**GROWTH, YIELD AND WATER USE EFFICIENCY OF
WINTER BARLEY IN RESPONSE TO CONSERVATION TILLAGE
IN A SEMI-ARID REGION OF SPAIN**

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1 **Abstract**

2 In the semi-arid areas of Aragón (NE Spain), dryland crop production is limited by low and
3 variable precipitation. Conservation tillage has been proposed as a promising strategy to improve soil
4 and water conservation in these areas. A long-term field research project to determine the feasibility
5 of conservation tillage was initiated in 1989 at four locations, three on loam to silt loam soils
6 (Xerollic Calciorthid) and one on a silty clay loam (Fluventic Ustochrept), receiving between 300
7 and 600 mm of average annual rainfall. This study compared, under both continuous cropping and
8 cereal-fallow rotation, the effects of conventional tillage (mouldboard plough) and two conservation
9 tillage systems, reduced tillage (chisel plough) and no-tillage, on winter barley (*Hordeum vulgare* L.)
10 growth and yield, and water use efficiency during the first two growing seasons. Whereas a similar
11 crop response between the conventional and reduced tillage treatments was generally found at all
12 locations, poor performance with no-tillage was observed at the most arid sites. At these sites, lower
13 early growth of barley with no-tillage resulted in a 53% reduction in grain yield, compared to
14 conventional tillage. This unfavourable crop response to no-tillage was due to a lower crop water use,
15 mainly starting with the stem elongation stage (20% lower than the tilled treatments), and a larger
16 proportion of total water use lost as evaporation (69% compared to 50% of tilled treatments). Values
17 of water use efficiency for grain production ($0.7\text{--}17.0 \text{ kg ha}^{-1} \text{ mm}^{-1}$) and transpiration efficiency (7.4--
18 $23.8 \text{ kg ha}^{-1} \text{ mm}^{-1}$) were within the ranges reported for cereal crops in Mediterranean environments.
19 Fallowing in the cereal-fallow rotation proved to be an inefficient practice for improving soil water
20 storage and subsequent crop yield, under both conventional and conservation management. Based on
21 the study, we conclude that, up to now, only reduced tillage provides an alternative to conventional
22 tillage to maintain crop production in the dryland cereal-growing areas of Aragón.

1 **Keywords:** Reduced tillage; No-tillage; Fallowing; Yield components; Evapotranspiration

1. Introduction

Water deficiency is the major constraint to dryland crop production in Aragón (NE Spain), where about one million hectares of rainfed arable land have an average annual precipitation of 500 mm or less. Winter cereal-fallow (one crop in 2 years) is the most common cropping system in these areas, whereas annual cropping is practiced where precipitation exceeds 500 mm annually. Barley is the cereal grown in most of the region (about 380,000 ha). In contrast to other semi-arid regions, the rainfall regime is characterized by the absence of any well-defined rainy season and in any month there is a strong probability of having either an extremely low amount (<10 mm) or no rain at all (McAneney and Arrúe, 1993). In Central Aragón, dry WNW winds (*Cierzo*) may also enhance the effects of limited available water. Consequently, grain yields are low and highly dependent on seasonal rainfall. In some years no harvestable yield is possible.

Although long-fallow (9-10 months) continues to be the traditional water conservation practice for dryland crop production in Aragón, there is limited information on its capability to store soil water and to ensure emergence and establishment of winter cereals. Conventional tillage using a mouldboard plow as the primary tillage implement followed by repeated shallow tillage is the standard method for controlling weeds during the fallow year. This practice, however, promotes incorporation of surface crop residue, which, in turn, may result in increased soil water losses by evaporation (Aase and Siddoway, 1982) and affect the wind erosion potential of the soil by influencing soil aggregation (Smika, 1990). Hence, the adoption of conservation tillage, which involves retention of surface crop residue, may be considered as an alternative to conventional tillage to slow evaporation losses and to increase water storage and water use by crops in the rainfed farming systems of Aragón, as suggested in many reviews on the subject (e.g., Fisher, 1987; Unger et al., 1991; Fereres et al., 1993). Nevertheless, before conservation tillage practices are readily adopted in any particular region, the suitability of these management systems needs to be locally assessed.

All the above considerations were of major concern in planning a long-term field experiment, initiated in 1989, in order to determine the agronomic feasibility of conservation tillage systems (reduced tillage and no-tillage) at different dryland cereal-growing areas of Aragón. In a previous paper (López et al., 1996), we presented and discussed results from the first two growing seasons of this experiment concerning the seasonal changes in soil water storage and penetration resistance and water storage efficiencies of fallowing under both conventional and conservation tillage techniques at

four different locations. The purpose of this paper is to report, for the same seasons and sites, the effects of these tillage systems on growth, yield, water use and water use efficiency of winter barley under both continuous cropping and cereal-fallow rotation.

2. Materials and methods

2.1. Sites, tillage and crop management

The study was conducted at four locations representing the main dryland barley production areas in Aragón. Site and soil characteristics, experimental design and crop management practices have been previously described in detail (López et al., 1996); therefore, only aspects relevant to this paper are repeated here. The soil is loam (fine-loamy, mixed, thermic Xerollic Calcicorthid) at the Peñaflor and Híjar sites, silt loam (fine-silty, mixed, thermic Xerollic Calcicorthid) at the Zuera site, and silty clay loam (fine-silty, mixed, thermic Fluventic Ustochrept) at the Banastás site. The sites are on an agroclimatic gradient with average annual rainfall ranging from 300 mm in Peñaflor to 600 mm in Banastás.

Three tillage treatments were examined: conventional tillage (CT), mouldboard ploughing (30-40 cm depth) followed by secondary tillage with a harrow or cultivator (10-15 cm); reduced tillage (RT), chisel ploughing (25-30 cm) followed by harrow or cultivator tillage; and no-tillage (NT), where the plots were not tilled and weeds were controlled by herbicides. 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. 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. A summary of the main cultural practices for both cropping systems, CC and CF, is presented in the previous paper (Fig. 2; López et al., 1996). Crop management details are given in Table 1.

Tillage treatments at all sites were arranged in an incomplete block design with three replications for the RT and NT treatments and four for the CT treatment (López and Arrúe, 1995). At the sites where the CF system was evaluated, all tillage treatments were duplicated under CC and CF rotation, arranged in a split block design with tillage as the main plot and cropping system as the subplot. The subplot size was 33.5 m × 10 m at Peñaflor and 50 m × 10 m at the remaining sites. During the 1990-

1 1991 growing season the plots under the CC system were cropped with barley while those under the
2 CF rotation were fallowed. In the 1991-1992 season all plots were cropped and data were collected in
3 all.

4 To compare the effects of tillage treatments within each cropping system, analysis of variance
5 (ANOVA) for the incomplete block design was used (López and Arrúe, 1995). To evaluate the
6 cropping systems irrespective of tillage treatment and the tillage x cropping system interaction,
7 ANOVA according to the split block design with three replicates was performed. Duncan's multiple
8 range test was used to compare treatment means.

10 2.2. *Sampling and measurements*

11 *Weather*

12 Daily precipitation, maximum and minimum air temperature and relative humidity for the
13 Peñaflor and Zuera sites were recorded at permanent meteorological stations located within the
14 experimental farms. At Híjar and Banastás, precipitation was measured with standard rain gauges
15 installed in the plots. For these sites, daily measurements of air temperature and relative humidity
16 were obtained from the closest National Weather Service stations (5-10 km from the sites).

18 *Crop growth and yield*

19 The study was mainly focused on the Peñaflor and Híjar sites. Thus, with the exception of the
20 grain yield (and yield components in the 1991-1992 season), results of the crop establishment and
21 growth are only available for these two sites. In the 1991-1992 season, due to the extremely dry
22 January-April period, the crop at Peñaflor was severely affected at the tillering stage. At that time, we
23 decided to abandon data collection at this site and to complete it at Banastás.

24 Plant sampling was made five times during each growing season at selected crop growth stages
25 (Zadoks et al., 1974): early seedling growth (ZGS 11-12), early stem elongation (ZGS 30-31),
26 heading (ZGS 50-59), milky doughy grain (ZGS 75-85) and maturity (ZGS 99). This last sampling
27 date corresponded to the harvest day. Soil water content and penetration resistance were determined
28 at these same dates, with the exception of the first one, which corresponded to the germination stage
29 (ZGS 00-09) (López et al., 1996).

Four 0.5-m long rows per subplot (per plot at Banastás) were selected for plant measurements at each sampling date. The time required for the total establishment of crop was determined from an emergence rate index (ERI). The number of plants per row was counted frequently during the time of plant emergence. The ERI was calculated as follows:

$$ERI = \sum_{i=1}^n (d_i p_i) / p$$

where d_i is the number of days after sowing, p_i is the number of plants emerged from the last counting day, and p is the final number of emerged plants. Crop establishment was determined as the percentage of seeds sown for which seedlings emerged. Seed depth was estimated by measuring the length of white stem above the seed of 10 plants randomly sampled from each row (i.e., 40 plants per subplot).

Similarly, at the different sampling dates the total number of plants per row was counted and subsamples of above-ground plant material (10 plants per row) were harvested and separated into stems, green and senescent leaves, and, when appropriate, ears. Leaf area index of green leaves (LAI) was measured with a Delta-T Mk2 area meter (Delta-T Devices, Cambridge, UK). Dry weight of all fractions was determined after oven-drying at 65-70°C for 48 h. Immediately prior to harvest (ZGS 99), total plants from each row were hand-harvested to determine grain yield and yield components. The ears were counted and, after oven-drying, threshed to determine the number of grains per ear and mean grain weight.

Water use and water use efficiency

Crop water use (evapotranspiration, ET) was calculated from rainfall (R) and the change in soil water storage to a depth of 80 cm (ΔS) for the different periods of crop development (i.e., $ET = \Delta S + R$). This method of ET calculation combines crop transpiration (T) and soil water evaporation (E), assuming zero runoff and drainage below the root-zone. Gravimetric soil water content was determined in 10-cm increments and converted to a volume basis using bulk densities of soil cores taken from each depth increment (López et al., 1996).

Water use efficiency (dry matter production per unit of water used) was determined for grain (WUE_g) and total above-ground biomass (WUE_b) at ZGS 99, using ET between the first sampling

1 date of soil water content (ZGS 00-09, 7-49 days after sowing depending on the experimental site
2 and growing season) and the harvest day.

3 **3. Results**

4 *3.1. Seasonal rainfall*

5 Growing season precipitation (November-June) during the experimental period was near the
6 long-term average at the Híjar site and well below average (30-50% lower) at other sites (Fig. 1).
7 Whereas the total precipitation was similar in the two seasons, its distribution varied considerably. In
8 the 1991-1992 season only 15-20% of the total rainfall was received from January to April. In
9 contrast, this percentage in 1990-1991 was generally higher than average, being 60% at Híjar.

10

11 *3.2. Crop establishment, growth and yield*

12 In the 1990-1991 growing season, tillage treatments had no significant effect on the percentage
13 of emerged seedlings at both Peñaflor and Híjar sites (Table 2). However, at Híjar emergence was
14 slower under NT, as indicated by its greatest ERI. At both sites, the shallowest seed placement
15 corresponded to the NT plots. Likewise, a delay in early growth under NT was reflected in the lowest
16 plant height and LAI values obtained for this treatment. In the 1991-1992 season, more favourable
17 weather and soil conditions during the germination period (see López et al., 1996) resulted in higher
18 percentages of emergence and more rapid emergence than in 1990-1991 (Table 2). At Peñaflor, no
19 important differences among tillage treatments were found. However, seed depth was least with RT
20 under the CC system and ERI was greatest with NT under the CF rotation (1-2 days of delay). At
21 Híjar, under both cropping systems the percentage of seedlings emerged was higher with NT than
22 with CT and RT. Under the CF rotation, RT resulted in the smallest seed depth and plant height.
23 Significant cropping systems effects or tillage x cropping system interactions were not found in any
24 case.

25 The slow early growth observed under NT in the 1990-1991 season persisted until maturity.
26 Thus, at Híjar, above-ground dry matter production (without ears) was significantly lower with NT
27 than with CT for almost all sampling dates (Fig. 2a). Likewise, ears weight tended to be greater for
28 CT and RT than for NT (Fig. 2b). However, tillage had no effect on LAI (Fig. 2c). With all
29 treatments LAI reached a maximum at ZGS 50-59 (third sampling date) after which it quickly
30 declined. A similar pattern of crop growth was found at Peñaflor (data not shown). At this site, dry

1 matter and LAI were lowest with NT, starting at the ZGS 50-59 stage. The well below average
2 rainfall received from January to April in the 1991-1992 season, was reflected in growth rates lower
3 than those observed in 1990-1991. At Híjar, although similar values of dry matter at ZGS 30-31 were
4 obtained in both seasons, the subsequent growth was markedly lower in 1991-1992, being more
5 apparent for the NT treatment and, particularly, under the CF rotation (Fig. 3a). The same differences
6 among tillage treatments and cropping systems were also found for ears weight (Fig. 3b) and LAI
7 (Fig. 3c). Significant tillage x cropping system interactions ($P < 0.05$) occurred at the last four
8 sampling dates. These interactions were due to the significantly higher values of the CT and RT
9 treatments under CF than for the same treatments under CC and, on the contrary, to the lower values
10 of NT under CF than under CC. At Banastás, where plant measurements were made only from ZGS
11 50-59 to ZGS 99, crop growth was unaffected by tillage (data not shown). The more favourable soil
12 and climate conditions at this site resulted in the highest values of biomass production obtained in
13 this study. For example, at Banastás the mean above-ground dry matter at harvest was almost four
14 times higher than that obtained at Híjar (i.e., 722 g m⁻² compared with 190 g m⁻²).

15 Grain yields and yield components are shown in Table 3. In the 1990-1991 growing season, at
16 Peñaflor the higher grain yield with CT resulted from a greater number of ears per unit area together
17 with a greater number of grains per ear than with RT and NT. At Híjar, the grain number was lower
18 with NT, resulting in a slightly lower grain yield than that obtained with the other treatments (16%
19 less). At the Zuera and Banastás sites, grain yield was not affected by tillage. At Zuera, yield was
20 960, 810 and 860 kg ha⁻¹ with CT, RT and NT, respectively. At Banastás, it was 3590 and 3550 kg
21 ha⁻¹ with CT and RT, respectively. In the NT plots barley seedlings were completely damaged as a
22 result of the persistence of herbicide (López et al., 1996). In 1991-1992, the severe drought in
23 January-April reduced yields at all sites, especially at the most arid ones where production was
24 negligible in some cases (Table 3). In this year, significant differences in grain yield among tillage
25 treatments were found only at Híjar, following the same trend observed in crop growth. Thus, the
26 lowest yield resulted from NT, especially under CF, and the highest from CT and RT under this same
27 cropping system. These differences were reflected in a significant tillage x cropping system
28 interaction (LSD = 360 kg ha⁻¹; $P < 0.05$). A similar interaction occurred for the mean grain weight
29 (LSD = 3.9 mg; $P < 0.05$). Whereas under the CC system the number of grains per ear was the major
30 determinant of yield, under the CF rotation mean grain weight was also a significant factor. At Zuera,

1 although no differences between cropping systems were found, there was a trend for grain yield in
2 CF to exceed that in CC with the RT and NT treatments. At Banastás, where grain yields were
3 always higher than those at the other sites, the lowest grain number under NT was compensated for
4 by the greatest mean grain weight. Overall, differences in harvest index during the experimental
5 period resulted mainly from differences among barley varieties rather than differences among
6 treatments. The only exception occurred at the Híjar site in 1991-1992, where NT resulted in the
7 lowest harvest index, particularly under the CF rotation (Table 3).

8

9 3.3. *Water use and water use efficiency*

10 The major differences among tillage treatments resided in the distribution of ET among the
11 different phases of crop growth rather than in the total ET. In the 1990-1991 season, the maximum
12 ET at all sites occurred from ZGS 00-09 to ZGS 30-31 (Fig. 4). Actually, this period was the longest
13 (about 100 days) and most humid (80-198 mm depending on the site) over the crop cycle, especially
14 at Híjar, where exceptional rains were received in February-March (153 mm). At Peñaflor and Híjar,
15 differences in crop growth among tillage treatments were reflected in ET. Thus, at Peñaflor the
16 lowest ET under NT from ZGS 50-59 to ZGS 75-85 was responsible for the lower ET under NT than
17 CT between ZGS 50-59 and ZGS 99 (LSD = 11 mm; $P < 0.05$) (Fig. 4a). At Híjar, the low ET with
18 NT was significant after the ZGS 30-31 stage (LSD = 11 mm; $P < 0.05$, for the total ET) (Fig. 4b).
19 No significant effect of tillage was found at Zuera (Fig. 4c) and Banastás (Fig. 4d).

20 In the 1991-1992 growing season, the rainfall between ZGS 00-09 and ZGS 30-31 was, on
21 average, 67% lower than that received in 1990-1991. During this period average ET for the four field
22 sites was reduced by 43 mm as compared with the 1990-1991 season. The greatest effects of tillage
23 and cropping system occurred at Híjar, starting with the early growing season (Fig. 5a). At this site,
24 the crop with NT under CF used significantly less water than crops with CT and RT during both pre-
25 heading (until ZGS 50-59, LSD = 13 mm; $P < 0.05$) and post-heading (since ZGS 50-59, LSD = 11
26 mm; $P < 0.05$) periods. Consequently, total ET with this treatment was markedly reduced (191 mm
27 vs. 250 and 245 mm with CT and RT, respectively; LSD = 18 mm; $P < 0.05$). Regardless of tillage
28 treatment, use of the CF rotation increased total ET by 24 mm in relation to the CC system (LSD =
29 24 mm; $P < 0.05$). This increase was due to a greater ET in the CT and RT plots under CF than under
30 CC (LSD = 24 mm; $P < 0.05$). Likewise, at Zuera, a trend toward a greater total water use under CF

than CC was observed (average of 162 mm vs. 145 mm), especially with the RT treatment, although the difference was not statistically significant (Fig. 5b). The high rainfall at Banastás resulted in the greatest values of total ET over the experimental period (average 257 mm), with 82% occurring from ZGS 00-09 to ZGS 50-59 (data not shown).

Values of WUE_g and WUE_b were, generally, lower in the 1991-1992 than in the 1990-1991 season (Table 4). In 1991-1992, with an exceptionally dry period during active plant growth at all sites, there was a correspondence between WUE and growing season rainfall, ranking as follows: Banastás > Híjar > Zuera. WUE values reflected the differences in yield observed among tillage treatments and cropping systems. At Híjar in 1991-1992, WUE was substantially lower with NT than with CT and RT, especially under the CF rotation (4 and 8 times lower for WUE_b and WUE_g , respectively).

Despite the differences in growth, total ET was generally similar for all treatments. A large proportion of ET lost as E could explain this lack of differences. On the basis of constancy of the transpiration efficiency for a cropping system (Tanner and Sinclair, 1983), seasonal T was calculated directly from the above-ground dry matter produced per unit area (DM) as follows:

$$T = DM (e^* - e) / k$$

where $(e^* - e)$ is the mean daytime vapour pressure deficit and k is a crop-specific efficiency coefficient. $(e^* - e)$ was calculated for the period of active DM accumulation (from ZGS 11-12 to ZGS 75-85) and k for barley was estimated to be 3.1 Pa, based on values reported in the literature for this species (Day et al., 1987; Gregory et al., 1992). E was estimated by subtraction of T from ET for the period between ZGS 00-09 and ZGS 75-85. Estimates of T , its contribution to ET, as well as transpiration efficiencies for grain yield (TE_g) are shown in Table 5. Over the experimental period, T ranged from 18 mm (NT under CF at Híjar in 1991-1992) to 168 mm (RT at Banastás in 1991-1992). In 1991-1992, with higher values of $(e^* - e)$ than in 1990-1991, T was considerably reduced at the Zuera and Híjar sites, whereas little differences between both growing seasons were found at Banastás. Effects of tillage and cropping system were the same as those indicated above for crop growth and WUE. Therefore, the contribution of E to ET showed a substantial variation, ranging from 20% of ET at Banastás in 1990-1991, to nearly 90%, once again, with NT under CF at Híjar in 1991-1992. The transpiration efficiency for grain yield (TE_g) ranged from 7.4 to 23.8 kg ha⁻¹ mm⁻¹ (Table 5).

4. Discussion

4.1. Crop growth

Consistently lower early growth of barley under NT in the 1990-1991 growing season could be related to the high values of soil penetration resistance (higher than 2 MPa) recorded in the top 10 cm of soil after sowing (López et al., 1996). Soil strength has been widely identified as a critical factor affecting root development and, hence, water and nutrient availability during early crop growth in no-tilled treatments (Chan et al., 1987; Masle, 1992). However, in 1991-1992, overall NT did not affect seedling growth, even though the soil strength in the topsoil was higher than in the first season. Presumably, there were other limiting factors besides soil compaction. Regardless of tillage treatments, a strong relationship ($P < 0.001$) was found between seed depth and plant height (Fig. 6). In our experimental conditions, a seed bed depth lower than 30 mm seemed to be responsible for the delay in the early growth observed (Table 2). Near the soil surface, the seed would be subjected more directly to the action of adverse environmental conditions (i.e., desiccation, freezing, predation). A shallow seed placement is frequent in the conservation tillage systems, especially under NT, due to either high levels of crop residues (Swan et al., 1994) or to an uneven or hard soil surface at sowing (Thomas et al., 1990), as occurred in our study.

The high variability in weather conditions in the semi-arid areas of Aragón explains why the differences found in barley yield were larger between years than among tillage treatments. Thus, in spite of better conditions for crop establishment in the second growing season than in the first, the lack of effective rains during active plant growth in 1991-1992 resulted in very low yield at Híjar and Zuera and, even, nil yield at Peñaflor (Table 3). On the basis of our results, the crop with NT seemed to be the most affected by adverse climatic conditions. At Peñaflor and Híjar, where tillage effects occurred, grain yields with NT and RT over the 2 years averaged 46% and 16% less, respectively, than the yield with CT. In agreement with other experiences (Schmidt et al., 1994), the higher soil strength initially recorded in NT plots would finally reduce crop yields, depending on rainfall distribution during the growing season. For example, at Peñaflor in 1990-1991, precipitation received during vegetative development of the crop was not enough for barley to overcome the negative effect of low soil water content and high soil strength at sowing. Soil compaction can restrict root growth and, hence, the access to water and nutrients from deeper layers (Kirkegaard et al., 1994; Hammel,

1 1995). This hypothesis appears to be supported by the observation of the changes in soil water
2 profiles (0-80 cm) during the growing season (López et al., 1996). Thus, a shallower rooting depth
3 could be expected under NT where soil water depletion was confined more to the upper soil layers
4 (0-40 cm) than in CT and RT plots. In contrast to Peñaflor, timely rainfall at Híjar at tillering in
5 1990-1991 resulted in an increase of soil water storage, a reduction of soil penetration resistance and,
6 finally, low yield differences among tillage treatments. At the Zuera and Banastás sites, similar yields
7 with the three treatments indicate that the initial higher soil strength under NT was not a limiting
8 factor to crop production. Due to the high biological activity observed at these sites, it would be
9 expected that the crop roots in NT plots have grown into biopores created by earthworms and root
10 channels of previous crops. A soil macroporosity study made at Banastás at the end of the
11 experimental period, indicated that the density of macropores greater than 5 mm (mainly earthworm
12 burrows) was three times greater under NT than under CT and RT (López and Arrúe, 1996).

13 Yield differences among tillage treatments resulted mainly from differences in grain number per
14 unit area (grains per ear x ears per m⁻²) rather than the variation in grain weight (Table 3). Reduction
15 of grain yield associated with a significantly lower grain weight was observed only in 1991-1992 at
16 Híjar with NT under CF. This small effect of tillage on grain weight may be related to the ability of
17 plants to translocate the pre-anthesis carbohydrate reserves to the grain. In dry seasons in temperate
18 climates, such reserves may contribute to 50% of final grain weight of barley (Gallagher et al., 1983).
19 For this reason, in Mediterranean environments, it is important to reach maximum biomass and LAI
20 values at anthesis in order to provide enough reserves that could be potentially used during grain
21 filling (Anderson, 1992; Ramos et al., 1995). In this study, LAI and above-ground biomass at
22 heading were good indicators of growth conditions, showing that in the most arid sites the lowest
23 values of both parameters corresponded, generally, to the NT treatment. Thus, at Peñaflor,
24 differences in grain number were significantly correlated ($P < 0.01$) with LAI ($r^2=0.32$) and biomass
25 ($r^2=0.39$) at heading across all treatments. Likewise, similar relations were found at Híjar across all
26 treatments and years ($r^2=0.57$ for LAI and $r^2=0.56$ for biomass; $P < 0.01$).

27 With regard to the comparison between cropping systems, CC and CF, a close relationship was
28 observed between fallow efficiencies in soil water storage (López et al., 1996) and barley growth and
29 yield. Figure 7 shows the relationship obtained by French (1978) between the additional soil water
30 content at sowing due to fallowing and the increase in wheat yield in a similar cereal-fallow rotation

1 in South Australia. It can be seen that the data of the present study (solid circles) generally fall below
2 the regression curve found by French. This poor response could be attributed to a particularly dry
3 growing period in 1991-1992. In Figure 7, our two highest values are from Híjar under the CT and
4 RT treatments, where 58 mm and 43 mm of additional water, respectively, resulted in a yield
5 increase of about 400 kg ha⁻¹ in both treatments. Taking into account the unfavourable weather
6 conditions mentioned above, this quantity was not very distant from the 605 kg ha⁻¹ of average yield
7 increase reported by French (1978) for a similar additional water storage (53 mm). However, as
8 previously discussed (López et al., 1996), if the probability of fallow efficiencies similar to those
9 found at Híjar is very low, in the same way, yields under CF greater than those obtained in this study
10 are very unlikely.

11

12 4.2. *Water use efficiency*

13 Amongst the possible ways in which WUE can be improved in the rainfed farming systems of
14 the Mediterranean region (Cooper and Gregory, 1987), increasing the soil water available to crop and
15 reducing the evaporation from soil could be achieved by conservation tillage through the beneficial
16 effects of crop residues retained on the soil surface. However, in these areas low stubble yields and
17 grazing after harvest usually limit the amount of residues. In the present study, WUE with RT was,
18 generally, similar to that with CT (Table 4). In contrast, the response to NT was inconsistent and only
19 at two of the experimental sites, Zuera and Banastás, may this practice be viable. At Peñaflor and
20 Híjar, the lower ET under NT during the vegetative growth of barley (mainly at stem elongation) and
21 the lack of a compensatory post-heading ET from the water conserved at heading, reflect the
22 incapacity of this treatment to satisfy crop water needs in these water-limited environments. As
23 reported in other experiments, the reduction of ET with NT may be associated with higher levels of
24 soil strength (Sharma, 1991; Schmidt et al., 1994) and/or lower soil water storage at sowing, as a
25 consequence, probably, of insufficient amounts of crop residues on the soil surface (Thomas et al.,
26 1990; Gibson et al., 1992). Values of WUE_g in this study varied from 0.7 to 17.0 kg ha⁻¹ mm⁻¹, being
27 consistent with the range cited by other authors for cereal crops in similar Mediterranean
28 environments. Thus, Gregory et al. (1992) reported values of 8.7-13.7 kg ha⁻¹ mm⁻¹ for three
29 different varieties of barley. In South Australia, French (1978) cited a range of 0.8-11.4 kg ha⁻¹ mm⁻¹
30 for wheat. Likewise, Perry (cited by Gibson et al., 1992) found values of 4.5-15.8 kg ha⁻¹ mm⁻¹ for

1 cereal crops in general. In a Mediterranean environment of Northern Spain, Cantero-Martínez et al.
2 (1996) have recently obtained in barley cultivars WUE_g values that varied from 5.9 to 9.5 kg ha⁻¹
3 mm⁻¹.

4 Separation of ET into its components showed a common characteristic of the Mediterranean
5 environment, namely, the large proportion of ET that occurs as *E*. With the exception of Banastás, *E*
6 was the principal component of ET at the rest of the sites, accounting for an average of 60% and 70%
7 of ET for the first and second growing season, respectively (Table 5). At Banastás, *E* did not
8 represent more than 30% of ET in any case. For barley crops, *E* values of 35-60% are common
9 (Gregory et al., 1992, Western Australia) and can reach 75-80% in the case of unfertilized crops, as
10 showed by Cooper et al. (1987) and Allen (1990) in Northern Syria. With regard to tillage, our data
11 indicate that reduction of *E* by conservation tillage was not possible in our environments.
12 Furthermore, *E* was increased by NT at the Peñaflor and Híjar sites due to a poor ground cover since
13 early crop stages. With the exception of the Híjar site in 1991-1992, values of TE_g (14.8-23.8 kg ha⁻¹
14 mm⁻¹) changed little among tillage treatments, cropping system and, even, field sites, supporting the
15 conservativeness of the TE for a given crop-environment combination. However, TE can be reduced
16 when soil nutrients severely limit crop growth (Tanner and Sinclair, 1983). Thus, limited
17 accessibility to soil nutrients, as a consequence of high soil strength, could be the reason of the low
18 TE_g values found at Híjar in 1991-1992 under NT. Finally, TE_g values in this study were similar to
19 those reported by Gregory et al. (1992) for barley (17.9-23.1 kg ha⁻¹ mm⁻¹) and by Connor et al.
20 (1992) for wheat (8.6-32.5 kg ha⁻¹ mm⁻¹).

21

22 **5. Conclusions**

23 Results from the first two seasons of a long-term conservation tillage experiment indicate that
24 RT can be recommended as a viable alternative to CT for the main dryland cereal production areas of
25 Aragón (NE Spain), without detrimental effect on crop yield. In contrast, in the most arid zones, NT
26 reduced barley growth, yield and WUE when compared with RT and CT. High soil strength and low
27 crop residue levels appear to be major factors limiting the suitability of NT in such areas. However,
28 owing to the time required for soil properties to improve and crop residues to accumulate, an accurate
29 assessment of NT will be possible only after a longer period of study. On the other hand, fallowing in

1 the CF rotation, with either traditional or conservation tillage management, proved to be an
2 inefficient practice for increasing soil water storage and subsequent crop yield.

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1 **References**

- 2 Aase, J.K. and Siddoway, F.H., 1982. Evaporative flux from wheat and fallow in a semiarid climate.
3 Soil Sci. Soc. Am. J., 46: 619-626.
- 4 Allen, S.J., 1990. Measurement and estimation of evaporation from soil under sparse barley crops in
5 northern Syria. Agric. For. Meteorol., 49: 291-309.
- 6 Anderson, W.K., 1992. Increasing grain yield and water use of wheat in a rainfed mediterranean type
7 environment. Aust. J. Agric. Res., 43: 1-17.
- 8 Cantero-Martínez, C., Villar, J.M., Romagosa, I. and Fereres, E., 1996. Growth and yield responses
9 of two contrasting barley cultivars in a Mediterranean environment. Eur. J. Agron., 4: 317-326.
- 10 Connor, D.J., Theiveyanathan, S. and Rimmington, G.M., 1992. Development, growth, water-use
11 and yield of a spring and a winter wheat in response to time of sowing. Aust. J. Agric. Res., 43:
12 493-516
- 13 Cooper, P.J.M. and Gregory, P.J., 1987. Soil water management in the rain-fed farming systems of
14 the Mediterranean region. Soil Use Manage., 3: 57-62.
- 15 Cooper, P.J.M., Gregory, P.J., Keatinge, J.D.H. and Brown, S.C., 1987. Effects of fertilizer, variety
16 and location on barley production under rainfed conditions in Northern Syria. 2. Soil water
17 dynamics and crop water use. Field Crops Res., 16: 67-84.
- 18 Chan, K.Y., Mead, J.A. and Roberts, W.P., 1987. Poor early growth of wheat under direct drilling.
19 Aust. J. Agric. Res., 38: 791-800.
- 20 Day, W., Lawlor, D.W. and Day, A.T., 1987. The effect of drought on barley yield and water use in
21 two contrasting years. Irrigation Science, 8: 115-130.
- 22 Fereres, E., Orgaz, F. and Villalobos, F.J., 1993. Water use efficiency in sustainable agricultural
23 systems. In: D.R. Buxton, R. Shibles, R.A. Forsberg, B.L. Blad, K.H. Asay, G.M. Paulsen and
24 R.F. Wilson (Editors), International Crop Science I. CSSA, Madison, WI, pp. 83-89.
- 25 Fisher, R.A., 1987. Responses of soil and crop water relations to tillage. In: P.S. Cornish and J.E.
26 Pratley (Editors), Tillage, new directions in Australian agriculture. Inkata Press, Melbourne, pp.
27 194-221.
- 28 French, R.J., 1978. The effect of fallowing on the yield of wheat. II. The effect on grain yield. Aust.
29 J. Agric. Res., 29: 669-684.

1 Gallagher, J.N., Biscoe, P.V. and Dennis-Jones, R., 1983. Environmental influences on the
2 development, growth and yield of barley. In: G.H. Wright and R.B. Wynn-Williams (Editors),
3 Agronomy Society of New Zealand, Special Publication No. 2, pp. 21-50.

4 Gibson, G., Radford, B.J. and Nielsen, R.G.H., 1992. Fallow management, soil water, plant-available
5 soil nitrogen and grain sorghum production in South West Queensland. *Aust. J. Exp. Agr.*, 32:
6 473-482.

7 Gregory, P.J., Tennant, D. and Belford, R.K., 1992. Root and shoot growth, and water and light use
8 efficiency of barley and wheat crops grown on a shallow duplex soil in a Mediterranean-type
9 environment. *Aust. J. Agric. Res.*, 43: 555-573.

10 Hammel, J.E., 1995. Long-term tillage and crop rotation effects on winter wheat production in
11 Northern Idaho. *Agron. J.*, 87: 16-22.

12 Kirkegaard, J.A., Angus, J.F., Gardner, P.A. and Müller, W., 1994. Reduced growth and yield of
13 wheat with conservation cropping. I. Field studies in the first year of the cropping phase. *Aust. J.*
14 *Agric. Res.*, 45: 511-528.

15 López, M.V. and Arrúe, J.L., 1995. Efficiency of an incomplete block design based on geostatistics
16 for tillage experiments. *Soil Sci. Soc. Am. J.*, 59: 1104-1111.

17 López, M.V. and Arrúe, J.L., 1996. Efecto del laboreo de conservación sobre la macroporosidad de
18 un suelo de secano en la provincia de Huesca. In: L. García, A. Valera and P. González (Editors),
19 Actas del Congreso Nacional sobre Agricultura de Conservación: Rentabilidad y Medio
20 Ambiente. AELC/SV, Córdoba, Spain, pp. 125-129.

21 López, M.V., Arrúe, J.L. and Sánchez-Girón, V., 1996. A comparison between seasonal changes in
22 soil water storage and penetration resistance under conventional and conservation tillage systems
23 in Aragón. *Soil Tillage Res.*, 37: 251-271.

24 Masle, J., 1992. Genetic variation in the effects of root impedance on growth and transpiration rates
25 of wheat and barley. *Aust. J. Plant Physiol.*, 19: 109-125.

26 McAneney, K.J. and Arrúe, J.L., 1993. A wheat-fallow rotation in North-Eastern Spain: water
27 balance-yield considerations. *Agronomie*, 13: 481-490.

28 Ramos, J.M., de la Morena, I. and García del Moral, L.F., 1995. Barley response to nitrogen rate and
29 timing in a Mediterranean environment. *J. Agric. Sci. (Camb.)*, 125: 175-182.

1 Schmidt, C.P., Belford, R.K. and Tennant, D., 1994. Effect of different direct drilling and
2 conventional sowing techniques on soil strength, root growth and grain yield of wheat on
3 sandplain soils in Western Australia. *Aust. J. Agric. Res.*, 45: 547-564.

4 Sharma, B.R., 1991. Effect of different tillage practices, mulch and nitrogen on soil properties,
5 growth and yield of fodder maize. *Soil Tillage Res.*, 19: 55-66.

6 Smika, D.E., 1990. Fallow management practices for wheat production in the Central Great Plains.
7 *Agron. J.*, 82: 319-323.

8 Swan, J.B., Higgs, R.L., Bailey, T.B., Wollenhaupt, N.C., Paulson, W.H. and Peterson, A.E., 1994.
9 Surface residue and in-row treatment effects on long-term no-tillage continuous corn. *Agron. J.*,
10 86: 711-718.

11 Tanner, C.B. and Sinclair, T.R., 1983. Efficient water use in crop production: Research or re-search?.
12 In: H.M. Taylor, W.R. Jordan and T.R. Sinclair (Editors), *Limitations to Efficient Water Use in*
13 *Crop Production*. ASA, Madison, WI, pp. 1-27.

14 Thomas, G.A., Standley, J., Hunter, H.M., Blight, G.W. and Webb, A.A., 1990. Tillage and crop
15 residue management affect Vertisol properties and grain sorghum growth over seven years in the
16 semi-arid sub-tropics. 3. Crop growth, water use and nutrient balance. *Soil Tillage Res.*, 28: 389-
17 407.

18 Unger, P.W., Stewart, B.A., Parr, J.F. and Singh, R.P., 1991. Crop management and tillage methods
19 for conserving soil and water in semi-arid regions. *Soil Tillage Res.*, 20: 219-240.

20 Zadoks, J.C., Chang, T.T. and Konzak, C.F., 1974. A decimal code for the growth stages of cereals.
21 *Weed Res.*, 14: 415-421.

Figure legends

Figure 1. Monthly precipitation during the experimental period (—) and long-term average precipitation (-----) at the Peñaflor (1954-1989), Zuera (1966-1989), Híjar (1961-1989) and Banastás sites (1955-1989). S, sowing; H, harvest. (From López et al., 1996).

Figure 2. Seasonal changes in (a) above-ground dry matter without ears, (b) ears dry matter and (c) leaf area index (LAI) of barley at the Híjar site in the 1990-1991 growing season, under different tillage treatments (■, conventional tillage; X, reduced tillage; and O, no-tillage). Bars indicate LSD ($P < 0.05$) for comparisons at the same date, where significant differences were found.

Figure 3. Seasonal changes in (a) above-ground dry matter without ears, (b) ears dry matter and (c) leaf area index (LAI) of barley at the Híjar site in the 1991-1992 growing season, under different tillage treatments (■, conventional tillage; X, reduced tillage; and O, no-tillage) and cropping systems (CC, continuous cropping; CF, cereal-fallow rotation). Bars indicate LSD ($P < 0.05$) for comparisons among tillage treatments at the same date and cropping system, where significant differences were found.

Figure 4. Crop water use (evapotranspiration, ET) during different phases of barley growth (Zadoks growth stages, ZGS) as affected by tillage (CT, conventional tillage; RT, reduced tillage; and NT, no-tillage) at (a) the Peñaflor, (b) Híjar, (c) Zuera and (d) Banastás sites in the 1990-1991 growing season. Bars indicate LSD ($P < 0.05$) for comparisons at the same phase of crop growth, where significant differences were found. At Banastás, crop failed in NT plots.

Figure 5. Crop water use (evapotranspiration, ET) during different phases of barley growth (Zadoks growth stages, ZGS) as affected by tillage (CT, conventional tillage; RT, reduced tillage; and NT, no-tillage) and cropping systems (CC, continuous cropping; CF, cereal-fallow rotation) at (a) the Híjar and (b) Zuera sites in the 1991-1992 growing season. Bars indicate LSD ($P < 0.05$) for comparisons among tillage treatments at the same phase of crop growth and cropping system, where significant differences were found.

1 **Figure 6.** Relationship between seed depth and plant height of barley at ZGS 11-12, for three tillage
2 treatments (■, conventional tillage; X, reduced tillage; and O, no-tillage).

3

4 **Figure 7.** Relationship between the additional water in fallow at sowing and yield response to fallow
5 found by French (1978) for wheat (O). The results for barley in the present study are included (●).

Table 1

Agronomic information for each field site and growing season

Field site	Growing season	Sowing date	Harvest date	Seed variety	Seed rate (kg ha ⁻¹)
Peñaflor	1990-1991	26.11.1990	20.6.1991	Albacete	170
	1991-1992	18.11.1991	21.6.1992	Albacete	170
Zuera	1990-1991	21.11.1990	19.6.1991	Alpha	150
	1991-1992	18.11.1991	22.6.1992	Alpha	150
Híjar	1990-1991	23.11.1990	2.7.1991	Steptoe	150
	1991-1992	12.12.1991	2.7.1992	Steptoe	150
Banastás	1990-1991	23.11.1990	27.6.1991	Reinette	185
	1991-1992	11.11.1991	9.7.1992	Reinette	185

Table 2

Crop establishment and early growth (ZGS 11-12) as affected by tillage (CT, conventional tillage; RT, reduced tillage; NT, no-tillage) and cropping system (CC, continuous cropping; CF, cereal-fallow rotation) at two field sites

Growing season	Field site ^a	Cropping system	Tillage treatment	Emergence (%)	ERI ^b (days)	Seed depth (mm)	Plant height (mm)	LAI
1990-1991	Peñaflor	CC	CT	62.8	45.1	37.9	76.8	0.112
			RT	63.7	45.8	45.1	81.2	0.111
			NT	57.2	45.8	26.7	66.5	0.090
			LSD (0.05) ^c	NS	NS	13.6	12.8	NS
	Híjar	CC	CT	68.9	61.5	42.0	68.1	0.054
			RT	62.5	59.7	45.9	68.8	0.042
			NT	73.2	86.8	20.3	35.6	0.020
			LSD (0.05)	NS	8.2	15.7	17.4	0.019
1991-1992	Peñaflor	CC	CT	99.3	22.4	65.1	88.7	0.152
			RT	96.3	22.5	38.2	71.3	0.132
			NT	82.2	22.7	61.4	84.2	0.103
			LSD (0.05)	NS	NS	11.9	NS	NS
		CF	CT	89.9	23.0	69.1	85.2	0.151
			RT	81.2	22.3	65.7	84.6	0.154
			NT	83.9	24.3	78.0	89.1	0.122
			LSD (0.05)	NS	1.1	NS	NS	NS
	Híjar	CC	CT	72.5	— ^d	22.7	56.8	0.066
			RT	68.7	—	25.5	57.6	0.060
			NT	93.4	—	32.4	63.5	0.102
			LSD (0.05)	20.6		NS	NS	0.025
		CF	CT	82.5	—	29.7	66.1	0.083
			RT	71.4	—	21.5	55.2	0.067
			NT	94.7	—	37.9	69.8	0.080
			LSD (0.05)	17.5		10.7	10.2	NS

^a In the 1990-1991 season, measurements were made on 11.2.1991 at Peñaflor and 28.2.1991 at Híjar; in the 1991-1992 season, on 26.12.1991 at Peñaflor and 26.2.1992 at Híjar

^b Emergence rate index

^c Least significant difference, $P < 0.05$. NS, not significant

^d Not determined

Table 3

Grain yield and yield components of barley as affected by tillage (CT, conventional tillage; RT, reduced tillage; NT, no-tillage) and cropping system (CC, continuous cropping; CF, cereal-fallow rotation) at different field sites

Growing season	Field site	Cropping system	Tillage treatment	Grain yield (kg ha ⁻¹)	Ears per m ²	Grains per ear	Grain weight (mg)	Harvest index
1990-1991	Peñaflor	CC	CT	2450	637	21.6	17.8	0.32
			RT	1520	495	16.9	18.1	0.28
			NT	1430	495	15.9	18.2	0.31
			LSD (0.05) ^a	670	103	5.6	NS	
	Híjar	CC	CT	2200	244	28.5	31.6	0.50
			RT	2210	282	27.2	28.9	0.54
			NT	1860	290	20.0	32.2	0.55
			LSD (0.05)	NS	NS	6.9	NS	
	Zuera	CC	CT	440	157	10.9	25.8	0.36
			RT	390	171	8.8	25.9	0.36
			NT	420	132	11.6	27.7	0.35
			LSD (0.05)	NS	NS	NS	NS	
		CF	CT	410	164	10.8	22.8	0.34
			RT	530	182	11.1	26.4	0.42
			NT	580	177	12.1	27.3	0.39
			LSD (0.05)	NS	NS	NS	4.5	
	Híjar	CC	CT	970	242	13.0	31.0	0.46
			RT	850	252	11.7	28.5	0.44
			NT	360	211	5.7	29.8	0.33
			LSD (0.05)	440	NS	5.8	NS	
		CF	CT	1370	267	14.4	35.6	0.45
			RT	1260	263	14.7	32.6	0.47
			NT	130	183	3.0	23.9	0.23
			LSD (0.05)	580	NS	7.4	3.7	
1991-1992	Banastás	CC	CT	3100	594	22.6	23.1	0.44
			RT	3430	696	23.1	21.4	0.47
			NT	3250	645	19.5	25.8	0.44
			LSD (0.05)	NS	NS	1.9	1.5	

^a Least significant difference, $P < 0.05$. NS, not significant

Table 4

Water use efficiency for above-ground biomass (WUE_b) and grain (WUE_g) of barley as affected by tillage (CT, conventional tillage; RT, reduced tillage; NT, no-tillage) and cropping system (CC, continuous cropping; CF, cereal-fallow rotation) at the four field sites

Field site	Tillage treatment	1990-1991		1991-1992			
		WUE _g	WUE _b	CC		CF	
				WUE _g	WUE _b	WUE _g	WUE _b
				kg ha ⁻¹ mm ⁻¹			
Peñaflor	CT	11.3	35.2	– ^b	–	–	–
	RT	7.7	27.2	–	–	–	–
	NT	7.5	24.2	–	–	–	–
	LSD (0.05) ^a	3.0	4.3				
Zuera	CT	4.5	– ^c	3.0	8.3	2.5	7.2
	RT	3.7	–	2.7	7.5	3.2	7.4
	NT	3.9	–	3.0	8.5	3.8	9.6
	LSD (0.05)	NS		NS	NS	NS	NS
Híjar	CT	9.2	18.2	4.7	10.3	5.5	12.1
	RT	8.9	16.5	4.0	9.1	5.1	10.9
	NT	7.9	14.3	1.8	5.6	0.7	3.0
	LSD (0.05)	NS	3.2	2.3	3.6	2.6	4.7
Banastás	CT	16.7	– ^c	12.5	28.2		
	RT	17.0	–	13.1	28.0		
	NT	– ^d	–	12.4	27.9		
	LSD (0.05)	NS		NS	NS		

^a Least significant difference, $P < 0.05$. NS, not significant

^b Crop failure due to drought

^c Not determined

^d Crop failure probably associated with herbicide persistence after sowing

Table 5

Values of transpiration (T), its contribution to water use (T/ET) and transpiration efficiency for grain yield (TE_g) of barley, estimated from vapour pressure deficit (e^*-e) and above-ground dry matter (DM), under different tillage treatments (CT, conventional tillage; RT, reduced tillage; NT, no-tillage) and cropping systems (CC, continuous cropping; CF, cereal-fallow rotation) at the four field sites.

Growing season	Field site	Cropping system	Tillage treatment	(e^*-e) (Pa)	ET (mm)	DM ($g\ m^{-2}$)	T (mm)	T/ET	TE_g (%)
1990-1991	Peñaflor	CC	CT	590	205	764	145	71	16.9
			RT		193	538	102	53	14.9
			NT		179	459	87	49	16.5
			LSD (0.05) ^a		NS	95	50	NS	NS
	Zuera	CC	CT	501	204	260 ^b	42	21	22.9
			RT		207	219 ^b	35	17	23.1
			NT		195	232 ^b	37	19	23.2
			LSD (0.05)		NS	NS	NS	NS	NS
	Híjar	CC	CT	753	226	437	106	47	20.8
			RT		233	407	99	42	22.3
			NT		222	337	82	37	22.7
			LSD (0.05)		NS	70	23	8	NS
	Banastás	CC	CT	612	199	817 ^b	161	81	22.3
			RT		184	755 ^b	149	81	23.8
			NT		— ^c	—	—	—	—
			LSD (0.05)		NS	NS	NS	NS	NS
1991-1992	Zuera	CC	CT	555	88	124	22	25	20.1
			RT		86	109	20	23	19.0
			NT		102	120	22	22	19.2
			LSD (0.05)		NS	NS	NS	NS	NS
		CF	CT		105	119	21	20	19.3
			RT		105	126	23	22	23.2
			NT		109	148	26	24	22.4
			LSD (0.05)		NS	NS	NS	NS	NS
	Híjar	CC	CT	936	132	213	64	48	15.2
			RT		138	190	57	41	14.8
			NT		130	110	33	25	10.9
			LSD (0.05)		NS	79	25	21	2.6
		CF	CT		168	303	91	54	15.0
			RT		168	266	80	48	15.7
			NT		129	58	18	14	7.4
			LSD (0.05)		11	103	31	17	3.4
	Banastás	CC	CT	708	225	699	160	71	19.4
			RT		228	735	168	74	20.4
			NT		226	731	167	74	19.4
			LSD (0.05)		NS	NS	NS	NS	NS

^a Least significant difference, $P < 0.05$. NS, not significant

^b Estimated from harvest index obtained in 1991-1992

^c Crop failure probably associated with herbicide persistence after sowing

Precipitation (mm)

← 1990 → 1991 → 1992 →

Fig. 1

Fig. 2

Fig. 2

Fig. 4

Fig. 5

Fig. 6

fig. 10