A COMPARISON BETWEEN SEASONAL CHANGES IN SOIL WATER STORAGE AND PENETRATION RESISTANCE UNDER CONVENTIONAL AND CONSERVATION TILLAGE SYSTEMS IN ARAGON

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Abstract

Low and extremely variable precipitations limit dryland crop production in the semi-arid areas of Aragón (NE Spain). These areas are also affected by high annual rates of topsoil losses by both wind and water erosion. A long-term experiment to determine the feasibility of conservation tillage in the main winter barley production areas of Aragón was initiated in 1989 at four locations, three on loam to silt loam soils (Xerollic Calciorthid) and one on a silty clay loam (Fluventic Ustochrept), receiving between 300 and 600 mm of average annual rainfall. In this study, we compared, under both continuous cropping and cereal-fallow rotation, the effects of conventional tillage (moldboard plow) and two conservation tillage systems, reduced tillage (chisel plow) and no-tillage, on soil water content and penetration resistance during the first two growing seasons. Whereas reduced and conventionally tilled treatments generally had similar soil water contents during the experimental period, the effects of no-tillage were inconsistent. No-tilled plots had from 26% less to 17% more stored soil water (0-80 cm) than conventional tilled ones at the beginning of the growing season. In contrast to the conventional and reduced tillage treatments, penetration resistances were between 2 and 4 MPa after sowing in most of the plow layer (0-40 cm) under no-tillage at all sites. Fallow efficiencies in moisture storage in the cereal-fallow rotation, when compared with the continuous cropping system, ranged from -8.7 to 12%. The highest efficiencies were recorded when the rainfall in the months close to primary tillage exceeded 100 mm. Since this event is very unlikely, long fallowing (9-10 months) appears to be an inefficient practice for water conservation under both conventional and conservation management. Our results suggest that, up to now, only reduced tillage could replace conventional tillage without adverse effects on soil water content and penetration resistance in the dryland cereal-growing areas of Aragón.

Key words: reduced tillage, no-tillage, dryland cropping, soil water content, soil strength

Introduction

In Aragón (NE Spain), about one million ha of the rainfed arable land (1.36 million ha) have an average annual precipitation of 500 mm or less. In these areas, the rainfall is sporadic and highly variable from year to year and during the growing season. In contrast to many other semi-arid regions, there is no well defined rainy season (McAneney and Arrúe, 1993). Consequently, there are low, variable, and, in some years, no harvestable yields. In addition, dry WNW winds (*Cierzo*) can accentuate the effects of limited available water. Because of their shallowness, poor structure, and low organic matter content (<20 g kg^{-1}), soils in these areas are susceptible to compaction and erosion. It has been estimated that about 55% of the rainfed land with less than 400 mm annual rainfall is affected by annual soil erosion losses greater than 12 t ha^{-1} (Arrúe and López, 1991). Hence, soil and water conservation is an issue of primary concern in this region. Conservation tillage is a promising alternative to traditional tillage for cereal production in Aragón. The adoption of these systems would reduce production costs and help to achieve the requirements for protection of soil and water resources imposed by the current Common Agricultural Policy of the European Union.

Benefits from conservation tillage, including improvement of soil properties, savings of time and energy, and water and wind erosion control, have been reported in many studies carried out under different environmental conditions. Cannell (1985), Griffith et al. (1986), and Lal (1989), among others, have reviewed these experiences. However, conservation tillage practices, and no-tillage in particular, do not always result in favourable soil conditions. Increased soil strength and decreased porosity and water infiltration have been observed by several authors under continuous no-tillage (Hill, 1990; Thorburn, 1992; Vyn and Raimbault, 1993). These contrasting responses to conservation tillage suggest the need for local evaluation. Conservation tillage research in Spain is relatively recent. First experiences with herbaceous crops started at the beginning of the eighties and in 1989 in Aragón. Long-term results, necessary for an accurate evaluation of conservation tillage, are not available yet.

The traditional farming system in the semi-arid areas of Aragón is the cereal-fallow rotation (one crop in two years), allowing livestock integration. Barley (*Hordeum vulgare* L.) is the cereal grown in most of the region. The suitability of a long fallow (9-10 months) has been questioned in relation to production costs, soil fertility, livestock use, soil erosion, and, especially, soil water conservation (López and Giráldez, 1992; McAneney and Arrúe, 1993). The ability of fallowing in the cereal-fallow rotation to increase soil water storage and water use by crops has still not been demonstrated in different regions of Spain, including Aragón.

A long-term research project was initiated in 1989, in cooperation with the Farming Techniques Section of the Aragón Department of Agriculture, in order to determine the feasibility of conservation tillage systems (reduced tillage and no-tillage) for different dryland cereal-growing areas of Aragón. In this paper we report and discuss the effects of reduced and no-tillage practices on soil water content and penetration resistance and their evolution over the first two growing seasons (1990-91 and 1991-92) in four different areas. Water storage efficiencies of fallowing in the cereal-fallow rotation with respect to the continuous cropping system are also compared under both conventional and conservation tillage techniques. The effects of these tillage practices and cropping systems on barley growth and yield, and water use efficiency will be reported in a subsequent paper.

Materials and methods

Site and soil characteristics

Four sites representing the main dryland cereal production areas in Aragón were selected to conduct the long-term conservation tillage research (Fig. 1). Two sites, Peñaflor and Zuera, were respectively located at the Consejo Superior de Investigaciones Científicas and Diputación General de Aragón experimental farms, both in the Zaragoza province. The soils are loam (fine-loamy, mixed, thermic Xerollic Calciorthid) at Peñaflor and silt loam (fine-silty, mixed, thermic Xerollic Calciorthid) at Zuera. The other two sites, Híjar and Banastás, were respectively located in the Teruel and Huesca provinces within collaborating commercial farms. The soil at the Híjar site is loam (fine-loamy, mixed, thermic Xerollic Calciorthid) and silty clay loam (fine-silty, mixed, thermic Fluventic Ustochrept) at Banastás. Details on the experimental sites and soils are shown in Table 1.

A preliminary geostatistical survey verified the apparent uniformity of soil characteristics over the selected fields (López and Arrúe, 1995). All sites were nearly level with the exception of the Híjar site where a slight slope (<2%) was present in the N-S direction. Prior to the establishment of the experimental plots in the summer of 1990, all sites had been conventionally tilled and barley had been grown under continuous cropping (Banastás site) and cereal-fallow rotation (Peñaflor, Zuera, and Híjar sites) for at least the previous 10 years.

The four sites were on an agroclimatic gradient with average annual rainfall ranging from 300 mm in Peñaflor to 600 mm in Banastás (Fig. 1). Likewise, average cereal yield varies between less than 1500 kg ha^{-1} at Peñaflor, about 2000 at Zuera and Híjar, and more than 3000 kg ha^{-1} at Banastás.

Tillage and crop management

The tillage treatments were conventional tillage (CT), reduced tillage (RT) and no-tillage (NT). At the Peñaflor, Zuera, and Híjar sites, where the traditional farming system is the crop-fallow rotation, the three tillage treatments were compared under both continuous cropping (CC) and cereal-fallow rotation (CF). At Banastás, the most humid location, only the CC system was considered. Figure 2 summarizes the main characteristics of both cropping systems, CC and CF. The numbers of days indicated in the figure are the mean values for the four sites and the two experimental growing seasons (1990-91 and 1991-92).

The CT treatment in the CC system consisted of moldboard plowing to 30-40 cm depth in summer followed by secondary tillage to 10-15 cm with a harrow or cultivator in the fall prior to sowing (Fig. 2). In the RT treatment, primary tillage was chisel plowing to 25-30 cm depth (non-inverting action) in summer followed, as in CT, by fall harrow or cultivator tillage. The NT plots were not tilled and weeds were controlled by herbicides. Under the CF rotation the deep tillage using a moldboard plow (in the CT treatment) or chisel (RT treatment) was carried out in winter during the fallow year (Fig. 2). In both CT and RT treatments a second tillage operation was done with a harrow or cultivator in spring. After this, the fields were not plowed until the fall when the seedbed was prepared prior to sowing (Fig. 2).

Fallow management in the NT treatment consisted of weed control entirely with herbicides. In the second year of the CF rotation the cereal was grown following the normal practices as in the CC system.

Barley (winter varieties) was sown in November. Conventional seeders were used in the CT and RT treatments. In the NT treatment the barley was sown directly into the crop residue from the previous harvest using a disc zero-till seeder (AMAZONE NT 250). The amounts of residues remaining at sowing under NT ranged from approximately 500 to 1200 kg ha^{-1} at the Peñaflor, Zuera and Híjar sites and 3000 to 4000 kg ha^{-1} at the Banastás site. Sowing and harvest dates are shown in Table 2. Dates of agronomic practices were the same for all tillage treatments at each site but varied among sites depending on their soil and crop conditions. Fertilizers and herbicides were applied following the recommendations of the Aragón Department of Agriculture, according to soil fertility tests and weeds present at each experimental site. Except for the NT treatment, which needed one to two more herbicide applications during each growing season at all sites, herbicides and fertilizers, and their rates, were the same for all treatments.

Experimental design

Tillage treatments were arranged at all sites in an incomplete block design with three replications for the RT and NT treatments and four for the CT treatment (to ensure a balanced design). This design, based on geostatistical concepts, was adapted to our tillage study from van Es et al. (1989). Details about this design and its efficiency are found in López and Arrúe (1995).

At the Peñaflor, Zuera, and Híjar sites, where the CF and CC systems were compared, each tillage plot was split transversely into two cropping system subtreatments. Thus, all tillage treatments were duplicated under CC and CF rotation, arranging in a split block design with tillage as the main plot and cropping system as the subplot. The subplot size was 33.5 m x 10 m at the Peñaflor site and 50 m x 10 m at the remaining sites. A separation of 1 and 10 m was established between tillage plots and cropping system subplots, respectively. During the 1990-91 growing season the plots under the CC system were cropped with barley while those under the CF rotation were fallowed. Only in the CC plots were soil and crop observations made. In the 1991-92 growing season all plots were grown and measurements were taken in all.

To compare the effects of tillage treatments within each cropping system, analysis of variance (ANOVA) for the incomplete block design was used (López and Arrúe, 1995). To evaluate the cropping systems irrespective of tillage treatment and the tillage x cropping system interaction, ANOVA according to the split block design with three replications was performed. Duncan's multiple range test was used to compare between treatment means. Computations were performed using FORTRAN-77 and BMDP-8V programs.

Sampling and measurements

Daily precipitation and air temperature for the Peñaflor and Zuera sites were collected at permanent weather stations located within the experimental farms. At Híjar and Banastás, precipitation was measured with standard rain gauges installed in the plots. Long-term climatic data for these sites, including monthly precipitation and air temperature, as well as daily air temperature during the experimental period, were obtained from the closest National Weather Service stations (5-10 km distant from the sites).

Soil water content was determined gravimetrically to a depth of 80 cm in 10 cm increments. Two soil samples per depth and subplot (per plot at Banastás) were taken by augering from the barley row. Water contents were converted to a volume basis using bulk densities previously determined by taking three soil cores (6 cm internal diameter and 6 cm height) from each depth increment. Measurements were made four to five times during each growing season at selected crop growth stages (Zadoks et al., 1974): germination (ZGS 00-09), early stem elongation (ZGS 30-31), heading (ZGS 50-59), milky-doughy grain (ZGS 75-85), and ripening (ZGS 99). No soil water measurements were taken in the fallowed plots (i.e. the plots under the CF rotation in the 1990-91 growing season). Additional soil water data from the surface layer (0-40 cm) were obtained at sowing at all field sites.

Soil penetration resistance (PR) was determined by a recording penetrometer with a 60° cone and either a 1 or 2 cm² base area, and a 0-5 MPa range (penetrograph Stiboka 06.02, Eijkelkamp, Netherlands). PR data were recorded to a depth of 40 cm in 5 cm increments. Measurements were made at the same time and close to the two sampling locations in each subplot for water content. A minimum of 5 readings per location were taken (i.e. more than 10 per subplot) and two average PR profiles for each replicate and treatment were determined.

Other physical and chemical properties of the Ap horizon were determined at the start of the study to characterize the four soils (Table 1). Particle size distribution was determined using the pipette method (Gee and Bauder, 1986). Soil pH and electrical conductivity were measured in a 1:2.5 and 1:5 soil/water suspension, respectively. Soil organic matter and total nitrogen were analysed respectively by the Walkley-Black and Kjeldahl methods described in MAPA (1986). Consistency limits were obtained according to the method described by Sowers (1965). Soil water content at -33 and -1500 kPa were determined to a depth of 80 cm at 10 cm intervals using a pressure plate and pressure membrane methods, respectively (USSL, 1954). Plant available water capacity was defined as the difference between the water content at -33 and -1500 kPa.

Results

Precipitation

Monthly precipitation during the experimental period and 23-35 year averages are shown in Figure 3. Rainfall during the two growing seasons (November-June) was nearly average at Híjar and well below average (30-50% lower) at the rest. Whereas the total precipitation was similar in the two seasons, its distribution varied considerably. In the 1991-92 season only 15-20% of the total growing season rainfall was received from January to April. In contrast, this percentage in the 1990-91 season was generally higher than average, being 60% at Híjar.

Plow layer water content at sowing

At sowing, differences in soil water content (0-40 cm) between the experimental sites reflect the amount and distribution of rainfall prior to sowing (Fig. 3) and the different soil water storage capacities (Table 1). The soil water content at Banastás was the greatest in both growing seasons (Table 3). In the 1990-91 season, the high precipitation received at this site since the date of primary tillage replenished the plow layer up to 92% of its available water capacity. At Híjar, the high water content in the 1991-92 season (Table 3) (close to the -33 kPa value) resulted from timely rainfall received just one week before. In contrast, at Zuera and Híjar in the 1990-91 growing season, because of the sporadic and limited precipitation, sowing had to be performed at low soil water contents (about 20% of the available water capacity). At Peñaflor in the 1991-92 season, where the precipitation between primary tillage and sowing was 33% lower than the 35 year average, the plow layer contained almost no plant available water.

Tillage had a significant effect on water content at Peñaflor and Híjar in both growing seasons (Table 3). In general, the smallest water content corresponded to the NT treatment and the greatest to CT. Although neither significant differences between cropping systems nor tillage x cropping system interactions were found, the Peñaflor and Zuera sites exhibited the same trend in soil water content: CF < CC system. The reverse trend was presented at Híjar.

Seasonal changes of soil water storage

In 1990-91, the low precipitation at Peñaflor, Zuera and Híjar during November and December did not improve soil water storage to 80 cm at the first sampling date (ZGS 00-09, 19-49 days after sowing depending on the experimental site). At Peñaflor, the lowest water storage over the growing season occurred under NT (Fig. 4a), which was always at or below the water held at -1500 kPa (112 mm). At Híjar, the high rainfall in January-April recharged the soil profile at the second date (25.4.91; ZGS 30-31) to, on average, 73% of the water held at -33 kPa (218 mm). From this date to harvest, the NT treatment retained significantly more water than CT and RT (Fig. 4b). At Zuera, where no significant effects of tillage were found, the changes in the water stored were similar to those of Peñaflor (data not shown). With a higher average water storage at sowing (200 mm), a similar pattern of water depletion was observed at Banastás (data not shown). At this site, the lack of crop water use in the NT plots (barley seedlings were completely damaged as a result of the persistence of herbicide after sowing) meant that these plots consistently had more water than CT and RT plots.

The dynamics of soil water storage in the 1991-92 growing season was strongly conditioned by the extremely dry January-April period. At Peñaflor, the site most affected by drought, the soil water content was less than the -1500 kPa value for most of the time and neither tillage nor cropping system affected the status of soil water at any sampling date (data not shown). At Zuera, significant tillage effects were found only under the CC system. Here, the NT treatment retained an average of 24 and 32 mm more water than CT and RT at the first date (9.12.91; ZGS 00-09) and harvest (22.6.92), respectively (Fig. 5a). At Híjar, NT under CC contained from 13 to 33 mm more soil water than the other treatments through the whole growing season (Fig. 5b). In contrast, NT under the CF rotation had significantly the smallest stored water at the first and second dates (19.12.91, ZGS 00-09 and 27.4.92, ZGS 30-31). At Banastás, with a similar pattern of soil water storage and greater profile water contents (from 141 to 245 mm), no significant differences among tillage treatments were found (data not shown).

Soil water depletion under the NT treatment was confined more to the upper soil layers than for the other treatments, especially at the most arid sites. A clear example is shown in Figure 6, corresponding to changes in soil water profile for the CF plots at Híjar during the 1991-92 growing season. Initially, the NT plots had the smallest water content at all measured depths. As the growing season progressed, soil water was depleted more rapidly under CT and RT, which led at the harvest day (2.7.92) to a markedly higher residual water content in the NT plots, particularly below 30-40 cm depth (Fig. 6). Whereas in the CT and RT plots 36% of total water depleted was extracted from the 40-80 cm depth, in the NT plots extraction from this deeper layer was nil.

Although the pattern of seasonal variation in water storage was similar in the CF and CC systems, differences were detected in the early growing season. Thus, at Zuera, at the first date and regardless of tillage treatment, the CF rotation stored 19 mm more water than the CC system (LSD=10 mm; $P<0.05$), especially below 30 cm (Fig. 7a). This increase was more evident in the RT treatment (Table 4), although no significant tillage x cropping system interaction occurred. At Híjar, the CF rotation also increased soil water storage at the first date by an average of 35 mm (LSD=31 mm; $P<0.05$) and at the second and third dates by about 27 mm (LSD=21 mm; $P<0.05$) (Fig. 5b). Significant tillage x cropping system interactions occurred at the two first dates. The CT and RT plots under CF had, on average, between 51 mm at the first date (LSD=35 mm; $P<0.05$) and 35 mm at the second (LSD=28 mm; $P<0.05$) more water than the same plots under CC, predominantly stored below 20 cm (Fig. 7b). In contrast, the NT treatment did not significantly improve the water storage under the CF rotation (Table 4). At Peñaflor, the CF plots held less water than the CC plots, particularly under the CT treatment (Table 4). However, neither significant cropping system effects nor tillage x cropping system interactions were found in this case.

These results indicate that the capacity of the CF rotation to increase soil water storage during the fallow period was very variable, depending on the experimental site and tillage treatment. Thus, fallow efficiencies ranged from -8.7% under CT at Peñaflor to 12% under the same treatment at Híjar (Table 4). Fallow efficiency was defined here as the additional water stored in the CF plots in relation to the CC plots at the beginning of the second growing season expressed as the percentage of rainfall received during the fallow period. The fallow period was considered from the time of primary tillage in the CC plots (August-September 1990) to 7-21 days after sowing in the 1991-92 growing season (first sampling date of profile water storage). Actually, the date of primary tillage in the CC system is the time of the first modification of the plow layer in relation to the CF rotation (Fig. 2) and, therefore, the starting point to differentiate the ability of both cropping systems to conserve water.

Soil penetration resistance

Differences in PR in the plow layer (0-40 cm) among sites and tillage treatments at the beginning of the growing may be attributed to differences in soil water content at the time of sampling and the period since the primary tillage date. In the 1990-91 season, the major differences among treatments occurred where primary tillage was carried out more recently, as in the case of Zuera (Fig. 8a). In the 1991-92 season, Banastás showed the greatest effect of tillage (CT and RT versus NT) (Fig. 9) and Peñaflor the smallest (Fig. 8c). Generally, the RT and CT treatments reduced PR in agreement with the depths of primary tillage (Fig. 8).

Tables 5 and 6 show the proportion of the plow layer associated with specific PR ranges at the first and second sampling dates. Between these two dates the major changes in PR were observed. Overall, at the first date the greatest proportion of the soil profile was within the 0-2 MPa range under CT and RT. In contrast, under NT the greatest percentage corresponded to the 2-4 MPa range or even to the range above 4 MPa in some cases. Only at Banastás in both growing seasons did PR values not exceed 4 MPa under any tillage treatment.

PR increased markedly in the 3-4 months after the first sampling date. This increase was faster under the CT and RT treatments than NT, particularly in the 1990-91 season (Table 5). Thus, at the second date, the differences among tilled and no-tilled treatments almost disappeared, as occurred at Peñaflor and Zuera. At Banastás, the lack of crop in the NT plots was shown by the lowest PR values. At Híjar, the high soil water content after the rains in March-April 1991 resulted in relatively low PR values at the second date. At this date, a greater proportion of the soil profile with PR values above 4 and 2 MPa was found, respectively, at Zuera and Híjar under CT as compared to RT (Table 5).

In contrast, differences in PR between the tilled and no-tilled treatments still existed at the second sampling date of the 1991-92 season (Table 6). This was probably associated with the persistence of soil loosening effect by tillage, enhanced by an overall higher initial soil moisture content. In addition, in the NT plots just two years have passed without any tillage operation. Under this treatment, PR values greater than 4 MPa were recorded in nearly 80% of the soil profile. Similar PR values under the CF and CC systems indicate that PR was relatively unaffected by cropping system.

Changes in PR profiles from the second sampling date to harvest followed the rainfall pattern during this period. In the 1990-91 season, as soil became drier, PR increased in all treatments, exceeding 4

MPa at almost all depths (Fig. 8a,b). In the 1991-92 season, PR continued increasing until the third sampling date, when there were no differences among tillage treatments (Fig. 9). Because of rains in late growing season, it was possible to observe that residual effects of soil loosening by tillage were still present on the harvest day at Híjar and Banastás (Figs. 8d and 9). Since soil water content at this date was similar in the three tillage treatments at Banastás or even greater in NT at Híjar, these differences in PR among treatments can not be attributed to differences in water content.

Discussion

Soil water content

During the experimental period, soil water content under RT was, generally, similar to that under CT. In contrast, effects of NT were inconsistent, varying between experimental sites, years, and cropping systems. Our results imply that NT is, in general, an ineffective practice for improving soil water retention under our environmental conditions. Two reasons could explain this lack of favourable response, namely that soil structural changes were still insufficient and that there was too little crop residue on the soil surface. Amelioration of soil structure under NT is only appreciable in the long-term. It takes between five and six years of NT for these changes to become measurable, resulting in higher water intake (Dickey et al., 1989). In our study, therefore, two years was, probably, too short a period to evaluate adequately the NT effect. Furthermore, residue production at the most arid sites (Peñaflor, Zuera, and Híjar) was too low to affect soil water conservation. A minimum quantity of 2500 kg ha^{-1} of surface residue may be needed to increase available soil water in NT fallow systems (Tanaka, 1985) and this quantity is very unlikely in these low yielding areas. Several experiences of tillage and crop residue management in areas with low annual rainfall have demonstrated that NT was the tillage treatment mostly affected by residue management (Nyborg and Malhi, 1989; Radford et al., 1992). In our opinion, the greater water stored by NT plots under CC at Zuera and Híjar in the second growing season (Fig. 5) could be attributed to residue accumulation after two experimental years.

Our data suggest that neither RT nor CT ensure in the most arid sites an optimum soil water content at sowing. Tillage cannot always give adequate soil water storage in these areas due to the low and erratic precipitation and to the temporary nature of tillage effects. In theory, the rainfall received from the time of primary tillage to sowing in the CC system (90 and 130 mm) is sufficient for recharging the soil profile to about 90% of the available water capacity. However, only 8% of this rainfall was received in the month following primary tillage and this occurred as non-effective showers (<10 mm), resulting in substantial evaporation, especially in the CT treatment with soil-inverting action.

The opportunity of primary tillage in relation to precipitation frequency and distribution, and the retention of surface crop residue, especially in NT, were more important factors under the CF rotation than under the CC system because of the long fallow period in the former (Fig. 2). French (1978) found that the benefit of fallowing in a dry Mediterranean environment of South Australia depends on the winter rainfall. He showed that it was important to receive 100 mm or more of rainfall particularly in the months close to the primary tillage during fallow. In our study the total rainfall in these months (February and March) was 73, 80, and 153 mm at Peñaflor, Zuera, and Híjar, respectively, following the same order as for fallow efficiencies (Table 4). Although at Híjar this rainfall was more than 100 mm, this was exceptional since it occurred only twice in the 1961-89 period. Therefore, the probability of fallow efficiences greater than those obtained in this study is very low. The lower soil water held in the CF plots at Peñaflor can be attributed to evapotranspiration by weeds regrowing during the fallow period.

Fallow efficiencies found in the present study are comparable to those reported in the literature for long-fallows. French (1978), comparing fallow with non-fallow treatments in Australia, recorded efficiencies ranging from 1 to 19%. Recently, Incerti et al. (1993) obtained 3-26% efficiencies of long-fallows when compared with short-fallows in Victoria, Australia. Our results suggest that the CF rotation in our environments can not be justified simply in terms of soil water conservation, supporting the conclusion arrived by López and Giráldez (1992) and McAneney and Arrúe (1993) for different semi-arid regions of Spain.

Because the soil water contents during the experimental period under both CF and CC systems were similar, only RT appears to be a viable alternative to CT. Greater infiltration and lower surface evaporation are advantages associated with the soil structure created by non-inverting tillage such as chisel plowing (Lindstrom et al., 1974; Allmaras et al., 1977).

Soil penetration resistance

A PR of 1.5 MPa has been used as a reference value to evaluate the effectiveness of a tillage treatment to loosen the soil or to maintain a loosened state over time (Carter, 1988). In our study, due to the long time between primary tillage and the first sampling date, and the range of PR values found over the experimental period, we chose 2 MPa as the most suitable reference value for comparison purposes. Thus, after sowing, only the CT and RT treatments showed a relatively loose soil condition with at least 50% of the plow layer (0-40 cm) between 0 and 2 MPa. In contrast, smaller percentages of the plow layer (always less than 50%) were found in this PR range under NT (Tables 5 and 6). Clearly, the NT treatment represented the most unfavourable condition of mechanical impedance for an adequate emergence and early growth of barley.

Soil reconsolidation and drying processes under the influence of plant roots caused the gradual increase in PR observed during the two growing seasons at all sites. After tillering the loosening effect of tillage disappeared in both CT and RT treatments, since PR values less than 2 MPa below the first 10 cm depth were unusual. PR values exceeding 4-5 MPa recorded at different sampling dates corresponded to very small soil water contents, confirming the strong influence of soil water content on PR. Karlen et al. (1991) also reported PR averages of 4.7 and 6.5 MPa in a disked and non-disked, soil respectively, at small soil water contents. Despite the transitory nature of tillage effects, differences in PR between tilled and no-tilled treatments were still present at the end of the experimental period when soil water contents were high (Figs. 8d and 9). Greater soil strength in the topsoil under NT compared with conventional tillage systems is commonly observed in long-term experiments, especially for soils with low organic matter content, coarse texture, and poor structure (Hill, 1990). The lowest PR values were generally recorded at Banastás due likely to the higher crop residue, clay, and water contents of the soil.

In spite of a smaller depth of soil loosening under RT than CT, PR was similar in both tillage treatments over the experimental period. Nevertheless, a slower increase of PR values over time was detected under RT in some cases, as occurred at Zuera and Híjar in the first growing season (Table 5) and at Peñaflor in the second (Table 6 and Fig. 8c). A greater persistence of the soil loosening after chisel plowing compared with moldboard plowing was also observed by Cassel et al. (1978) on a sandy loam soil under soybean and by Sommer and Zach (1992) on a loamy sand soil under barley.

Conclusions

Results from the first two years of our long-term tillage study suggest that RT, under both CC and CF systems, could replace CT without adverse effects on soil water content and penetration resistance in the main dryland cereal-growing areas in Aragón (NE Spain). On the contrary, NT was not a viable alternative to CT in the most arid zones due to its low ability for soil water storage and the high values of soil strength detected even at the beginning of the growing season. However, owing to the time required for crop residues to accumulate, data for a longer period would be needed for an accurate evaluation of NT. Regardless of tillage method, fallowing in the CF rotation was found to be an inefficient practice for improving soil water storage when compared with the CC system. Due to the uncertain nature of rainfall distribution, the timing of primary tillage was a key factor for soil water conservation.

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Figure legends

Figure 1. Location of experimental sites and average annual rainfall isohyets (mm).

Figure 2. Summary of cultural practices for the traditional cereal-fallow rotation and continuous cropping systems in the study areas.

Figure 3. Monthly precipitation during the experimental period (solid line) and long-term average precipitation (dashed line) at the Peñaflor (1954-89), Zuera (1966-89), Híjar (1961-89), and Banastás sites (1955-89). S=sowing, H=harvest.

Figure 4. Seasonal changes in soil water storage in the 0-80 cm depth under different tillage treatments (■ conventional tillage; **x** reduced tillage; and ○ no-tillage) at (a) the Peñaflor and (b) Híjar sites in the 1990-91 growing season. Bars indicate LSD (*P*<0.05) for comparisons at the same date, where significant differences were found. S=sowing, H=harvest.

Figure 5. Seasonal changes in soil water storage in the 0-80 cm depth under different tillage treatments (■ conventional tillage; **x** reduced tillage; and ○ no-tillage) and cropping systems (CC continuous cropping; CF cereal-fallow rotation) at (a) the Zuera and (b) Híjar sites in the 1991-92 growing season. Bars indicate LSD (*P*<0.05) for comparisons among tillage treatments at the same date and cropping system, where significant differences were found. S=sowing, H=harvest.

Figure 6. Profile water distribution as affected by tillage (■ conventional tillage; **x** reduced tillage; and ○ no-tillage) under the cereal-fallow rotation at the Híjar site on selected dates during the 1991-92 rowing season. Bars indicate LSD (*P*<0.05) for comparisons at the same depth and date, where significant differences were found.

Figure 7. Profile water distribution during crop germination in the 1991-92 growing season as affected by tillage (■ conventional tillage; **x** reduced tillage; and ○ no-tillage) and cropping systems (CC continuous cropping; CF cereal-fallow rotation) at (a) the Zuera (9.12.91) and (b) Híjar sites (19.12.91). Bars indicate LSD (*P*<0.05) for comparisons among tillage treatments at the same depth and cropping system, where significant differences were found.

Figure 8. Penetration resistance profiles at germination (solid line) and harvest (dashed line) as affected by tillage (■ conventional tillage; **x** reduced tillage; and ○ no-tillage) at (a) Zuera in the 1990-91 growing season, (b) Banastás in the 1990-91 growing season, (c) Peñaflor under the cereal-fallow rotation in the 1991-92 growing season, and (d) Híjar under the continuous cropping system in the 1991-92 growing season. Bars indicate LSD (*P*<0.05) for comparisons among tillage treatments at the same depth and date, where significant differences were found.

Figure 9. Penetration resistance profiles as affected by tillage (■ conventional tillage; **x** reduced tillage; and ○ no-tillage) at the Banastás site on selected dates during the 1991-92 growing season. Bars indicate LSD (*P*<0.05) for comparisons at the same depth and date, where significant differences were found.

Table 1

Site characteristics

	Peñaflor	Zuera	Híjar	Banastás
Latitude	41°44'30''N	41°51'30''N	41°04'14''N	42°10'42''N
Longitude	0°46'18''W	0°41'16''W	0°21'43''W	0°27'07''W
Elevation (m)	270	400	440	538
Soil properties (0-40 cm)				
Particle size distribution (g kg^{-1})				
Sand (2000-50 μm)	282	344	407	202
Silt (50-2 μm)	473	397	380	525
Clay (<2 μm)	245	259	213	273
pH (H_2O,1:2.5)	8.2	8.2	8.2	8.0
EC_e (dS m^{-1})	0.29	0.25	0.40	0.11
Organic matter (g kg^{-1})	19.3	25.8	13.2	19.0
Total N (g kg^{-1})	1.60	1.62	0.80	1.27
Bulk density (Mg m^{-3})	1.44	1.32	1.50	1.71
Consistency limits (g kg^{-1})				
Liquid	265	269	214	249
Plastic	187	216	182	217
Water content (g kg^{-1}) at				
-33 kPa	198	203	166	198
-1500 kPa	105	118	88	111

Table 2

Agronomic information for each field site and growing season

		First tillage date			
Field site	Growing season	Continuous cropping	Cereal-fallow rotation	Sowing date	Harvest date
Peñaflor	1990-91	6.8.90	11.2.91	26.11.90	20.6.91
	1991-92	20.9.91		18.11.91	21.6.92
Zuera	1990-91	20.9.90	31.1.91	21.11.90	19.6.91
	1991-92	31.7.91		18.11.91	22.6.92
Híjar	1990-91	3.10.90	28.2.91	23.11.90	2.7.91
	1991-92	23.9.91		12.12.91	2.7.92
Banastás	1990-91	31.7.90		23.11.90	27.6.91
	1991-92	9.10.91		11.11.91	9.7.92

Table 3

Soil water content (mm) in the 0-40 cm depth at sowing as affected by tillage (CT, conventional tillage; RT, reduced tillage; and NT, no-tillage) and cropping system (CC, continuous cropping; CF, cereal-fallow rotation) at the four field sites

Field site	Tillage treatment	Cropping system	Growing season	
			1990-91	1991-92
Peñaflor	CT	CC	97.6	80.7
	RT		85.7	66.6
	NT		66.7	60.5
	LSD (0.05)[1]		14.4	12.5
	CT	CF		66.7
	RT			55.0
	NT			60.4
	LSD (0.05)			NS
Zuera	CT	CC	69.4	68.1
	RT		77.2	75.1
	NT		68.8	72.6
	LSD (0.05)		NS	NS
	CT	CF		67.7
	RT			71.1
	NT			67.3
	LSD (0.05)			NS
Híjar	CT	CC	67.5	87.8
	RT		61.9	87.9
	NT		54.7	79.7
	LSD (0.05)		9.7	NS
	CT	CF		104.4
	RT			94.9
	NT			85.3
	LSD (0.05)			14.7
Banastás	CT	CC	131.2	102.5
	RT		130.1	109.7
	NT		130.3	112.0
	LSD (0.05)		NS	NS

[1] Least significant difference, *P*<0.05. NS = not significant

Table 4

Storage efficiency of fallow in the cereal-fallow rotation (CF) with respect to the continuous cropping (CC) as affected by tillage (CT, conventional tillage; RT, reduced tillage; and NT, no-tillage) at three field sites

Field site (%)	Rainfall over fallow (mm)[1]	Tillage treatment	Additional water storage in CF (mm)[2]	Fallow efficiency
Peñaflor	471	CT	-41.2	-8.7
		RT	-8.1	-1.7
		NT	-6.1	-1.3
Zuera	457	CT	13.4	2.9
		RT	32.3	7.1
		NT	10.7	2.3
Híjar	481	CT	57.7	12.0
		RT	43.2	9.0
		NT	5.3	1.1

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[1] Rainfall received from the date of primary tillage in the CC system, after harvest of the 1990-91 growing season, to sowing of the 1991-92 growing season.

[2] Difference in the water storage to 80 cm depth between the CF and the CC systems at the beginning of the 1991-92 growing season (exactly, at 7-21 days after sowing depending on field site).

Table 5

Percentage (%) of the soil profile to the 40 cm depth having penetration resistances (PR) in different ranges under different tillage treatments (CT, conventional tillage; RT, reduced tillage; and NT, no-tillage) at the two first sampling dates in the 1990-91 growing season.

Field site	Date	PR (MPa)	Tillage treatment		
			CT	RT	NT
Peñaflor	17.12.90	0-2	68	72	33
		2-4	32	24	58
		> 4	0	4	9
	3.4.91	0-2	27	23	15
		2-4	61	65	63
		> 4	12	12	22
Zuera	19.12.90	0-2	58	48	15
		2-4	32	25	36
		> 4	10	27	49
	8.4.91	0-2	10	7	7
		2-4	16	43	15
		> 4	74	50	78
Híjar	11.1.91	0-2	30	48	9
		2-4	63	26	29
		> 4	7	26	62
	25.4.91	0-2	17	62	9
		2-4	83	38	91
		> 4	0	0	0
Banastás	24.1.91	0-2	78	68	28
		2-4	22	32	72
		> 4	0	0	0
	22.4.91	0-2	7	12	10
		2-4	43	41	90
		> 4	50	47	0

Table 6

Percentage (%) of the soil profile to the 40 cm depth having penetration resistances (PR) in different ranges under different tillage treatments (CT, conventional tillage; RT, reduced tillage; and NT, no-tillage) and cropping systems (CC, continuous cropping; CF, cereal-fallow rotation) at the two first sampling dates in the 1991-92 growing season

			Treatment					
			CC			CF		
Field site	Date	PR (MPa)	CT	RT	NT	CT	RT	NT
Peñaflor	27.11.91	0-2	29	38	19	30	34	22
		2-4	63	45	62	49	53	57
		> 4	8	17	19	21	13	21
	27.3.92	0-2	13	13	11	10	14	10
		2-4	20	34	12	24	64	24
		> 4	67	53	77	66	22	66
Zuera	9.12.91	0-2	64	54	29	74	55	45
		2-4	24	19	41	15	21	30
		> 4	12	27	30	11	24	25
	31.3.92	0-2	11	17	18	16	16	12
		2-4	68	41	3	61	37	12
		> 4	21	42	79	23	47	76
Híjar	19.12.91	0-2	78	66	25	76	59	25
		2-4	21	27	60	24	41	62
		> 4	1	7	15	0	0	13
	27.4.92	0-2	14	8	9	9	8	12
		2-4	65	33	11	53	23	11
		> 4	21	59	79	38	69	77
Banastás	22.11.91	0-2	88	63	9			
		2-4	12	37	91			
		> 4	0	0	0			
	18.3.92	0-2	13	16	8			
		2-4	72	49	13			
		> 4	15	35	79			

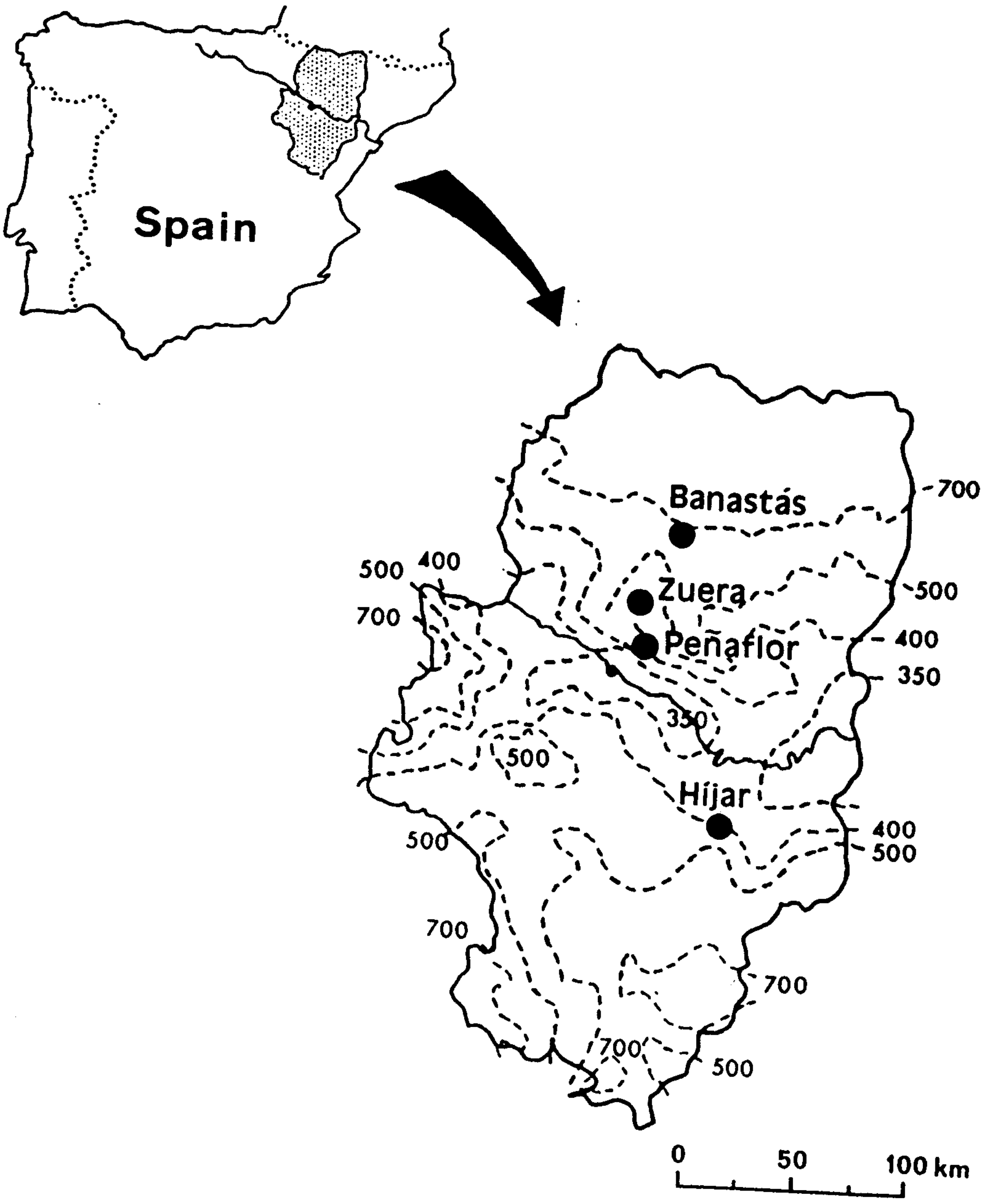
Spain
Banastás
Zuera
Peñaflor
Híjar
700
500
400
350
350
500
400
500
700
500
400
700
500
500
700
700
500
0
50
100 km

Fig. 1

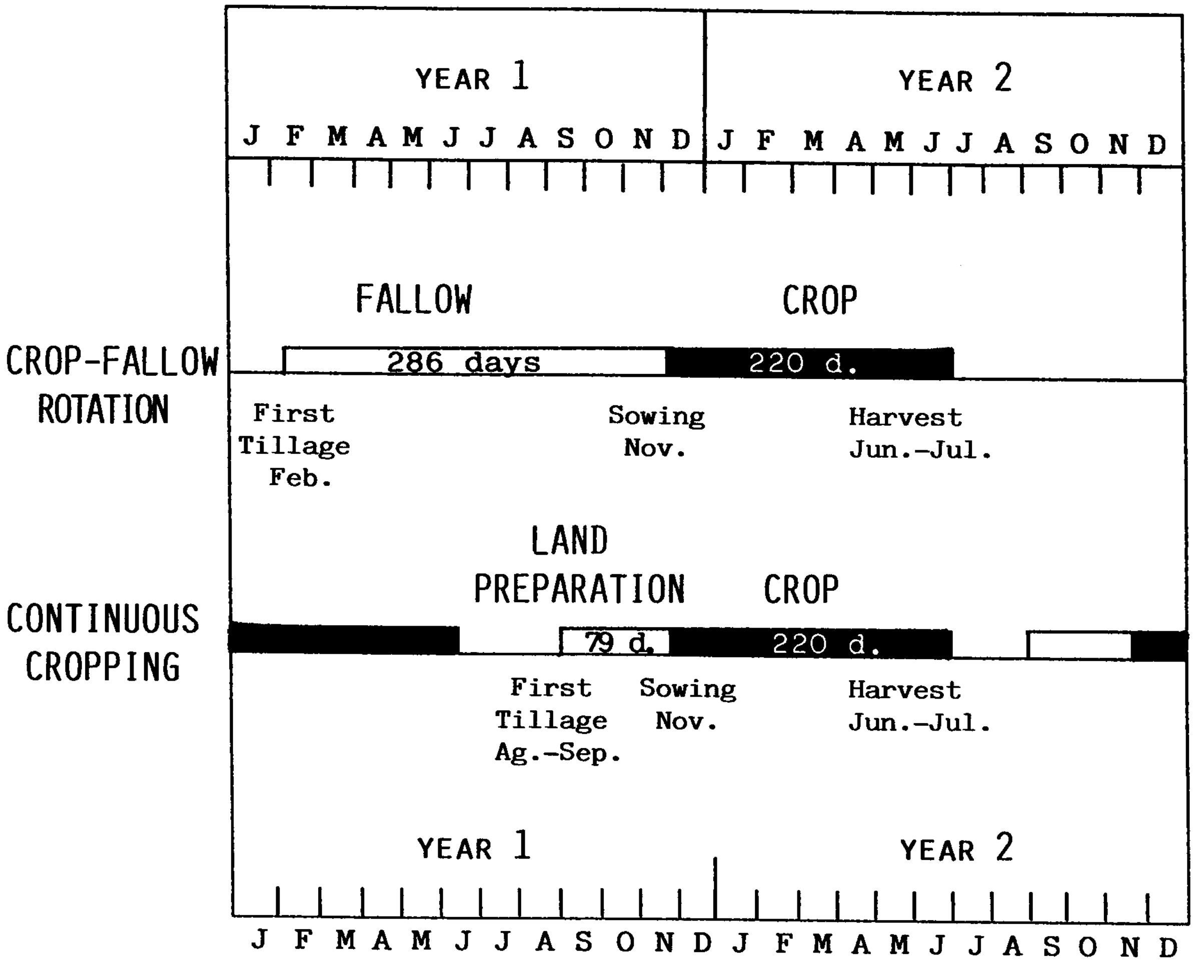
YEAR 1
YEAR 2
J F M A M J J A S O N D J F M A M J J A S O N D
FALLOW
CROP
CROP-FALLOW ROTATION
286 days
220 d.
First Tillage Feb.
Sowing Nov.
Harvest Jun.-Jul.
LAND PREPARATION
CROP
CONTINUOUS CROPPING
79 d.
220 d.
First Tillage Ag.-Sep.
Sowing Nov.
Harvest Jun.-Jul.
YEAR 1
YEAR 2
J F M A M J J A S O N D J F M A M J J A S O N D

Fig. 2

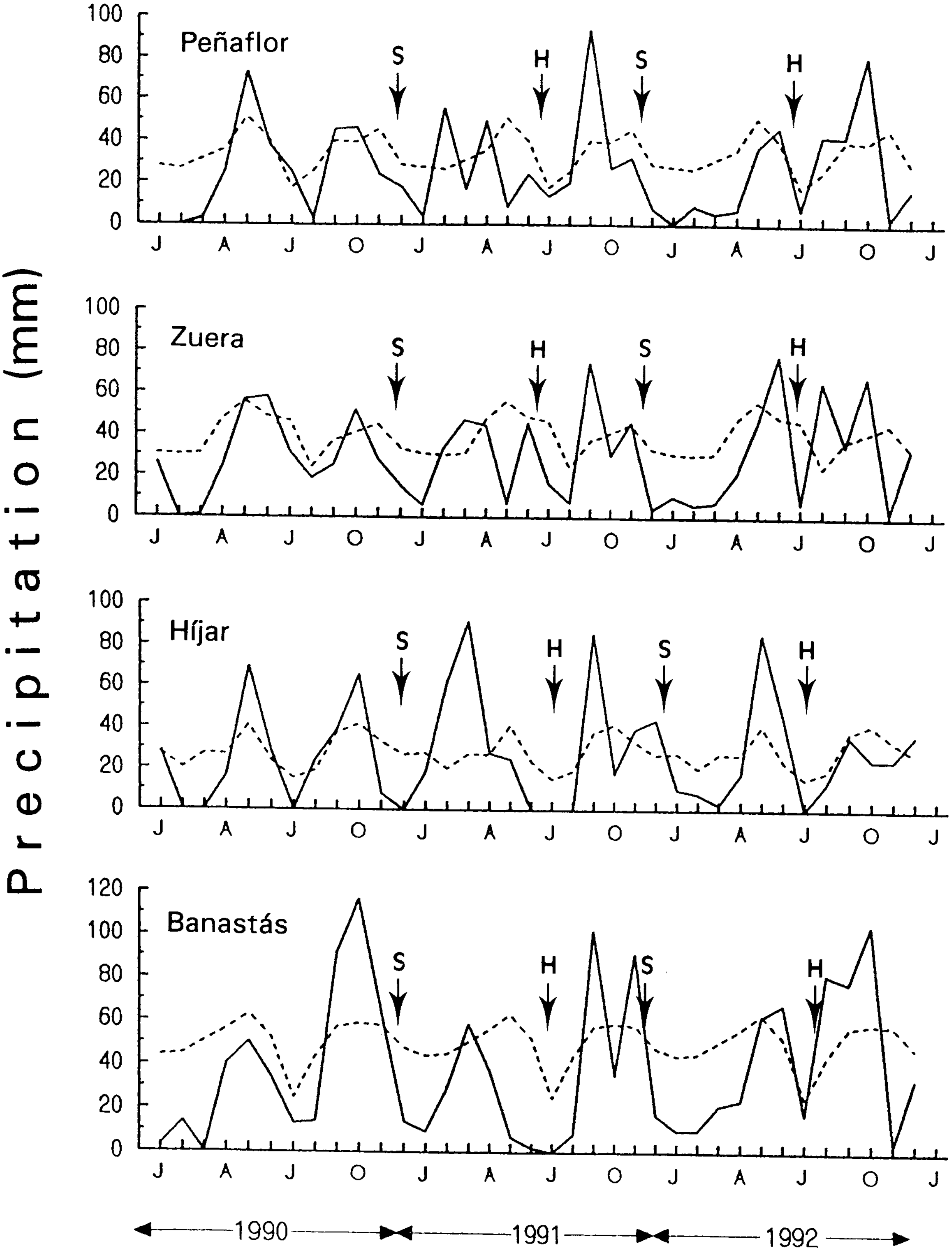
Precipitation (mm)
Peñaflor
100
80
60
40
20
0
S
H
S
H
J A J O J A J O J A J O J
Zuera
100
80
60
40
20
0
S
H
S
H
J A J O J A J O J A J O J
Híjar
100
80
60
40
20
0
S
H
S
H
J A J O J A J O J A J O J
Banastás
120
100
80
60
40
20
0
S
H
S
H
J A J O J A J O J A J O J
1990
1991
1992

Fig. 3

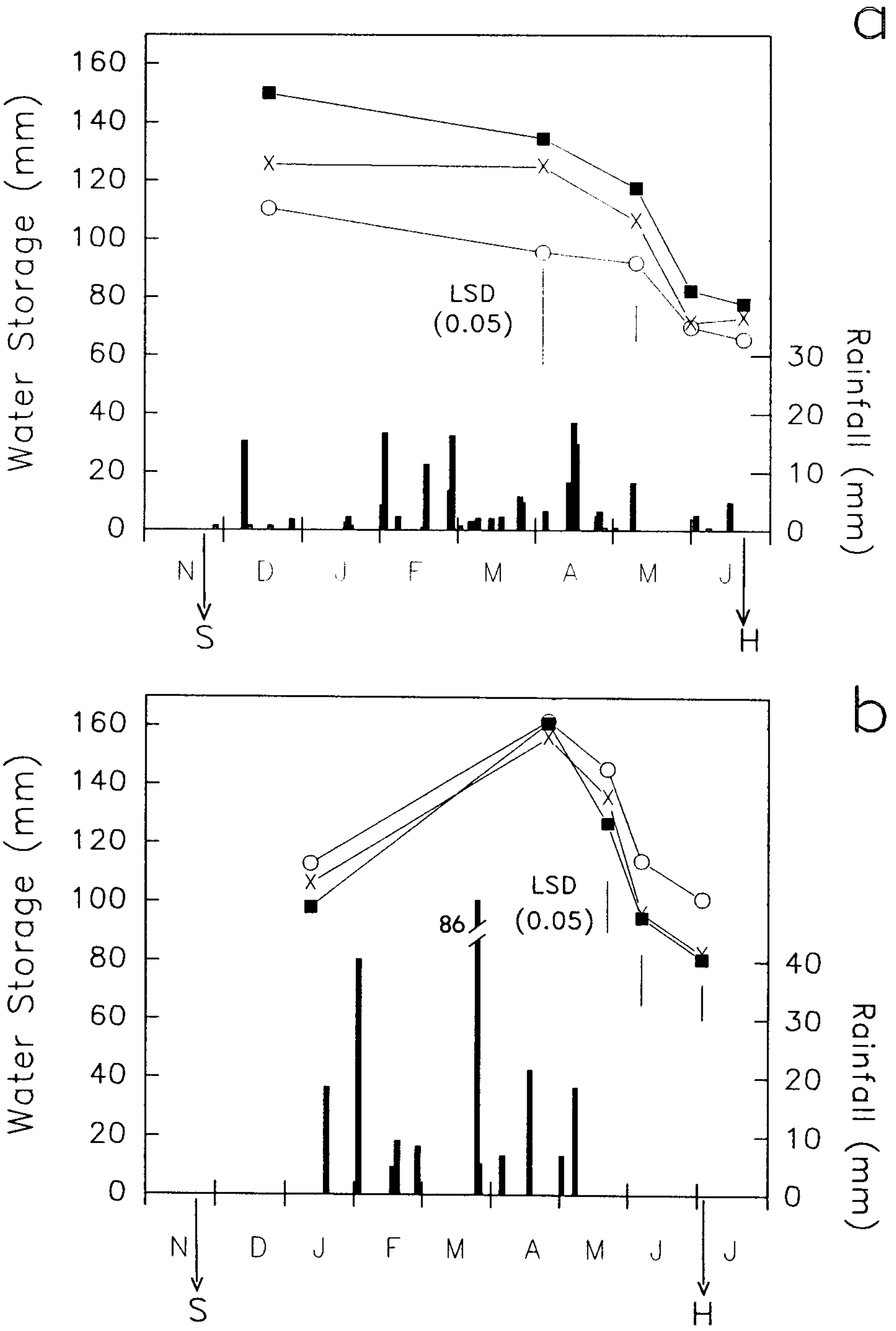
a
Water Storage (mm)
160
140
120
100
80
60
40
20
0
Rainfall (mm)
30
20
10
0
LSD
(0.05)
N
D
J
F
M
A
M
J
S
H
b
Water Storage (mm)
160
140
120
100
80
60
40
20
0
Rainfall (mm)
40
30
20
10
0
86
LSD
(0.05)
N
D
J
F
M
A
M
J
J
S
H

Fig 4

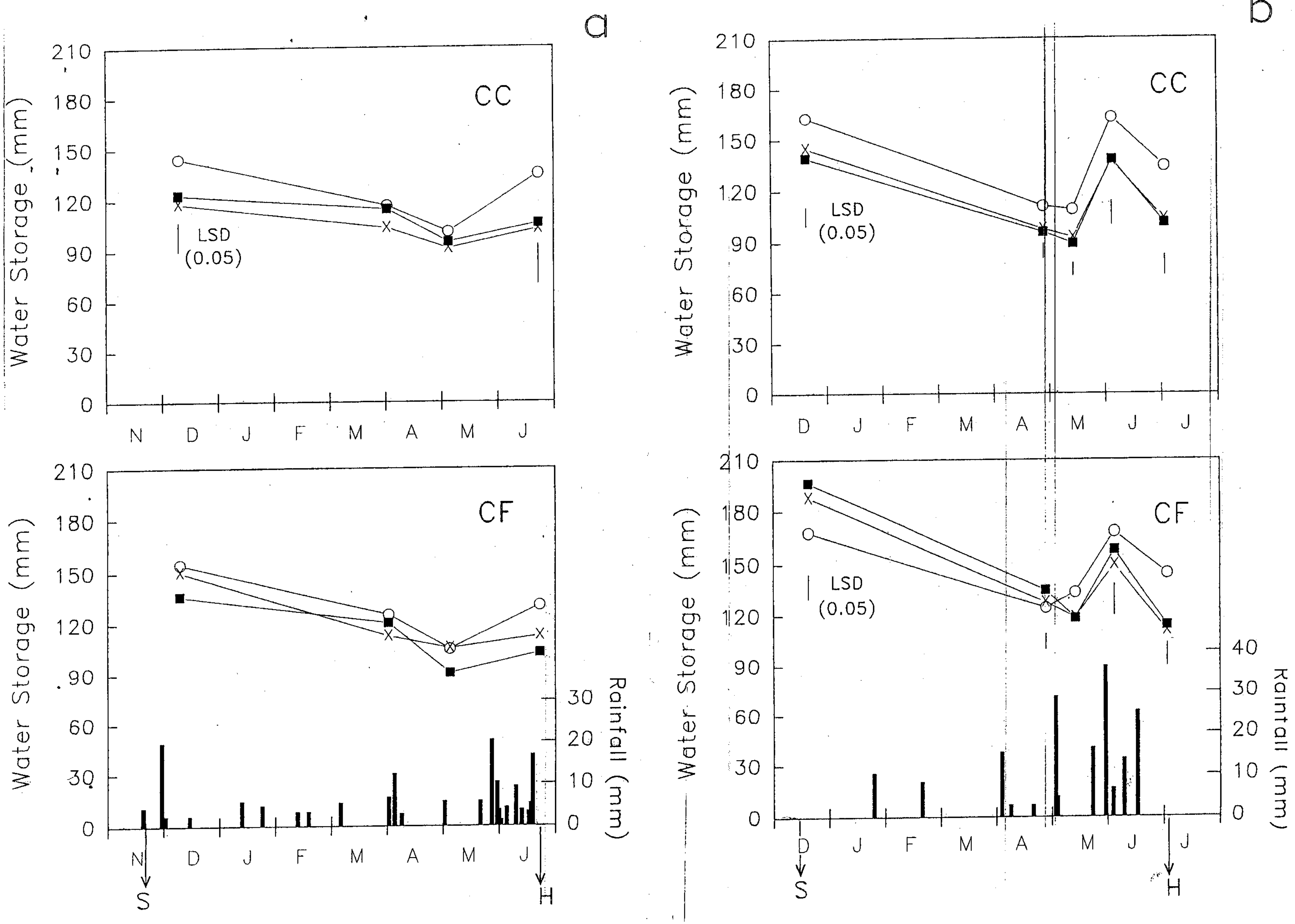a
b
CC
CF
Water Storage (mm)
210
180
150
120
90
60
30
0
LSD
(0.05)
N
D
J
F
M
A
M
J
Rainfall (mm)
40
30
20
10
0
S
H

Fig. 5

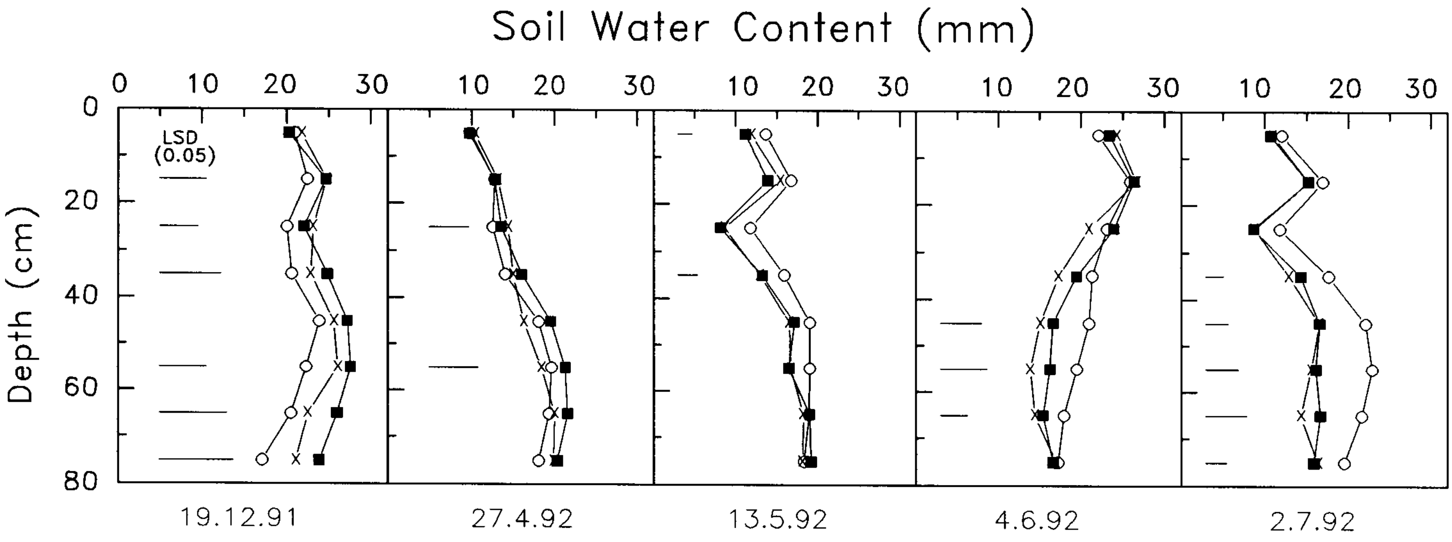
Soil Water Content (mm)
0
10
20
30
Depth (cm)
0
20
40
60
80
LSD
(0.05)
19.12.91
27.4.92
13.5.92
4.6.92
2.7.92

Fig. 6

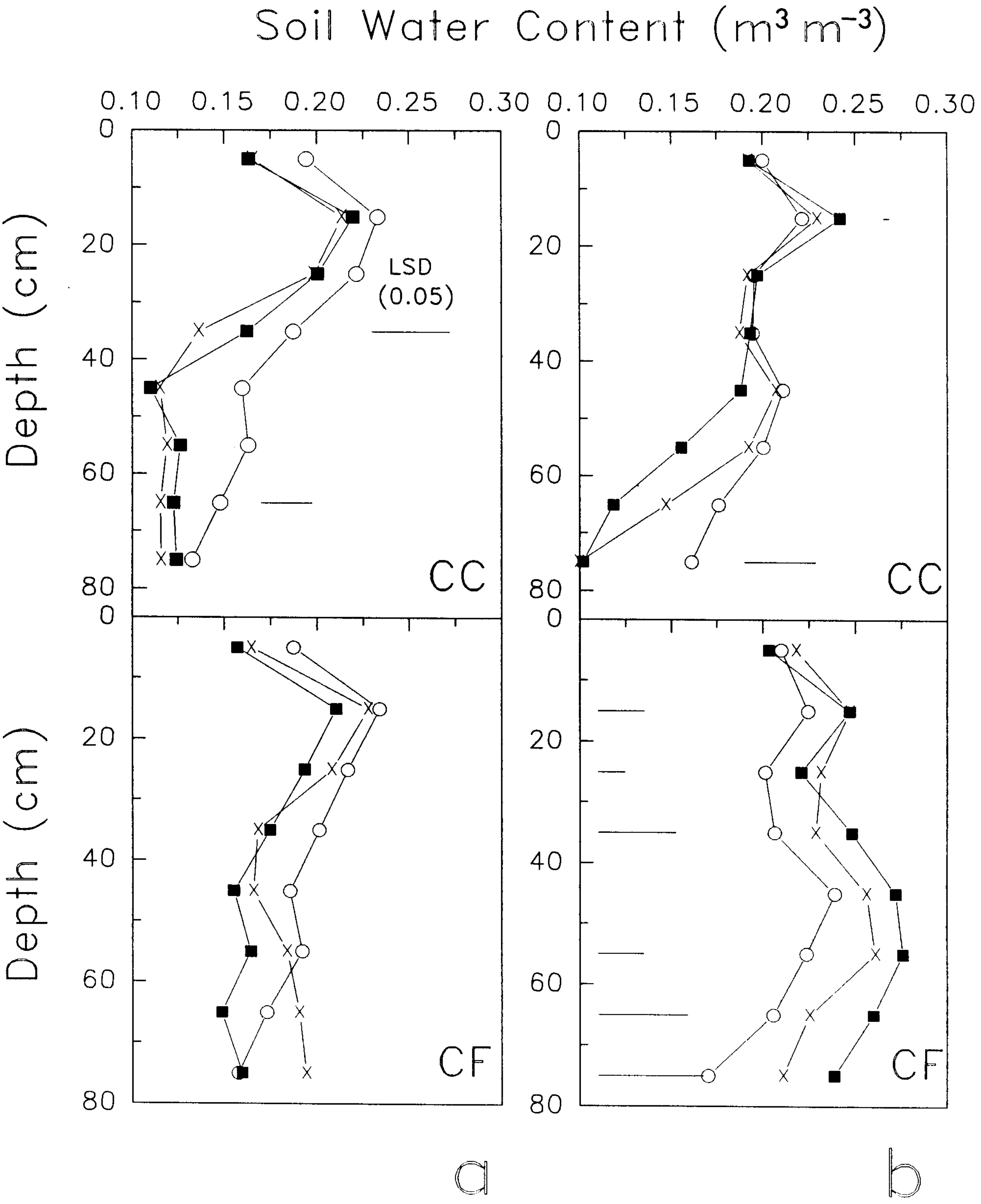
Soil Water Content (m³ m⁻³)
0.10
0.15
0.20
0.25
0.30
0.10
0.15
0.20
0.25
0.30
Depth (cm)
Depth (cm)
0
20
40
60
80
LSD
(0.05)
CC
CC
CF
CF
a
b

Fig. 4

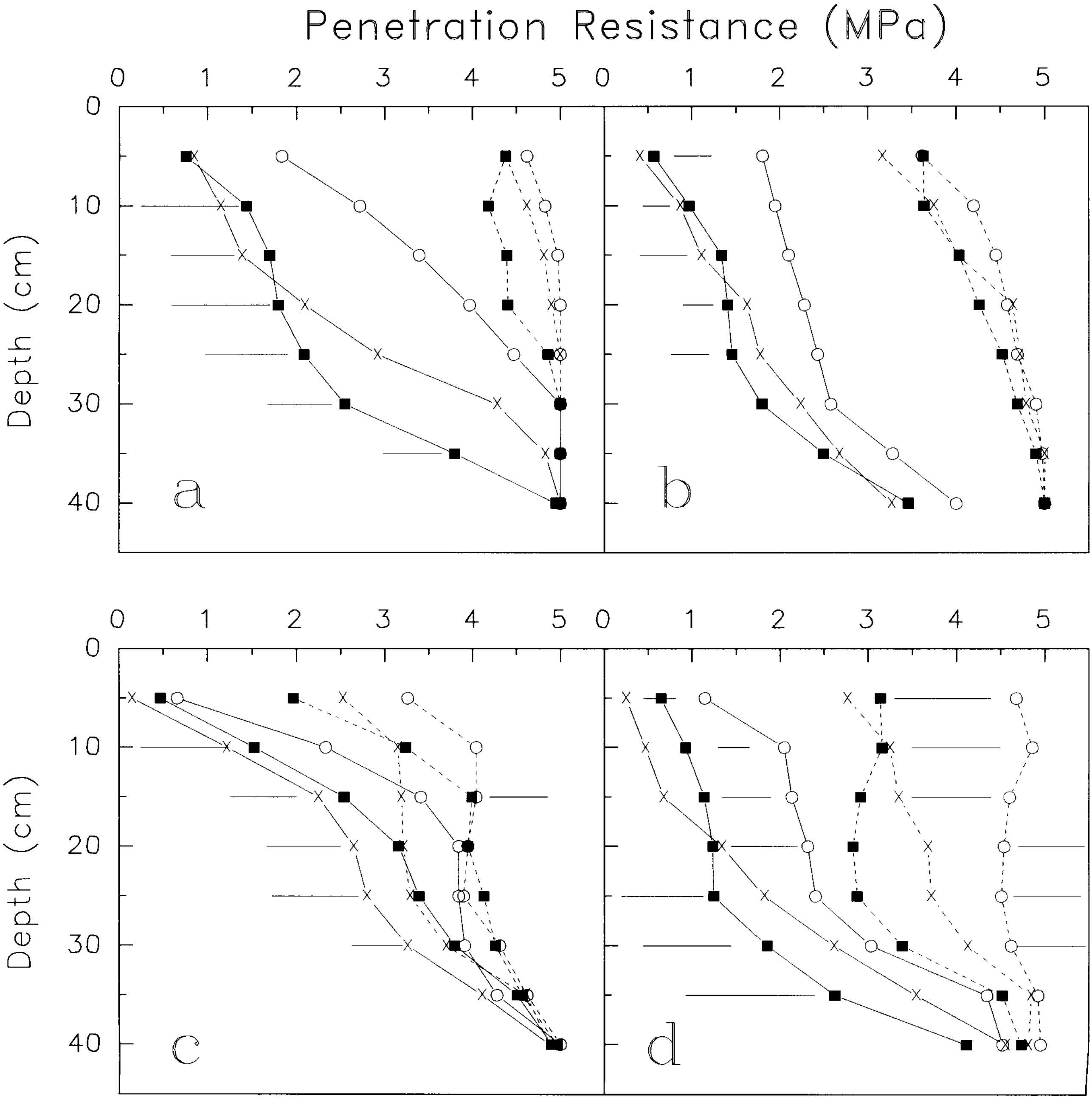
Penetration Resistance (MPa)
0
1
2
3
4
5
Depth (cm)
0
10
20
30
40
a
b
c
d

Fig. 8

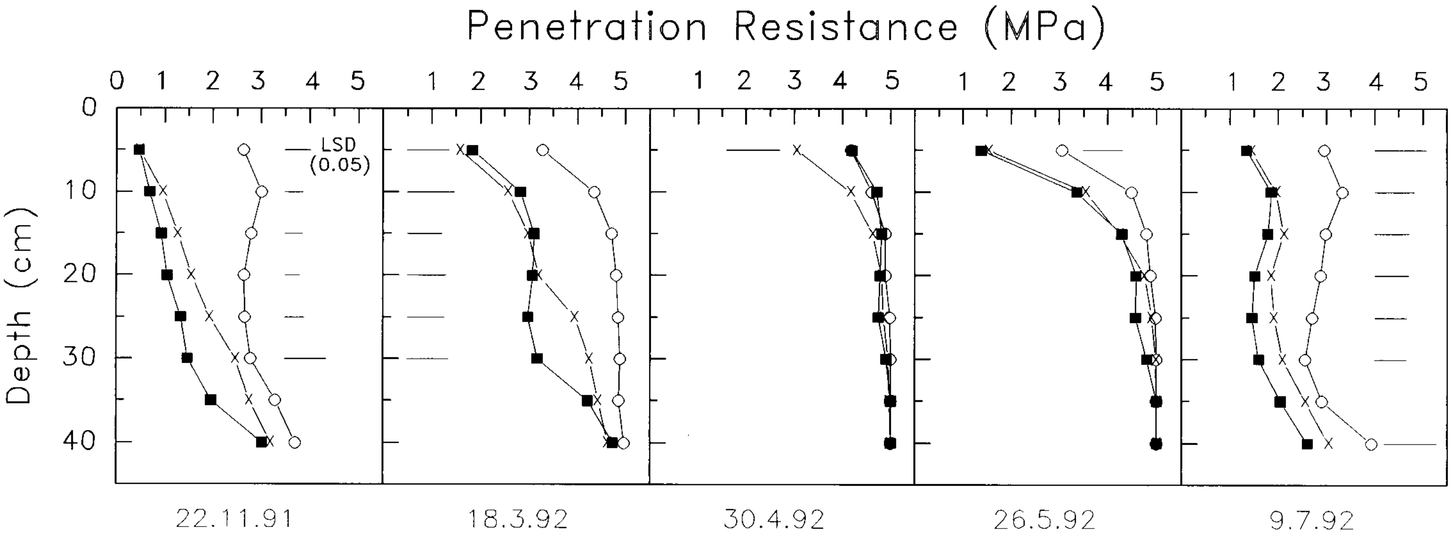
Penetration Resistance (MPa)
0
1
2
3
4
5
Depth (cm)
0
10
20
30
40
LSD
(0.05)
22.11.91
18.3.92
30.4.92
26.5.92
9.7.92

Fig. 9