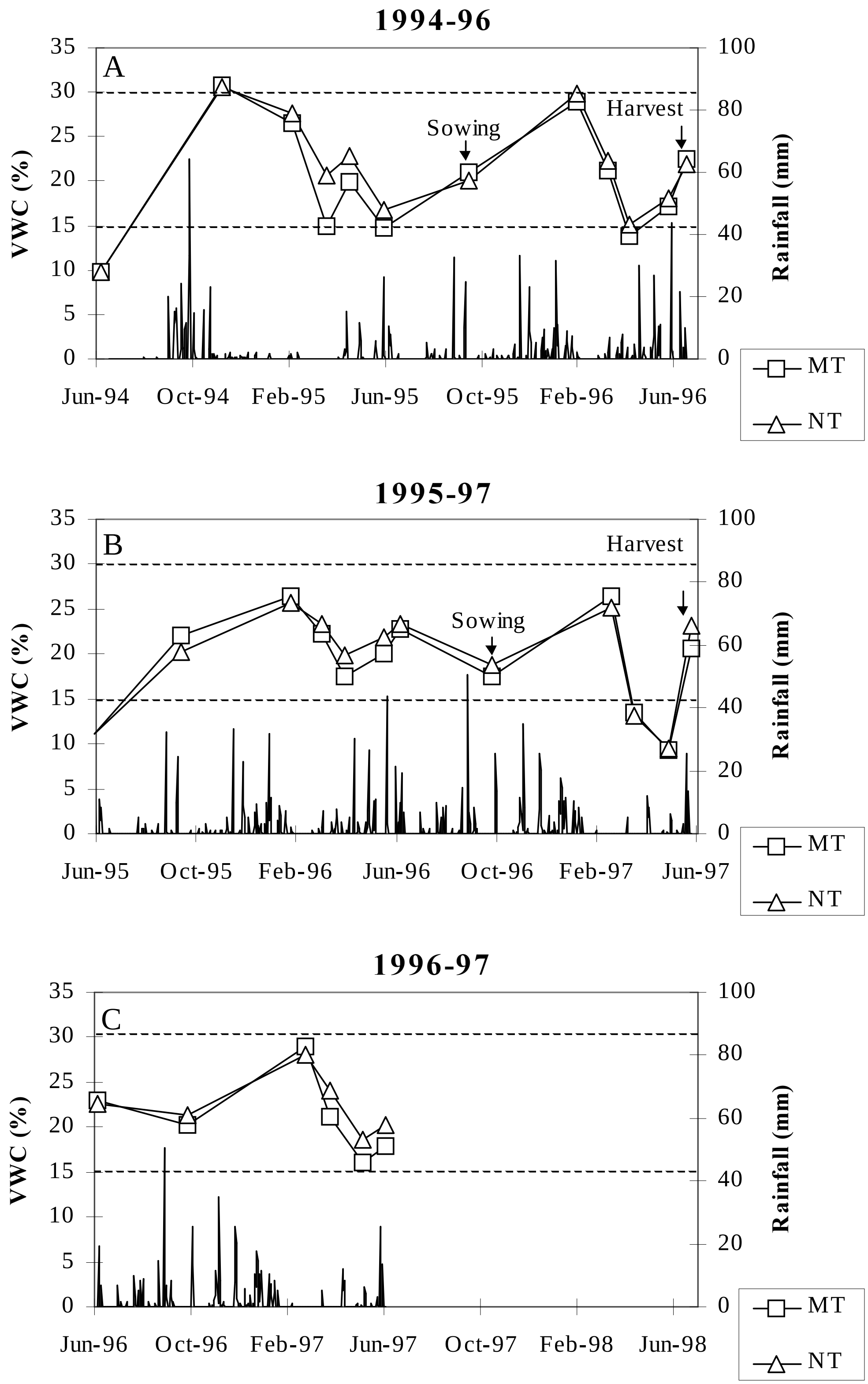

Fig. 7. Mean Volumetric Water Content (VWC) trends and daily rainfall during each fallow-crop period for two tillage systems: Minimum Tillage (MT) and No-Tillage (NT). Soil B.

Table 4
ANOVA and mean separation for Evaporation (EV), Water Storage (WE) and Water Storage Efficiency (WSE) during fallow under two tillage systems: Minimum Tillage (MT) and No-Tillage (NT). Soil B.

Source of Variation		EV (mm)			WS (mm)			WSE (%)		
		June-February	February-October	**Total**	June-February	February-October	**Total**	June-February	February-October	**Total**
YEAR		0.006	0.0001	**0.0001**	0.007	0.01	**NS**	0.007	NS	**0.05**
TILL		0.05	NS	**NS**	0.05	NS	**NS**	0.05	NS	**NS**
TILLxYEAR		0.04	NS	**NS**	0.04	NS	**NS**	0.04	NS	**NS**
Model Pr > F		0.0001	0.0001	**0.0001**	0.0001	NS	**NS**	0.0001	NS	**NS**
R-Square		0.99	0.99	**0.99**	0.99	0.78	**0.47**	0.99	0.61	**0. 70**
C.V.		0.6	3.7	**2.0**	3.2	-55.8	**40.9**	3.2	-60.2	**37.2**
YEAR	TILL									
1994-95	MT	285	204	**489**	42	-8	**34**	13	-4	**7**
	NT	285	207	**492**	42	-10	**31**	13	-5	**6**
	$LSD_{0.05}$	2	18	**18**	2	18	**18**	1	9	**4**
1995-96	MT	271	418	**689**	55	-30	**25**	17	-8	**4**
	NT	266	423	**690**	59	-35	**24**	18	-9	**3**
	$LSD_{0.05}$	5	32	**33**	5	32	**33**	2	8	**5**

YEAR Fallow year.
TILL Tillage system.
NS Non-significant at the 0.1 probability level.
C.V. Coefficient of Variation.

3.3.2. Crop

In the ANOVA (Table 5), YEAR had a significant effect on VWC, DM, WU and YIELD but not on LV.

The WVC trends in Fig. 7 show, in general, that the soil was wetter in 1995-96 than in 1996-97, though precipitation during the crop was greater in 1996-97 because rainfall was better distributed in 1995-96. VWC distribution in depth was different for MT and NT, as is indicated by the significant TILLxDEPTH interaction (P<0.007). In general, VWC was similar or slightly greater for MT in the 0 to 10 cm depth layer, and greater for NT in the 10 to 30 cm layer (tillering and stem elongation 1995-96 and tillering and maturity 1996-97, Fig 8).

The decrease in LV with depth was significantly greater for MT than for NT (P<0.002) , which showed a more homogeneous root profile. LV was greater for MT in the first 10 cm of soil, with values of up to 4.5 cm cm^{-3} (tillering and anthesis 1995-96 and maturity 1996-97, Fig 9), and greater for NT from 10 to 30 cm depth (stem elongation 1995-96 and stem elongation and anthesis 1996-97, Fig. 9).

TILLxYEAR interaction was significant for DM (P<0.05) and YIELD (P<0.03). In 1995-96 there were no significant differences between MT and NT, but in 1996-97 NT showed greater values of DM and Yield (Figs. 10 and Fig. 11). Consequently, in the two years NT averaged 3111 kg ha^{-1} and MT 2871 kg ha^{-1}.

Table 5
Probability values from ANOVA for the Volumetric Water Content (VWC), the Root Length Density (LV), the Dry Matter (DM) and Yield (YIELD). Soil B.

Source of Variation	VWC (%)	LV (cm cm^{-3})	DM (g m^{-2})	WU (mm)	YIELD (kg ha^{-1})
YEAR	0.003	NS	0.006	0.002	0.02
TILL	NS	NS	NS	0.08	NS
TILLxYEAR	NS	NS	0.05	NS	0.03
BBCH(YEAR)	0.0001	0.002	0.0001	-	-
TILLxBBCH(YEAR)	NS	NS	NS	-	-
DEPTH	0.0001	0.0006	-	-	-
DEPTHxYEAR	0.001	NS	-	-	-
TILLxDEPTH	0.007	0.002	-	-	-
TILLxDEPTHxYEAR	NS	NS	-	-	-
DEPTHxBBCH(YEAR)	0.02	NS	-	-	-
TILLxDEPTHxBBCH(YEAR)	NS	NS	-	-	-
Model Pr > F	0.0001	0.0001	0.0001	0.003	0.005
R-Square	0.97	0.83	0.95	0.95	0.94
C.V.	9.7	12.3	12.4	2.0	14.0
Transformation	Unnecessary	$LV^{0.3}$	SQRT(DM)	Unnecessary	Unnecessary

YEAR Crop year.
TILL Tillage system. MT: Minimum Tillage; NT: No-Tillage.
BBCH Development stage.
DEPTH Depth of soil profile.
NS Non-significant at the 0.1 probability level.
C.V. Coefficient of Variation.

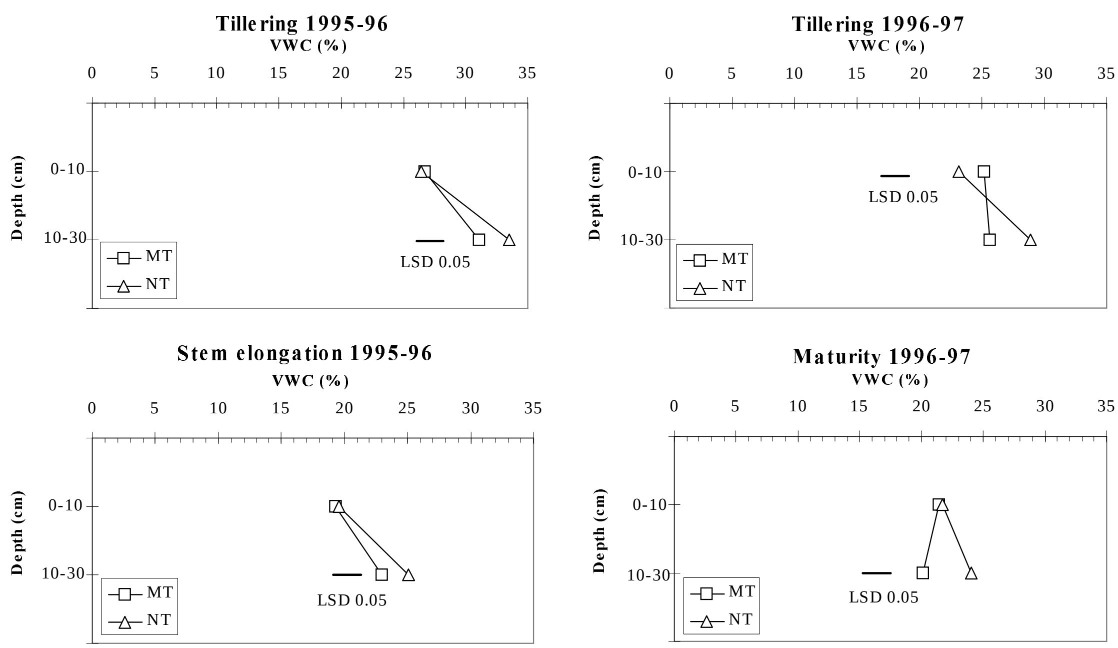

Fig. 8. Volumetric Water Content (VWC) profiles at different development stages for two tillage systems: Minimum Tillage (MT) and No-Tillage (NT). Soil B.

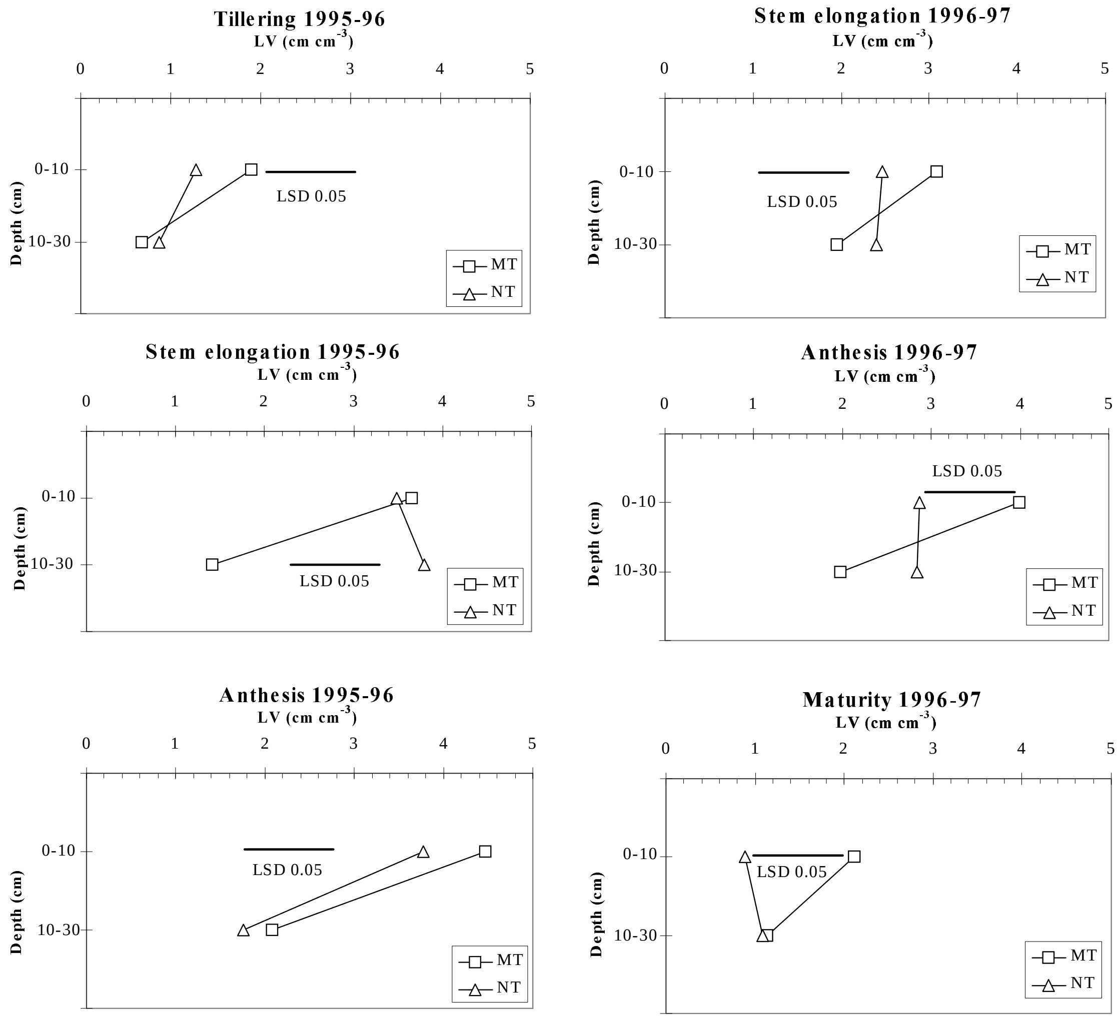

Fig. 9. Root Length Density (LV) profiles at different development stages for two tillage systems: Minimum Tillage (MT) and No-Tillage (NT). Soil B.

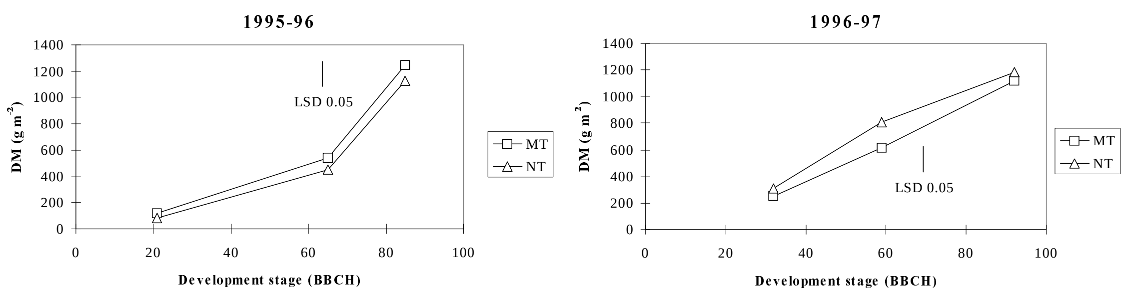

Fig. 10. Dry Matter (DM) trends in each year for two tillage system: Minimum Tillage (MT) and No-Tillage (NT). Soil B.

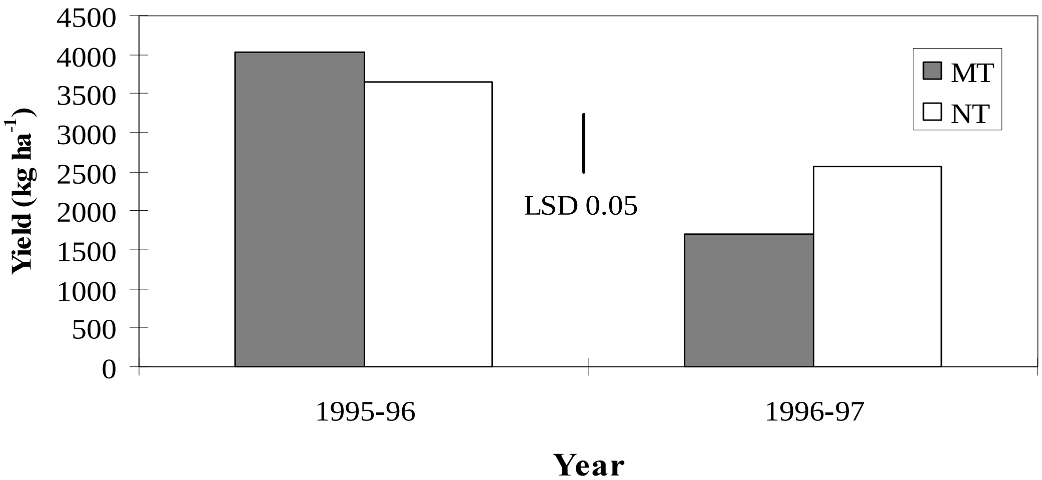

Fig. 11. Grain yield in two growing seasons for each tillage system: Minimum Tillage (MT) and No-Tillage (NT). Soil B.

Discussion

1. Fallow

According to the recommendations given by French (1978b), in our area the conditions are favourable for fallow. Rainfall during the growing season is less than 440 mm (mean of 290 mm, Table 1) and the soil is fine textured (>20% of clay in the 15 to 30 cm horizon). In these conditions, water content at sowing is of major importance for the water supply to the crop (French, 1978b). In fact, only in the first two years was precipitation below 440 mm during the season in Soil A, but it was very low (135 in 1993-94 and 114 mm in 1994-95).

The WSEs obtained in Soil A (Table 2) were in the range reported by French (10-30%, 1978a) during the first three fallows. In the 1995-96 fallow WSE fell to less than 3% owing to the high evaporation during the February to October period, which led to a low VWC at sowing (Fig. 2-D).

To look for benefits of fallow, we compare the soil water content at sowing of this experiment with that of a contiguous experiment with continuous barley (Lampurlanés *et al.*, 2000). We found in the deep Soil A that in 1993 and 1995 the sowing water content in the soil was greater after fallow than after barley (Table 6), but in 1994 and 1996 sowings the water content was greater after barley. These results indicate that the value of fallow for conserving out of season precipitation varies from year to year, as was pointed out by Connor and Loomis (1991).

There was also a great difference in water storage between different periods during fallow because water accumulated during rainy periods is lost to a large extent by evaporation during the dry ones, reducing the efficiency of fallow (Papastylianou and Jones, 1988; López and Giráldez, 1996; López and Arrúe, 1997).

Table 6
Soil water content (mm) at sowing after fallow and after barley crop for two soils of contrasting depth.

SOIL	SOWING YEAR			
	1993	1994	1995	1996
Deep soil (Soil A)				
After fallow	277 a†	247 b	245 a	189 b
After barley	242 b	285 a	188 b	221 a
$LSD_{0.05}$	19	11	11	21
Shallow soil (Soil B)				
After fallow			206	186
After barley			197	183
$LSD_{0.05}$			22	34

† Different letters follow the means that are statistically different (LSD test at 0.05 probability level).

The soil and climatic conditions during fallow in our area were very similar to those described by McGee *et al.* (1997) for the Wheat-Fallow system in the semiarid Great Plains. After harvest of the previous crop, the soil is generally at its lowest VWC. Temperatures are high and daylength is at its maximum. Therefore, evaporative demand is high, but evaporation from soil is low because there is no water to evaporate.

When rains begins, around the end of September, the soil becomes wet, but evaporation is also low because evaporative demand is low during autumn and winter. Autumn rains bring the soil to its maximum water content, which is maintained during the winter.

During the spring, new rain falls and is stored in the soil, but evaporative demand starts to increase and then so does evaporation. During the summer, evaporation is high and rainfall is low. Therefore, the water content of the soil falls, resulting in a low VWC at sowing if the first autumn rains are delayed.

This was the case of the 1995-96 fallow, which showed the lowest WSE. In the other three fallows, heavy rainfall before sowing raised the soil water content, which was high at sowing. This indicates that not only winter rains are important during fallow (French, 1978a) but rains before sowing also help the soil to recover from summer evaporation. It is therefore very important to investigate systems to reduce evaporation during the summer, the limiting factor for raising fallow WSE.

Differences between tillage systems during fallow were only significant in 1992-93 and 1993-94 for Soil A (Table 2). All the parameters indicate that NT performs better than ST or MT during the June to February period, in which shows lower EV and higher WS and WSE. On the other hand, in the February to October period, NT shows the worst results, with higher EV and lower WS and WSE than the other two systems.

Soil conditions are favourable to soil recharge under NT because the natural soil structure preserved in this system enhances water infiltration. Also, residues left on the soil surface protect the soil against evaporation (McDonald and Fischer, 1987; Connor and Loomis, 1991). On the other hand, during the February to October period, when evaporation is more important, the soil under NT is more disfavoured. Pore continuity and cracks probably favour water evaporation from soil even deep in the profile (Cantero-Matínez and Vilardosa, 1996). Furthermore, the residues that cover the soil surface during fallow decrease dramatically from February to October (Fig. 12), leaving the soil unprotected against evaporation.

Under ST or MT, tillage during spring creates a soil mulch that reduces evaporation (Godwin, 1990). To increase the WSE of NT during the February to October fallow period, more residues must be left on the soil surface at harvest to prevent evaporation. If, in spite of this, the amount of residues on the soil is low at the beginning of the summer, a shallow pass with the cultivator (about 5-10 cm) to create a soil mulch may also avoid evaporation.

The general explanation for fallow periods is also valid for Soil B. The June to February period is a recharge period with positive WS (Table 4), and the February to October period is an evaporative period with negative WS. In addition, in this soil the water holding capacity is low and consequently the WSE is low. French (1978a, 1978b) found that in coarse-textured soils fallowing conserved little additional water. We found that in shallow Soil B low WSE was obtained. In both cases the reason is the low water holding capacity of the soil.

In Soil B, the differences between MT and NT in VWC profiles at sowing time (Fig. 7) were not significant, probably due to the low water holding capacity of the soil and the smaller differences in the residue covered surface (Fig. 13) compared with Soil A. Despite this, in general NT showed greater VWC in the 10-30 cm layer. This system seems to accumulate water deep in the soil were it is more protected against evaporation and conserved for the plant. This effect may be important only during the crop because during fallow the summer water in the top 30 to 45 cm is usually lost by evaporation (Papastylianou and Jones, 1988).

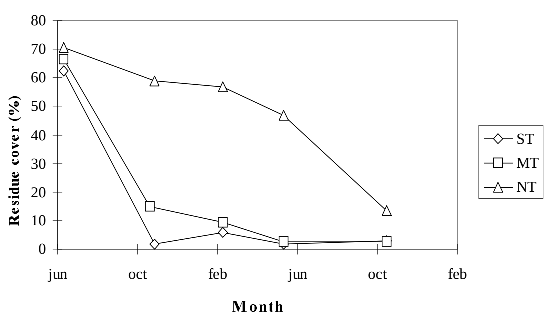

Fig. 12. Residue Covered Surface (RCS) evolution. Data from different fallows. Soil A.

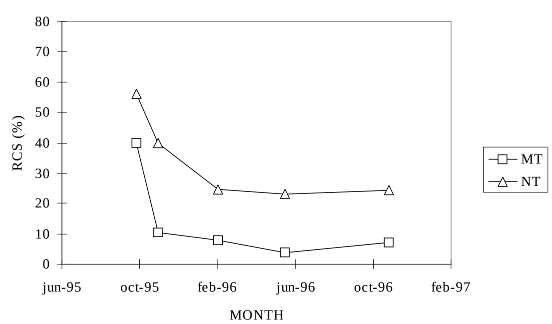

Fig. 13. Residue Covered Surface (RCS) evolution. Data from different fallows. Soil B.

In general, years with greater precipitation during fallow have greater VWC at sowing time. But for 1996-97, with near to the maximum precipitation during fallow (Table 1), the VWC at sowing was the lowest of the four years. Excessive and high intensity rainfall during the storage period produced water loses by runoff or by drainage below the root zone (Lawrence *et al.*, 1994). The fact that NT showed greater VWC at sowing in the year of lowest rainfall during fallow (1994-95, Table 1) indicates the potential of this system for conserving soil water in dry years (Cantero-Martínez *et al.*, 1999).

2. Crop

During crop, differences between tillage systems in VWC were practically negligible (Fig. 2, Fig. 7). In Soil A, NT showed slightly higher VWC in 1995-96 at sowing and maturity (Fig. 3). This difference was not reflected in yield (Fig. 6) but probably promoted a greater development of nodal axes (Gregory, 1987), which resulted in higher LV values for NT during tillering (Fig. 4). In Soil B, slightly greater values of VWC in the 10 to 30 cm horizon (Fig. 8) also promoted greater LV at stem elongation (Fig. 9), which could be related to the higher yield of NT in 1996-97 (Fig. 11).

Yield results shows that the NT system is potentially better for dry conditions. It was precisely in 1996-97, the year with the lowest soil VWC trends during crop (Fig. 2-D and Fig. 7-B) that the yield of NT plots was significantly greater in Soil A (Fig. 6) as well as in Soil B (Fig. 11). In this year no differences in VWC or LV were found in favour of NT in Soil A. Therefore, other non-controlled factors, in addition to soil water content and root system, could act to produce this result.

The comparison between the yields after fallow presented in this paper and yields in continuous barley from a contiguous experiment (Lampurlanés *et al.* 2000), shows that mean yield across the years is greater after fallow (Table 7), but in some years yield is greater in continuous barley. In addition the yield increase with fallow (128 kg ha^{-1} in Soil A and 371 kg ha^{-1} in Soil B) does not compensate for the year without crop (López and Giráldez, 1996).

Table 7
Comparison of yield after fallow and after barley crop for two soils of contrasting depth.

SOIL	SOWING YEAR				MEAN
	1993	1994	1995	1996	
Deep soil (Soil A)					
After fallow	3788 a†	1137 b	4473		3132 a
After barley	2906 b	1731 a	4376		3004 b
LSD $_{0.05}$	365	198	258		104
Shallow soil (Soil B)					
After fallow			3461 a	1923	2692 a
After barley			2389 b	2252	2321 b
LSD $_{0.05}$			616	580	348

† Different letters follow the means that are statistically different (LSD test at 0.05 probability level).

Conclusions

Overall, the value of fallow is low in our conditions and is year-dependent. The July to February fallow period has the best conditions for water accumulation and the February to October one has the worst. Therefore, the total WSE is low. To increase WSE, evaporation in the February to October period must be reduced by residue or soil mulch.

In our area, the yield increase observed in some years after fallow compared with continuous crop does not compensate for the year without crop.

Finally, NT is potentially the best system for executing fallow, but residues of the preceding crop should be left spread over the soil. Furthermore, if residue mulch at the end of the spring is insufficient to prevent summer evaporation, a soil mulch should be performed with a shallow pass with the cultivator.

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