Soil bulk density and penetration resistance under different tillage and crop management systems, and their relationship with barley root growth

Abstract

Few studies have been reported on the effect of fallow on physical properties of soil and the root growth of the following crop. It is known that soil strength increases in the first few years after NT introduction. To detect whether this increase could affect the root growth of barley and whether fallow can have a beneficial effect on the physical behaviour of soil, bulk density and penetration resistance were measured at different times in a tillage experiment on two soils of contrasting depths. Soil A was a Fluventic Xerochrept of 120 cm depth and Soil B was a Lithic Xeric Torriorthent of 30 cm depth. In Soil A three tillage systems were compared: subsoil tillage, minimum tillage and no-tillage. In Soil B only two were compared: minimum tillage and no-tillage. Three field situations were compared in both soils: continuous crop, fallow, and crop after fallow. Gravimetric water content, gravel content and root length density were also determined. Analysis of covariance was used to analyse bulk density and penetration resistance, using as covariables gravimetric water content and gravel content for bulk density, and gravimetric water content and bulk density for penetration resistance. Bulk density ranged from 0.69 to 1.66 Mg m^{-3} in Soil A, and from 0.67 to 1.46 Mg m^{-3} in Soil B. In Soil A, bulk density was lower in the fallow and crop after fallow plots (1.26 Mg m^{-3}) than in the continuous crop plots (1.32 Mg m^{-3}). In this soil, no-tillage showed the largest bulk densities (mean of 1.34 Mg m^{-3}), followed by minimum tillage (mean of 1.27 Mg m^{-3}), and finally subsoil tillage (mean of 1.22 Mg m^{-3}), according to tillage intensity. In Soil B no differences were found between field situations or tillage systems. Larger penetration resistance (sometimes 0.5 to 1.0 MPa) was found in no-tillage than in subsoil tillage and minimum tillage in both soils soon after tillage operations. 59% of the penetration resistance readings ranged from 1.3 to 3.7 MPa, and these values are reported to produce a 50% to 100% reduction in root growth. However, root length density profiles sometimes showed greater values for no-tillage than for the other tillage systems, revealing a good soil condition for root growth under no-tillage. Therefore, there is an increase in soil strength under no-tillage in the first years after its introduction that does not greatly affect root growth in well-structured soils. Fallow reduces soil strength due to the effect of tillage and natural loosening factors. This effect extends to the following crop.

Keywords: soil strength, bulk density, penetration resistance, cone index, penetrometer, root growth, fallow, no-tillage.

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Introduction

Interest in no-tillage is growing in the rainfed cereal cropping areas of Spain due to the effective reduction in time and costs which this tillage system allows. However, the concept "do not disturb the soil" clashes strongly with most farmers, who for years have disturbed the soil to obtain a soft medium for better crop growth. For the farmer, undisturbed soil seems to be harder and more resistant to root penetration than tilled soil. In fact, high soil strength has been proved to reduce and even to stop root growth.

The most common variables used to assess soil strength in tillage studies are bulk density and penetrometer resistance. They are interrelated and the use of only one of these variables may lead to misleading results (Campbell and Henshall, 1991).

Bulk density is inversely related to total porosity (Carter and Ball, 1993), which gives us an idea of the porous space left in the soil for air and water movement. The optimal bulk density for plant growth is different for each soil. In general, less-than-optimal bulk density (high porosity) leads to poor water relations, and high bulk density (low porosity) reduces aeration and increases penetration resistance, limiting root growth (Cassel, 1982).

Bulk density is related to natural soil characteristics such as texture, organic matter, soil structure (Cassel, 1982; Chen *et al.*, 1998) and gravel content (Franzen *et al.*, 1994), and varies over the year due to the action of several processes: freezing and thawing (Blevins *et al.*, 1983; Unger, 1991), settling by desiccation and kinetic energy of rainfall (Cassel, 1982), and loosening by root action and animal activity. Crop operations, especially tillage, may also alter bulk soil density.

One of the goals of tillage is to reduce bulk density (increasing soil porosity). This effect of tillage on bulk density is temporary, and after tillage the soil rapidly settles, recovering its former bulk density (Hernanz and Girón, 1988; Campbell and Henshall, 1991; Franzen *et al.*, 1994; Franzluebbers *et al.*, 1995). In the first years of no-tillage, bulk density of the soil may increase due to the repeated passes of the tractor and the lack of the loosening action of tillage.

Numerous experiments performed to compare no-tillage with other conservation or more conventional tillage systems have given different results. In most of them, bulk density was greater in no-tillage in the first 5 to 10 cm of soil (Ehlers, *et al*., 1983; Pelegrin *et al.*, 1988; Radclifee *et al.*, 1988; Hammel, 1989; Hill, 1990; Campbell and Henshall, 1991; Grant and Lafond, 1993; Rhoton *et al.*, 1993; Franzen *et al.*, 1994; Hubbard *et al.*, 1994; Franzluebbers *et al.*, 1995; Unger and Jones, 1998; Tebrügge and Düring, 1999; Wander and Bollero, 1999). In others, no differences in bulk density were found between tillage systems (McCalla and Army 1961; Cassel, 1982; Blevins *et al.*, 1983; Burch *et al.*, 1986; Blevins and Frye, 1993; Taboada *et al.*, 1998; Arshad *et al.*, 1999; Logsdon *et al.*, 1999; Ferreras *et al.*, 2000; Logsdon and Cambardella, 2000). In a third group, bulk density even decreased under no-tillage (Moran *et al.*, 1988; Pikul and Asae, 1995; Edwards, 1996; Crovetto, 1998), especially when an increase in organic matter was observed in the first layer of the soil (Edwards, 1996; Crovetto, 1998).

Owing to the progressive increase in bulk density after tillage, the difference between tillage and no-tillage becomes smaller as the time since tillage increases. In some soils, porosity under no-tillage decreases in the first few years until the soil recovers its natural structure (Kinsella, 1995).

The most important factors affecting penetration resistance or the cone index of the soil are soil water content and bulk density (Cassel, 1982; Hamblin, 1985; Bradford, 1986; Klepper, 1990; Campbell and O'Sullivan, 1991; Unger and Jones, 1998). Texture, organic matter, particle surface roughness (Cassel, 1982, Campbell and O'Sullivan, 1991) and structure (Bradford, 1986; Campbell and O'Sullivan, 1991) may also produce a different penetration resistance in different soils or in different layers of the same soil.

Penetration resistance increases with depth due to the increase in shaft friction (Bradford, 1986; Campbell and O'Sullivan, 1991; Franzen *et al.*, 1994), and values from the different depths are correlated with each other (Stelluti *et al.*, 1988; Campbell and O'Sullivan, 1991). Yasin *et al.* (1993) found a cubic relationship between cone index and depth.

In several studies comparing tilled and non-tilled soils, greater penetration resistance was found under no-tillage, especially in the upper 10 cm (Ehlers *et al.*, 1983; Radclifee, 1988; Hammel, 1989; Hill, 1990; Pelegrin *et al.*, 1990; Agenbag and Maree, 1991; Grant and Lafond, 1993; López *et al.*, 1996; Wander and Bollero, 1999; Ferreras *et al.*, 2000). Franzen *et al.* (1994) observed significantly smaller cone index values under no-tillage down to 10 cm soil depth due to mulching. As for bulk density, differences between no-tillage and more conventional soil-disturbing tillage methods are great soon after tillage operations, but fall quickly during the growing season and may disappear at the end (Pelegrin *et al.*, 1990; Franzen *et al.*, 1994; López *et al.*, 1996).

The tillage system affects not only penetration resistance but also its related variables: soil water content and bulk density. For this reason some researchers have tried to separate the direct effect of tillage on cone index from its indirect effect through the effect on water content and bulk density in different ways in order to allow better comparisons. Campbell and O'Sullivan (1991), proposed measuring at field capacity and simultaneously measuring bulk density. Busscher *et al.* (1997) adjusted different functions to correct cone index values from water content. Others used analysis of covariance to reduce the effect of water content and bulk density in the cone index comparisons (Yasin *et al.*, 1993; Franzen *et al.*, 1994). After correction, the dependence of cone index on these variables is reduced (Busscher *et al.*, 1997).

The most important physical factors affecting root growth are porosity, mechanical impedance, water content and soil structure (Klepper, 1990; Gregory, 1994). In general, root tips are unable to penetrate pores narrower than their diameter (Taylor, 1983; Hamblin, 1985; Campbell and Henshall, 1991). They can exert a vertical pressure ranging from 0.7 to 2.5 MPa, depending on crop species (Gregory, 1994). Bulk density values that limit root growth are dependant on soil water content (Pabin *et al.*, 1998) and range between 1.46 and 1.90 Mg m-3 (Campbell and Henshall, 1991).

Mechanical impedance increases as bulk density increases and water content decreases (Ehlers *et al.*, 1983). Penetration resistance measured with the penetrometer is usually 2 to 8 times greater than that actually undergone by the root tip (Bengough, 1991; Atwell, 1993; Gregory, 1994), owing to the different way in which roots and probes penetrate the soil. However, it is well correlated with the soil strength perceived by roots in soils with a relative homogeneous matrix (Atwell, 1993).

Root growth decreases as penetration resistance increases (Taylor, 1983; Atwell, 1993; Gregory, 1994), showing a linear (Ehlers, 1983), inverse (Bengough, 1991; Atwell, 1993) or exponential (Hamblin, 1985) relationship. Penetrometer values greater than 2 MPa are generally reported to produce a significant root growth reduction (Atwell, 1993). However, in well-structured soils or those in which biochannels are preserved (as in non-tilled soils), roots continue to extend at greater penetrometer readings because they can grow in the interaggregate spaces (Ehlers, 1983; Taylor, 1983; Klepper, 1990; Campbell and Henshall, 1991).

Fallow has been proved to affect water and nitrogen balances in the soil (French, 1978; McDonald and Fischer, 1987). It also seems reasonable to hypothesise that fallow can have an effect on soil strength because greater humidity generally encountered under fallow than under cultivated soils may modify the restructuring process of the soil and its biological activity. Better knowledge of this effect can help to elucidate the best way to perform fallow in the set-aside fields forced by the European Union Agricultural Policy.

The objective of this study was to follow the evolution of bulk density and penetration resistance in the firsts few years after no-tillage was established on fallow and continuous crops of barley, and to determine whether it had limiting or beneficial effects on root growth.

Materials and methods

The experimental fields of this study were located in El Canós, in the semiarid area of the north-east Ebro Valley, Spain (mean annual precipitation of 440 mm), on two soils of contrasting depth that are representative of the soils in the area. The deep soil (Soil A) was a fine-loamy, mixed, mesic Fluventic Xerochrept (Villar, 1989) of 120 cm depth. The shallow soil (Soil B) was a loamy, mixed, calcareous, mesic, shallow Lithic Xeric Torriorthent of 30 cm depth. The two soils showed a high gravel content, mainly at the surface (≈ 15%). Some selected soil properties are shown in Table 1.

Table 1
Selected properties for the layers of Soil A (Villar, 1989) and Soil B.

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

The experiment was designed 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. With this arrangement we investigated three field situations: Continuous Crop (CC), Crop After Fallow (CAF) and Fallow (F). 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 tilling at 40 cm depth in August, and a field cultivator at 15 cm depth in October (and a cultivator in spring in the fallow plots if weeds were present). Minimum Tillage (MT) consisted of a field cultivator working to a depth of 15 cm before sowing (and in May in the fallow plots if weeds were present). 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, and in spring if weeds were present.

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

Bulk Density (BD) was determined by taking two undisturbed soil cores from each plot, from 0 to 7 and from 7 to 14 cm depth. We took the cores by hammering into the ground stainless steel cutter edge cylinders 50 mm high and 60 mm in diameter (141.37 cm^3 inner volume). The cores were stored and transported in hermetic cans to determine the Gravimetric Water Content (GWC). The cores were dried, weighed, and washed through a 2 mm sieve to determine the Gravel Content (GC). Bulk density of the fine soil (< 2 mm) was calculated as (Mc-Mg)/(Vc-Vg)*100, where Mc and Vc are the dry mass and the volume of the soil core, and Mg and Vg are the mass and the volume of the gravel. This is another form of Russos's equation (cited by Franzen *et al.*, 1994). Gravel content was calculated as Mg/Vc to allow comparison with Franzen's (1994) results. Gravimetric water content was obtained from the fresh and dry weights of the cores. Gravimetric rather than volumetric water content was used because volumetric water content is affected by bulk density that at the same time varies during penetration measurements (Campbell and O'Sullivan, 1991).

To measure Penetration Resistance (PR) we used a hand-held penetrograph (Stiboka penetrograph, EIJKELKAMP®) that draws a graph of the resistance to penetration vs. depth to a depth of 80 cm. The conical point was 1 cm^2 in area and the point angle was 60º. The measurement range was 0 to 5 MPa. At each measurement time we obtained two graphs per plot with a total of 8 replications per treatment.

Water content and root length density profiles were obtained by taking soil cores between rows with Edelman or Riverside augers (EIJKELKAMP®) at important developmental stages of the barley: tillering, stem elongation, anthesis, maturity and harvest. Additional samples for water content were taken at sowing and during winter. 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.

The dates on which tillage operations and bulk density and penetrometer resistance determinations were made are shown in Table 2. More details about crop operations and root length density determination can be found in Lampurlanés *et al.* (2000a and 2000b).

Statistical analyses were accomplished using SAS® software, grouping the plots by their condition: continuous crop, crop after fallow or fallow. The 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 plot (Littell *et al.*, 1991) with tillage as a main plot and sampling date and depth as successive sub-plots. For bulk density analysis, we used gravimetric water content and gravel content of the sample as covariables. For penetrometer resistance data, we used gravimetric water content and bulk density of the nearest sampling time as covariables. Least square means (corrected by the covariables) were used, and differences for main effects and interactions were tested with the PDIFF option of the LSMEANS statement (Littell *et al.*, 1991).

Table 2

Dates of tillage operations, Penetration Resistance (PR) or Bulk Density (BD) measurements, and days and rainfall from the last tillage operation in Soil A and Soil B.

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			
01.12.94		PR (except fallow plots)	36	51
07.02.95	Resowing			
14.03.95		BD	139	69
29.03.95	Cultivator in ST and MT (fallow plots)			
02.05.95		PR (fallow plots)	(34) ‡	(23)
04.05.95		BD (fallow plots)	(36)	(23)
15.08.95	Subsoiling of ST plots			
15.09.95		BD	25	37
20.09.95		PR	30	72
16.10.95	Cultivator in ST and MT plots			
23.10.95	Sowing			
07.11.95		BD	22	5
15.02.96		PR	122	212
23.02.96		BD	130	212
08.05.96	Cultivator in ST and MT fallow plots			
07.06.96		PR BD	235 (30)	401 (109)
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			
03.12.96		PR	78	79
28.02.97	Resowing continuous crop plots			
11.03.97		PR BD	176	274
Soil B				
26.10.94	Cultivator in MT plots			
01.11.94	Sowing			
24.11.94	Resowing			
28.11.94		PR	33	49
15.02.95		PR	112	66
07.03.95		BD	132	69
29.03.95	Cultivator in MT fallow plots			
02.05.95		PR (fallow plots)	(34)	(23)
04.05.95		BD (fallow plots)	(36)	(23)
26.09.95		PR	335(181)	263(194)
16.10.95	Cultivator in MT plots			
23.10.95	Sowing			
08.11.95		BD	23	5
12.02.96		PR	119	212
22.02.96		BD	129	212
08.05.96	Cultivator in MT (fallow plots)			
07.06.96		PR BD	235 (30)	401 (109)
16.09.96	Cultivator in MT plots			
24.10.96	Cultivator in MT plots			
25.10.96	Sowing			
04.11.96	Compactor roller			
04.12.96		PR	41	79
13.03.97		PR BD	140	274

† ST, Subsoil Tillage; MT, Minimum Tillage; NT, No-Tillage.

‡ Values in parenthesis are for fallow plots and were computed from the spring tillage.

Results

1. Rainfall

Daily rainfall and tillage operations are shown in Fig 1. The driest year was 1994-95, with little winter and spring rainfall. The wettest years were 1995-96 and 1996-97, with high winter rainfall. In 1995-96, spring rainfall was also high.

In 1994-95, rainfall between the first and second tillage operations (142 mm) was higher than in 1995-96 (74 mm) or in 1996-97 (52 mm). On the other hand, rainfall between the second and third tillage operations was higher in 1995-96 (294 mm) and 1996-97 (275 mm) than in 1994-95 (69 mm). Precipitation between the third and first tillage was also higher in 1995-96 (293 mm) than in 1994-95 (122 mm).

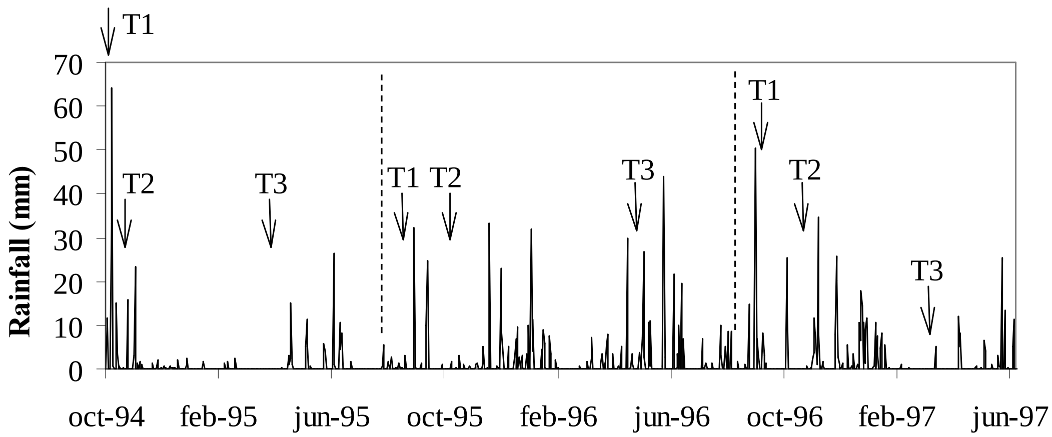

Fig. 1. Daily rainfall and tillage operations during the experiment. (T1: Subsoiler in subsoil tillage plots; T2: Cultivator in subsoil and minimum tillage plots; T3: Cultivation in subsoil and minimum tillage fallow plots).

2. Bulk Density (BD)

2.1. Soil A

Preliminary results (Lampurlanés and Cantero-Martínez, 1996), showed a significant positive relationship between Gravimetric Water Content (GWC) and Bulk Density (BD). Working in a soil with a gravel layer, Franzen *et al.* (1994) also found a negative relationship between BD and Gravel Content (GC). Therefore, the first step to analyse our BD data was to investigate its relationship with GWC and GC.

The general regression of BD vs. GWC and GC (Table 3) was significant for both variables, with coefficients of 0.0083 for GWC and –0.135 for GC. In spite of this, the test of homogeneity of slopes (Littell *et al.*, 1991) showed that this relationship was different for each strip: Continuous Crop (CC), Crop After Fallow (CAF) and Fallow (F). For this reason, we performed a separate analysis of covariance for each strip, including as covariables GWC, GC or both, according to their significance in the regression analysis. Therefore, we use as covariables GWC and GC for F, GWC for CC, and neither for CAF.

Table 3
Coefficients of the general and by strip regressions of Bulk Density (BD) vs. Gravimetric Water Content (GWC) and Gravel Content (GC) for Soil A and Soil B.

	Intercept	GWC	GC	R^2	C.V.
Soil A					
General	1.15^{***}	0.0083^{***}	-0.135^{*}	0.05^{***}	13.1
Continuous crop (CC)	1.16^{***}	0.0090^{*}	-0.004	$0.04^{\dagger}$	12.7
Crop after fallow (CAF)	1.17^{***}	0.0044	0.088	0.01	13.2
Fallow (F)	1.06^{***}	0.0148^{***}	-0.256^{***}	0.15^{***}	12.7
Soil B					
General	1.05^{***}	0.00652^{***}	-0.287^{***}	0.14^{***}	12.3
Continuous crop (CC)	1.06^{***}	$0.0072^{\dagger}$	-0.399^{***}	0.15^{**}	13.7
Crop after fallow (CAF)	1.20^{***}	-0.0025	-0.197^{*}	$0.07^{\dagger}$	10.3
Fallow (F)	0.89^{***}	0.0152^{***}	-0.336^{***}	0.31^{***}	11.6

C.V. Coefficient of Variation.
Significance † P<0.10; * P<0.05; ** P<0.01; *** P<0.001.

As is shown in Table 4, no transformation was necessary to meet the assumptions of the ANOVA model. Measured BDs ranged between 0.69 and 1.66 Mg m^{-3}. Mean BD was similar for CAF and F strips (1.26 and 1.27 Mg m^{-3}), and greater for CC strip (1.32 Mg m^{-3}). As expected, the most significant factors affecting BD were DATE and DEPTH (P<0.0001). The smallest BDs were found during the fall and winter months (about 1.12 Mg m^{-3}), and the greatest in spring and summer (1.36 Mg m^{-3}). BD was smaller in the 0 to 7 cm soil layer (1.22 Mg m^{-3}) than in the 7 to 14 cm layer (1.34 Mg m^{-3}).

The effect of tillage on BD was significant in the three strips (P<0.03 for CC, P<0.09 for CAF, and P<0.002 for F). BD was greater, in general, for NT (mean of 1.34 Mg m^{-3}), medium for MT (1.27 Mg m^{-3}), and smaller for ST (1.22 Mg m^{-3}), according to tillage intensity.

The BD trends in Fig. 2 show that over the three strips BD was greater under NT in the 0 to 7 cm layer, and smaller under ST in the 7 to 14 cm layer, though differences were more significant in F, the only strip with significant TILLxDEPTH interaction (P<0.0001, Table 4). The greatest difference between tillage systems was found in F in June 1996 from 0 to 7 cm depth, 30 days and 109 mm after the last tillage operation.

Table 4
Bulk Density (BD, Mg m^{-3}) analysis of covariance and LSMEANS separation for the different field conditions. Soil A.

Source of Variation	Continuous crop (CC)	Crop after fallow (CAF)	Fallow (F)
GWC	0.0003	-	0.0001
GC	-	-	0.0001
TILL	0.03	0.09	0.002
DATE	0.0001	0.0001	0.0006
TILLxDATE	NS	NS	NS
DEPTH	0.0001	0.0001	0.0001
TILLxDEPTH	NS	NS	0.0001
DATExDEPTH	NS	NS	0.05
TILLxDATExDEPTH	NS	NS	0.07
Model Pr>F	0.0001	0.002	0.0001
MSE	0.011	0.016	0.008
D.F.	52	54	61
R-square	0.87	0.78	0.90
C.V.	7.9	10.0	6.9
Transformation	Unnecessary	Unnecessary	Unnecessary
TILL			
ST	1.27 b	1.22 b	1.19 c
MT	1.31 ab	1.26 ab	1.25 b
NT	1.36 a	1.31 a	1.36 a
DATE			
Mar/95	1.46 ab	1.30 a	1.27 cd
May/95	-	-	1.26 cd
Sep/95	1.26 c	1.22 b	1.16 d
Nov/95	0.78 d	1.12 b	1.16 d
Feb/96	1.40 ab	1.34 a	1.38 ab
Jun/96	1.58 a	1.34 a	1.29 bc
Mar/97	1.40 ab	1.31 a	1.36 ab
DEPTH			
0-7	1.26 b	1.21 b	1.20 b
7-14	1.37 a	1.32 a	1.34 a

GWC Gravimetric Water Content (%).
GC Gravel Content (Mg m^{-3}).
TILL Tillage system: Subsoil Tillage (ST), Minimum Tillage (MT), No-Tillage (NT).
DATE Date on which measurements were made.
DEPTH Depth of soil (cm).
MSE Mean Square Error.
D.F. Degrees of Freedom.
NS Non-significant at the 0.1 probability level.
C.V. Coefficient of Variation.

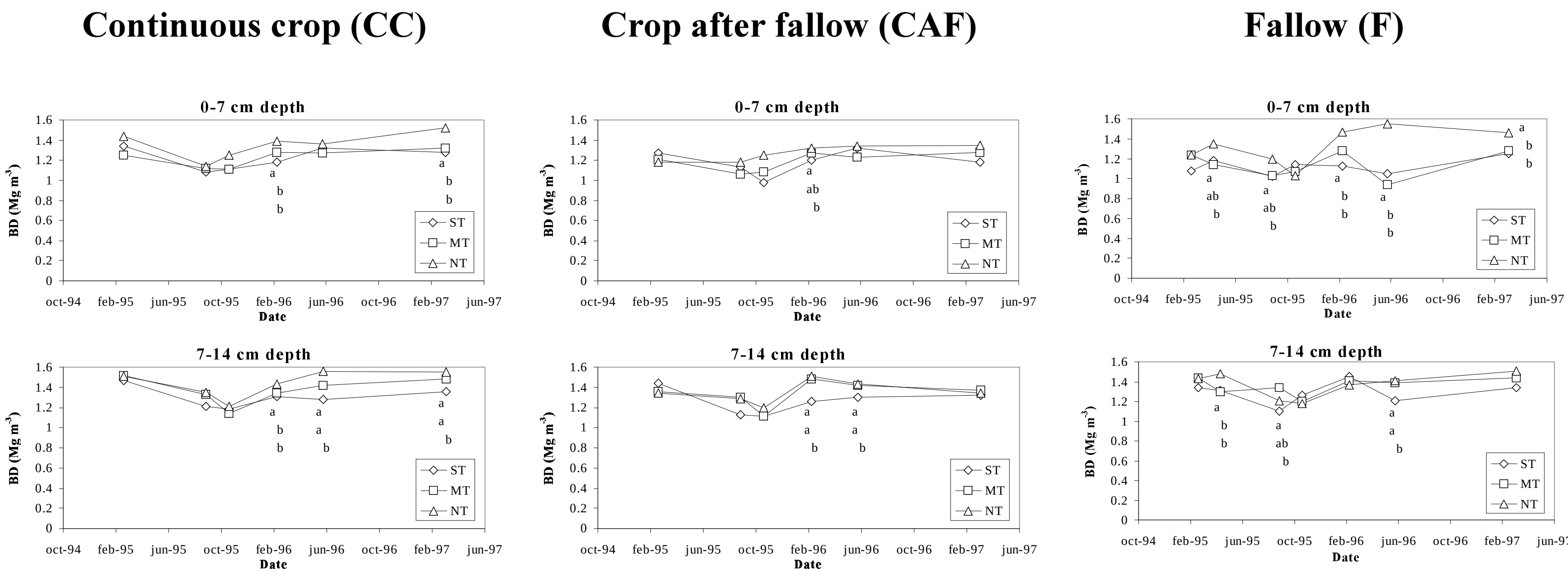

Fig. 2. Bulk Density (BD) trends for three tillage systems: Subsoil Tillage (ST), Minimum Tillage (MT) and No-Tillage (NT). Soil A.

2.2. Soil B

The regression analysis of BD vs. GWC and GC found significant regression coefficients (P<0.0001) for both variables (Table 3), though the slopes were significantly different for each strip, especially for GWC. Accordingly, GC and GWC were used as covariables in the analysis of covariance of CC and CAF strips, whereas only GC was used in the F strip.

The results of the analysis of covariance (Table 5) show that neither TILL nor TILLxDEPTH interaction were significant in any strip. BD ranged from 0.67 to 1.46 Mg m^{-3}. Mean BD for both tillage systems was 1.10 Mg m^{-3}. Clearly, DEPTH had a significant effect (P<0.0001), with a mean BD of 1.04 Mg m^{-3} from 0 to 7 cm depth and 1.17 Mg m^{-3} from 7 to 14 cm. For CC (P<0.003) and F (P<0.02) strips, BD increased with time (from 1.01 Mg m^{-3} in March 95 to 1.20 in March 97 for CC, and from 1.11 to 1.25 Mg m^{-3} for F on the same dates), whereas for CAF it decreased (from 1.21 to 1.14 Mg m^{-3}), though this decrease was not statistically significant.

Table 5
Bulk Density (BD, Mg m^{-3}) analysis of covariance and LSMEANS separation for the different field conditions. Soil B.

Source of Variation	Continuous crop (CC)	Crop after fallow (CAF)	Fallow (F)
GWC	0.02	-	0.0001
GC	0.0008	0.001	0.0001
TILL	NS	NS	NS
DATE	0.003	NS	0.02
TILLxDATE	NS	NS	NS
DEPTH	0.0001	0.0001	0.0001
TILLxDEPTH	NS	NS	NS
DATExDEPTH	NS	NS	0.07
TILLxDATExDEPTH	NS	NS	0.08
Model Pr>F	0.002	0.0002	0.0001
MSE	0.012	0.005	0.007
D.F.	28	29	34
R-square	0.84	0.86	0.90
C.V.	10.0	6.4	7.4
Transformation	Unnecessary	Unnecessary	Unnecessary
TILL			
MT	1.12	1.10	1.08
NT	1.09	1.15	1.10
DATE			
Mar/95	1.01 c	1.21	1.11 b
May/95	-	-	0.98 b
Sep/95	0.97 c	1.09	0.93 b
Feb/96	1.13 bc	1.07	1.13 ab
Jun/96	1.21 ab	1.13	1.14 ab
Mar/97	1.20 a	1.14	1.25 a
DEPTH			
0-7	1.03 b	1.08 b	1.02 b
7-14	1.18 a	1.17 a	1.16 a

GWC Gravimetric Water Content (%).
GC Gravel Content (Mg m^{-3}).
TILL Tillage system: Minimum Tillage (MT), No-Tillage (NT).
DATE Date on which measurements were made.
DEPTH Depth of soil (cm).
MSE Mean Square Error.
D.F. Degrees of Freedom.
NS Non-significant at the 0.1 probability level.
C.V. Coefficient of Variation.

3. Penetration Resistance (PR)

3.1. Soil A

To analyse PR we considered GWC and BD as covariables. Both showed strongly significant regression coefficients (-0.092 for GWC and 5.15 for BD, Table 6). As coefficients were different in each strip, separate covariance analysis was performed for by strips.

As is shown in Table 7, though TILL factor was not significant, TILLxDEPTH interaction was very significant in the three strips (P<0.0001). TILLxDATExDEPTH interaction was also significant in the CAF (P<0.02) and F (P<0.007) strips. Differences between tillage systems were more evident in the first 20 cm depth, principally on the following dates (Fig. 3): May 1995 in the F strip, 34 days after cultivator tillage (23 mm of accumulated rainfall); September 1995, 30 days after tillage (72 mm); and March 1997, 176 days after last tillage (274 mm). On these dates, NT had a PR that was 0.5 to 1 MPa greater than MT and ST in the first 10 cm depth, especially in the F strip. Also ST showed a PR that was about 1 MPa lower than MT and NT from 10 to 25 cm depth in September 1995, especially on the CAF and F strips.

The greatest differences between CC and CAF strips were found in the first 20 cm of soil. In this layer, mean PR was greater for CC than for CAF (0.43 MPa on ST, 0.27 on MT, and 0.36 on NT).

Table 6
Coefficients of the general and by strip regressions of Penetration Resistance (PR) vs. Gravimetric Water Content (GWC) and Bulk Density (BD) for Soil A and Soil B.

	Intercept	GWC	BD	R^2	C.V.
Soil A					
General	-3.15^{***}	-0.092^{***}	5.15^{***}	0.31^{***}	40.8
Continuous crop (CC)	-3.10^{***}	-0.087^{***}	5.00^{***}	0.28^{***}	39.4
Crop after fallow (CAF)	-2.82^{***}	-0.116^{***}	5.18^{***}	0.40^{***}	42.0
Fallow (F)	-3.31^{***}	-0.072^{***}	5.09^{***}	0.26^{***}	40.8
Soil B					
General	1.94^{***}	-0.099^{***}	1.89^{***}	0.12^{***}	50.8
Continuous crop (CC)	2.45^{***}	-0.067^{***}	1.12^{***}	0.06^{***}	48.4
Crop after fallow (CAF)	1.16^{***}	-0.107^{***}	2.51^{***}	0.23^{***}	50.2
Fallow (F)	1.53^{***}	-0.111^{***}	2.34^{***}	0.15^{***}	51.9

C.V. Coefficient of Variation.
Significance *** P<0.001.

Table 7
Penetration Resistance (PR) analysis of covariance for the different field conditions. Soil A.

Source of Variation	Continuous crop (CC)	Crop after fallow (CAF)	Fallow (F)
GWC	0.0001	0.0001	0.0001
BD	0.0001	0.0001	0.0001
TILL	NS	NS	NS
DATE	0.001	NS	0.0002
TILLxDATE	NS	NS	NS
DEPTH	0.0001	0.0001	0.0001
TILLxDEPTH	0.0001	0.0001	0.0001
DATExDEPTH	0.0001	0.0001	0.0001
TILLxDATExDEPTH	NS	0.02	0.007
Model Pr>F	0.0001	0.0001	0.0001
MSE	5296	6101	7086
D.F.	2102	1522	2189
R-square	0.70	0.70	0.64
C.V.	27.5	31.7	30.8
Transformation	Unnecessary	Unnecessary	Unnecessary

GWC Gravimetric Water Content (%).
GC Gravel Content (Mg m^{-3}).
TILL Tillage system.
DATE Date on which measurements were made.
DEPTH Depth of soil (cm).
MSE Mean Square Error.
D.F. Degrees of Freedom.
NS Non-significant at the 0.1 probability level.
C.V. Coefficient of Variation.

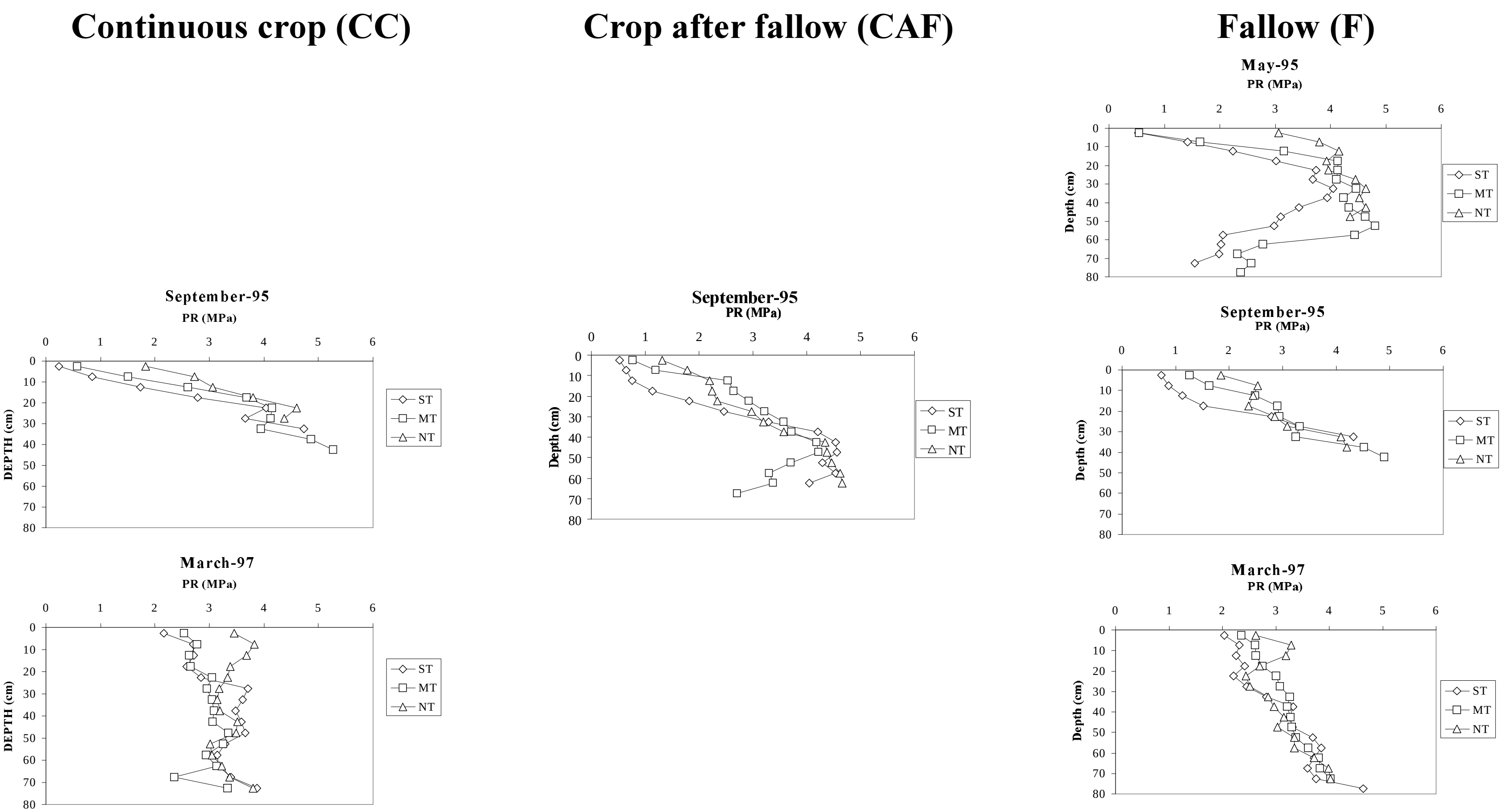

Fig. 3. Penetration resistance (PR) profiles in the three strips at different times for the three tillage systems: Subsoil Tillage (ST), Minimum Tillage (MT) and No-Tillage (NT). Soil A

.

3.2. Soil B

As in Soil A, GWC and BD were used as covariables because their regression coefficients were significantly different from zero (P<0.0001): -0.099 for GWC and 1.89 for BD (Table 6), and separate covariance analysis was performed by strips.

TILL, as a main factor, was only significant (P<0.012) in the F strip (Table 8). On the other hand, TILLxDEPTH interaction was significant in the three strips (P<0.009 for CC, P<0.0001 for CAF and F strips). Fig. 4 shows PR profiles for February 1995, February 1996 and March 1997, 112, 119 and 140 days after the last tillage operation respectively. In CC, PR increased with year from about 3 MPa in 1994 to nearly 4 MPa in 1996. The differences between MT and NT also increased from zero to 1 MPa in the 0 to 10 cm layer for the same period of time. On the CAF strip, PR increased with year and the differences between MT and NT also increased from 0.5 MPa in February 1996 to 1 MPa in March 1997. In the F strip, both mean PR and differences in PR between tillage systems decreased with year. The largest differences in PR between MT and NT, up to 2 MPa, were found in the first 10 to 15 cm of soil in the F strip in May 1995 (34 days after tillage), and June 1996 (30 days after tillage) (Fig. 5).

In the first 20 cm of soil, PR was greater in the CC than in the CAF strip, with a difference of 55 MPa for MT and 32 MPa for NT.

Table 8
Penetration Resistance (PR) analysis of covariance for the different field conditions. Soil B.

Source of Variation	Continuous crop	Crop after fallow	Fallow
GWC	0.0001	0.0001	0.0001
GC	0.0001	0.0001	0.0001
TILL	NS	NS	0.012
DATE	0.038	0.0001	0.0001
TILLxDATE	NS	NS	0.028
DEPTH	0.0001	0.0001	0.0001
TILLxDEPTH	0.0094	0.0001	0.0001
DATExDEPTH	0.0001	0.0001	0.0001
TILLxDATExDEPTH	NS	0.0043	0.04
Model Pr>F	0.0001	0.0001	0.0001
MSE	7139	4976	6138
D.F.	792	649	1041
R-square	0.62	0.74	0.69
C.V.	33.0	31.5	33.9
Transformation	Unnecessary	Unnecessary	Unnecessary

GWC Gravimetric Water Content (%).
GC Gravel Content (Mg m^{-3}).
TILL Tillage system.
DATE Date on which measurements were made.
DEPTH Depth of soil (cm).
MSE Mean Square Error.
D.F. Degrees of Freedom.
NS Non-significant at the 0.1 probability level.
C.V. Coefficient of Variation.

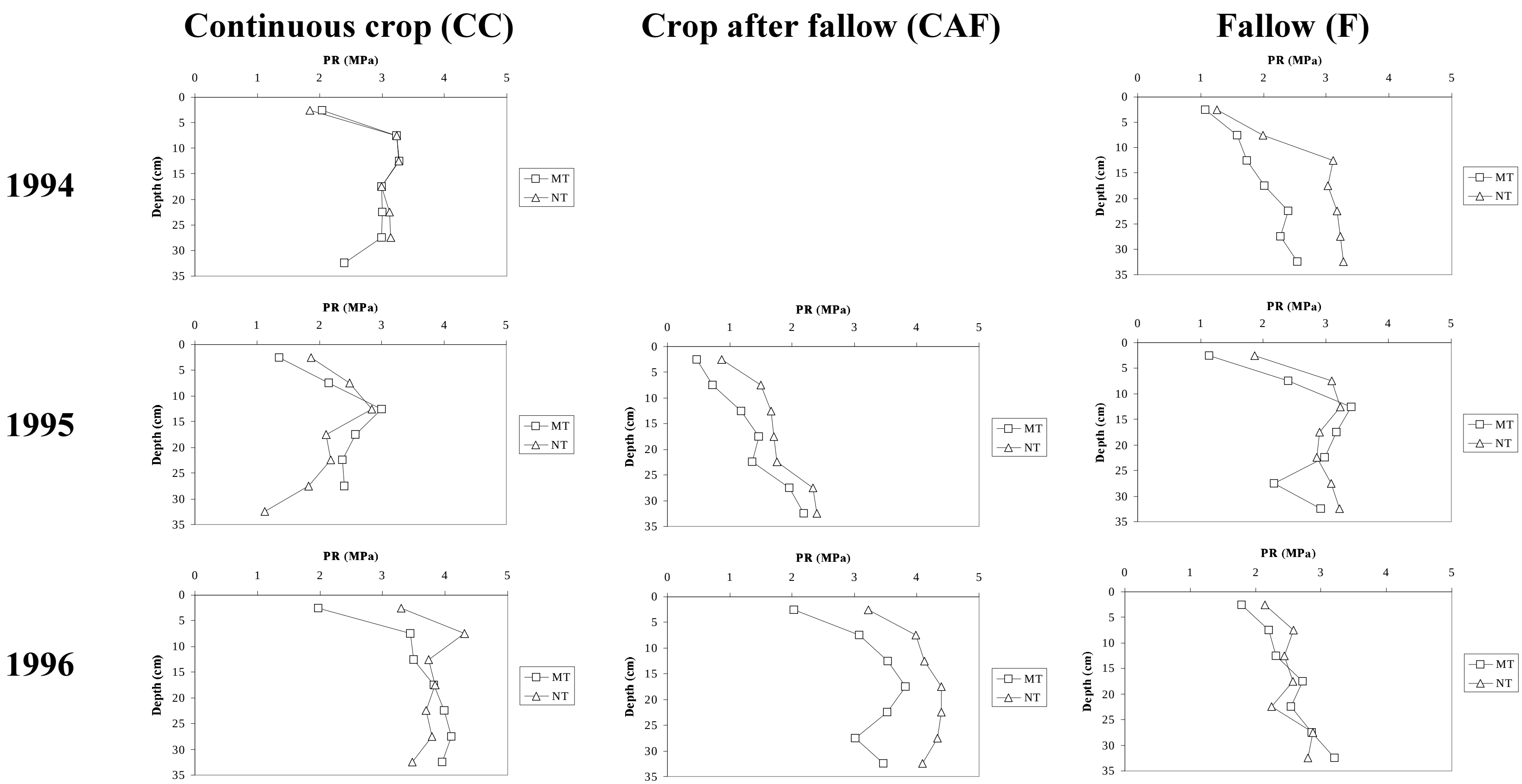

Fig. 4. Penetration Resistance (PR) changes in time for the three strips and the two tillage systems: Minimum Tillage (MT) and No-Tillage (NT). Soil B.

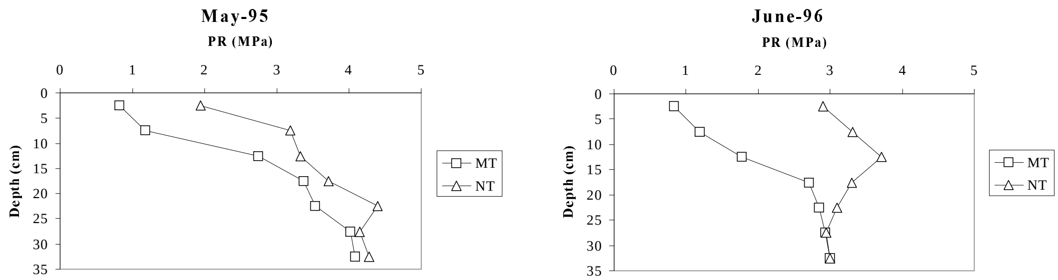

Fig. 5. Two Penetration Resistance (PR) profiles in the fallow strip showing the largest PR differences between the tillage systems: Minimum Tillage (MT) and No-Tillage (NT). Soil B.

Discussion

1. Fallow effect on soil strength

During fallow, tillage was performed to control weeds in ST and MT plots. This tillage also had a loosening action that reduced BD and PR in these plots. This effect extended to the following crop, as is shown by the lower BD and PR found on the CAF strip than on the CC strip. In NT plots lower soil strength was also found on the CAF strip than on the CC strip. In these plots only natural soil-loosening factors, such as drying and wetting cycles or fauna activity, could reduce soil strength because weeds were removed chemically. Strength reduction due to fallow in NT plots was greater than in MT plots of Soil A and smaller than in MT plots of Soil B. This indicates that in some situations natural factors induced by fallow may be as effective as tillage in reducing soil strength.

2. Tillage effects on soil strength

Bulk density on NT was greater than on tilled plots in the first 7 cm of Soil A, as has also been reported by a number of authors (Pelegrin *et al.*, 1988; Radclifee *et al.*, 1988; Hammel, 1989; Hill, 1990; Grant and Lafond, 1993; Rhoton *et al.*, 1993; Franzen *et al.*, 1994; Hubbard *et al.*, 1994; Franzluebbers *et al.*, 1995; Unger and Jones, 1998; Tebrügge and Düring, 1999; Wander and Bollero, 1999), and increased from 1.29 Mg m^{-3} in March 1995 to 1.44 Mg m^{-3} in March 1997. This effect was especially clear on fallow plots (Fig. 2).

There could be two reasons for these results. First, we measure BD in the first five years after the change from conventional tillage to no-tillage. According to Kinsella (1995), the soil was in the transition or repair period in which it builds humus, regains its structural stability and restores the pore space. During this period there is first an increase in BD until a maximum, and then a decrease due to the restructuring process, until an equilibrium level is reached when the structure is fully restored. The second reason was the low quantity of residues left on the soil (straw was packed and removed after harvest), which delayed the increase in organic matter and the restructuring process of the soil.

Subsoiling was effective in reducing BD in depth (7 to 14 cm). Larger differences would probably have been found if BD had been measured at greater depths.

In Soil B, with a greater gravel content than Soil A, no differences were found in BD between tillage systems due to the structural effect of gravel (Franzen *et al.*, 1994), which protected the soil against compaction in both MT and NT plots.

When significant differences were found between tillage systems in PR, plots under NT showed larger PR in the first 10 to 20 cm of soil than tilled plots, as has also been observed by a number of authors (Radclifee, 1988; Hammel, 1989; Hill, 1990; Pelegrin *et al.*, 1990; Agenbag and Maree, 1991; Grant and Lafond, 1993; Franzen et al, 1994; López *et al.*, 1996; Wander and Bollero, 1999; Ferreras *et al.*, 2000). In Soil A, differences found in the first 20 cm depth were according to tillage intensity: lower PR for ST, medium for MT, and higher for NT. In March 1997, far from tillage operations, great differences were found between NT and ST or MT on CC in Soil A (Fig. 3), and between NT and MT on CC and CAF in Soil B (Fig 4). This seems to indicate, as in the case of BD, that the soil under NT is in the transition period, when the soil strength increases.

3. Soil strength and root growth

The maximum BDs recorded in Soil A were between the critical (1.67 Mg m^{-3}) and the non-limiting (1.46 Mg m^{-3}) BD values for root growth stated by Pierce *et al.* 1983 (cited by Godwin, 1990). In Soil B, BD was below the non-limiting value. On the other hand, 59% of the PR recorded in Soil A and Soil B ranged from 1.3 to 3.7 MPa. This PR values are reported to produce a 50-100% reduction in elongation rate for barley (Hadas, 1997). On the other hand, root length density profiles (Lampurlanés *et al.*, 2000a, Lampurlanés *et al.*, 2000b) do not denote wrong conditions for root growth in these soils because the greatest root length densities were found on NT, the tillage treatment that also showed the greatest soil strength.

In Soil A, under CC, the root profile in February 1996 (Fig. 6-A) showed a 0.7 cm cm^{-3} smaller root length density (LV) for NT than for ST or MT in the 0-30 cm depth layer. BD (Fig. 2, continuous crop) was also significantly larger for this treatment (0.14 Mg m^{-3}). In September 1995, at the beginning of the root growth, PR was more than 1 MPa higher for NT than for ST or MT in the first 10 cm of soil (Fig. 3, continuous crop). High soil strength, as measured by BD and PR, could produce this result.

On the other hand, in the CAF strip in February 1996 ST showed less root length density (Fig. 6-B), although BD in February 1996 and PR in 1995 were smaller for this system than for the other. Lower water relations in these conditions may have reduced root growth (Cassel, 1982). In Soil B, MT showed a consistently higher root length density than NT in 1996-97 in the 0-10 cm layer of the CAF strip (Lampurlanés *et al.*, 2000b, Fig. 9). PR was also consistently higher under NT at this depth (Fig. 4) and may be responsible for the observed root growth differences.

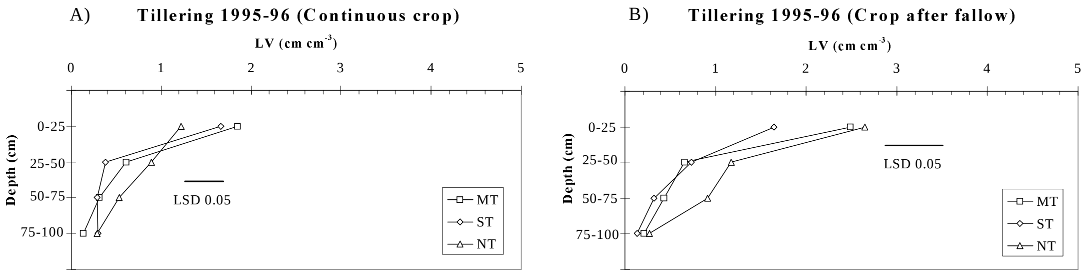

Fig. 6. Two Root Length Density (LV) profiles in the Continuous Crop (CC) and Crop After Fallow (CAF) strips under three tillage systems: Subsoil Tillage (ST), Minimum Tillage (MT) and No-Tillage (NT). Soil A.

To quantify the relationship between soil strength and root growth, a multiple regression analysis was performed on each soil (Table 9), with the growth rate of the root length density as the response variable and GWC, BD and PR as predictors. The results indicate a positive and very significant relationship between the growth rate and the GWC, a negative but not significant relationship with BD, and a significant relationship with PR which was negative for Soil A and positive for Soil B. The relationship with GWC was positive because most PR data were from the pre-anthesis period. The fact that the relationship with BD was not significant corroborates the idea that BDs in these soils were below the critical range for root growth. Though significant, both regression coefficients found for PR were very low, indicating a small effect of PR on root growth. The positive regression coefficient found in Soil B my be due to the high gravel content in this soil, especially in the first layer where root length density is also greater. Low regression coefficients may also be caused by the high PR encountered in both soils.

Table 9
Regression coefficients of the growth rate of the root length density vs. Gravimetric Water Content (GWC), Bulk Density (BD) and Penetration Resistance (PR) for Soil A and Soil B.

	Intercept	GWV	BD	PR	R^2	C.V.
Soil A	0.02	0.0006^{**}	-0.14	-0.00002^{*}	0.12^{***}	142
Soil B	-0.02	0.0023^{***}	-0.02	0.00006^{*}	0.10^{***}	212

C.V. Coefficient of Variation.
Significance * P<0.05; ** P<0.01; *** P<0.001.

Several factors could contribute to these high PR readings. Firstly, the soil has a high gravel content. The gravel interfered with the penetrometer measurements, increasing the values (Hamblin, 1985) and the variance of the PR readings (Campbell and O'Sullivan, 1991). Secondly, these soils have a moderately high clay content (Table 1) that increases with depth and leads to the formation of strong columnar aggregates (Villar, 1989) which increase the PR readings (Atwell, 1993). Finally, the organic matter was relatively high for these semiarid soils (2-3% in the top layer of the soil, Table 1), which is also reported to increase PR (Campbell and O'Sullivan, 1991).

The stress required to drive a probe into compacted soil is four to eight times that required for the roots to penetrate the soil (Bengough, 1991; Atwell, 1993), because roots grow along the boundaries between the peds, thereby avoiding the resistance to penetration of the bulk soil (Cambell and Henskall, 1991; Atwell, 1993), as was observed by Villar (1989) in Soil A.

The reduction in soil strength in the CAF strip due to fallow resulted in higher growth rates of the root length density than in the CC strip (Table 10). This effect was observed in both Soil A and Soil B, demonstrating the favourable effect that fallow can have on root growth in the first stages of the crop.

Table 10
Growth rate of the root length density (cm cm^{-3} day^{-1}) in the pre-anthesis stages for three tillage systems (Subsoil Tillage (ST), Minimum Tillage (MT), No Tillage (NT)) and two field situations (Continuous Crop (CC) and Crop After Fallow (CAF)). Soil A and Soil B.

	Soil A Field situation			Soil B Field situation		
Tillage	CC	CAF	**Mean**	CC	CAF	**Mean**
ST	0.0038	0.0079	**0.0056**	-	-	**-**
MT	0.0063	0.0080	**0.0071**	0.0109	0.0126	**0.0118**
NT	0.0054	0.0067	**0.0060**	0.0105	0.0192	**0.0149**
Mean	**0.0052**	**0.0075**		**0.0107**	**0.0159**	

Conclusions

Fallow has been effective in reducing soil strength for the following crop. This effect is as important in tilled as in non-tilled fallows, indicating that natural loosening factors may be as effective as tillage in reducing soil strength.

After the introduction of no-tillage there is an increase in soil strength compared with tilled soils. In our well-structured soils, this increase in strength does not limit root growth because roots can grow between the aggregates. In gravely soils, the increase in strength is smaller due to the structural supporting effect of gravel.

Differences in root growth due to the cropping (fallow or continuous crop) or tillage system were small because the soil strength do not raised limiting levels for root growth.

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