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7 **Winter Barley Performance under different Cropping and Tillage**
8 **Systems in Semiarid Aragon (NE Spain)**
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Abstract

Winter barley is the major crop on semiarid drylands in central Aragon (NE Spain). In this study we compared, under both continuous cropping (BC) (5-6 month fallow) and a crop-fallow rotation (BF) (16-18 month fallow), the effects of three fallow management treatments (conventional tillage, CT; reduced tillage, RT; and no-tillage, NT) on the growth, yield and water use efficiency (WUE) of winter barley during three consecutive growing seasons in the 1999 to 2002 period. Daily precipitation measurements and monthly measurements of soil water storage to a depth of 0.7 m were used to calculate crop water use (ET) and its components. The average growing season precipitation was 195 mm. Above-ground dry matter (DM) and corresponding WUE were high in years with high effective rainfalls ($>10 \text{ mm day}^{-1}$) either in autumn or spring. However, the highest values of WUE for grain yield were mainly produced by effective rainfalls during the time from stem elongation to harvest. Despite the similarity in ET for the three tillage treatments, NT provided the lowest DM production, corresponding to a higher soil water loss by evaporation and lower crop transpiration (T), indicated by the lowest T/ET ratio values found under this treatment. No clear differences in crop yield were observed among the tillage treatments in the study period. On average, and regardless of the type of tillage, BF provided the highest values of DM and WUE and yielded 49% more grain than BC. These differences between cropping systems increased when water-limiting conditions occurred in the early stages of crop growth, probably due to the additional soil water storage under BF at sowing. Although no significant differences in precipitation use efficiency (PUE) were observed between BC and BF, PUE was higher under the BC system, which yielded 34% more grain than the BF rotation when yields were adjusted to an annual basis including the length of the fallow. The crop yield under BF was not dependent on the increase in soil water storage at the end of the long fallow. In conclusion, this study has shown that although conventional tillage can be substituted by reduced or no-tillage systems for

fallow management in semiarid dryland cereal production areas in central Aragon, the practice of long-fallowing to increase the cereal crop yields is not longer sustainable

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Keywords: Barley; Fallow; Conservation tillage; Dryland farming; Water use efficiency.

1. Introduction

In semiarid rainfed cereal-growing areas, bare long fallowing enables two seasons' rainfall to be conserved for growing a single crop. Through this practice, levels of soil nitrogen and water storage at sowing time and water use efficiency are increased, and weed and disease control are improved in comparison with continuous cropping (Unger, 1994; Aase and Pikul, 2000). However, long fallowing is a controversial practice because of its inefficiency in terms of soil water storage (Amir et al., 1991; Farahani et al., 1998). From the point of view of fallow management, the use of conventional mouldboard ploughing as the primary tillage to control weeds during fallow results in many cases in an inefficient practice as regards soil water conservation (Singh et al., 1998; Moret et al., 2006). For this reason, conservation tillage systems have been used as an alternative to traditional soil management. However, although in general conservation tillage has been shown to improve soil properties, save time and energy, and help control water and wind erosion, different and contradictory results have been obtained in semiarid dryland areas when cereal growth and yields are compared under conventional and conservation tillage treatments. Whereas some authors have thus ascertained no differences in cereal production between tillage systems (Unger, 1994; Schillinger, 2001), other researchers have observed greater soil water storage under no-tillage and thus better crop yields and water use efficiencies (Lawrence et al., 1994; Johnston et al., 1995; Singh et al., 1998; Bonfil et al., 1999).

1 In central Aragon, rainfed cropland is located in areas with an average annual rainfall of less
2 than 400 mm. In these areas, the most common cropping system is the traditional cereal-fallow
3 rotation, which extends over about 430,000 ha (López et al., 2001) and involves a long-fallow
4 period of 16-18 months running from harvest (June-July) one year to sowing (November-
5 December) the following year. Although the main purpose of long fallowing is to increase soil
6 water storage and the water available for the next crop, the cereal-fallow rotation does not
7 always result in an improved water economy for cereals (López and Arrúe, 1997; Lampurlanés
8 et al., 2002; Moret et al, 2006). Based on barley yield/rainfall regressions for data from a dry
9 area in the Ebro valley, Austin et al. (1998a) estimated that the annual yields from a crop-
10 fallow system would be 15% greater than those obtained with continuous cropping and stated
11 that for fallowing to be economic, grain yields from the traditional cereal-fallow would need to
12 be at least twice those obtained with annual cropping. These findings suggest that the benefits
13 from water storage during the long-fallow period in central Aragon and other semiarid areas in
14 the Ebro river valley can still be seriously questioned.

15 However, mouldboard ploughing, which is the traditional fallow tillage management in the
16 region's cereal cropping systems, is being slowly replaced by conservation tillage practices,
17 such as reduced and no-tillage systems. Even so, the knowledge available on the response of
18 cereal crops to conservation tillage as an alternative fallow tillage management in the semiarid
19 Ebro river valley is still limited. In central Aragon, López and Arrúe (1997) found a 53%
20 reduction in grain yield with no-tillage compared to conventional tillage after two years of trial.
21 By contrast, Angás (2001) and Lampurlanés et al. (2002) found in the eastern Ebro river valley
22 after 8 years of trial that no-tillage fallow appears to be the best management system for barley
23 production.

24 The aim of this study was to compare the effects of three fallow management treatments
25 (conventional tillage, CT; reduced tillage, RT; and no-tillage, NT) on winter barley growth,

yield and water use efficiency during three consecutive growing seasons under both continuous cropping (BC) and a crop-fallow rotation (BF) in a dryland cereal-growing area of central Aragon after 9 years of conservation tillage.

2. Material and methods

2.1. Site, tillage, crop management and experimental design

The site is located at the dryland research farm of the Estación Experimental de Aula Dei (CSIC) in the province of Zaragoza (latitude 41° 44'N; longitude 0° 46'W; altitude 270 m). The climate is semiarid with an average annual precipitation of 390 mm and an average annual air temperature of 14.5 °C. The soil is a loam (fine-loamy, mixed thermic Xerollic Calciorthid) according to the USDA soil classification (Soil Survey Staff, 1975). Main soil characteristics in the plough layer (0-40 cm) are the following: pH (H₂O, 1:2.5): 8.2; electrical conductivity: 0.29 dSm⁻¹; organic matter: 19.3 g Kg⁻¹; CaCO₃: 428 g Kg⁻¹; sand (2000-50 µm), silt (50-2 µm) and clay (< 2 µm) content: 282, 473 and 245 g Kg⁻¹, respectively; and water retention at -33 and -1500 kPa: 198 and 105 g Kg⁻¹, respectively (López et al., 1996). More details on soil hydrophysical properties are given in Moret et al. (2006).

The study was conducted on three adjacent large blocks of plots, which were set up on a nearly level area (slope < 1-2 %) in 1990 (Field 1), 1991 (Field 2) and 1992 (Field 3) within a long-term tillage comparison experiment. Winter barley (*Hordeum vulgare* L.; c.v. Albacete) was cultivated in Field 1 under continuous cropping (BC), after a 5-6 month fallow period, and under the traditional cereal–fallow rotation (BF) in Fields 2 (BF1) and 3 (BF2), after a long-fallow period of 16-18 months, during three cropping seasons. Field soil and crop measurements were taken from November 1999 to June 2002 and comprised three consecutive growing seasons, which extended, respectively, from 4 November 1999 to 20 June 2000 (in BC and BF2), from 13 December 2000 to 29 June 2001 (in BC and BF1) and from 23 November

2001 to 27 June 2002 (in BC and BF2). A schematic of the BC and BF cropping systems with indication of dates for sowing and harvesting is given in Fig. 1.

Three soil tillage systems, implemented during the fallow period, were compared: conventional tillage (CT), reduced tillage (RT) and no-tillage (NT). In the BF system, the CT treatment consisted of mouldboard ploughing to a depth of 30-40 cm in late winter or early spring, followed by secondary tillage with a sweep cultivator to a depth of 10-15 cm in late spring. In the RT treatment, the primary tillage was chisel ploughing to a depth of 25-30 cm followed by secondary tillage as in CT. The NT treatment consisted of controlling weeds exclusively by means of herbicides (glyphosate). In the BC system, the tillage operations of the CT and RT treatments were implemented in fall. More details on the fallow tillage operations can be found in Moret et al. (2006). Whereas a conventional seeder was used to sow the CT and RT treatments, a tine zero-till seeder was used for planting the NT plots. The average sowing rate for the three growing seasons was 175 kg ha⁻¹. Before sowing, an 8-15-15 grade fertilizer was broadcast at a rate of 325 kg ha⁻¹. Except for the NT treatment, which needed one or two more herbicide applications than CT and RT, herbicide and fertiliser rates were the same for all treatments.

The tillage treatments were arranged in an incomplete block design based on geostatistical concepts, with three replications for the RT and NT treatments and four for the CT treatment (López and Arrúe, 1995). The three large blocks of ten plots were arranged according to a split block design with the tillage treatment as the main plot and the cropping system as the subplot. The size of the basic plot was 33.5 m x 10 m, with a separation of 1 m between plots. Within each incomplete block a 7 m x 7 m region was delimited for field measurements at two observation points (one per treatment) separated by a distance of 5 m. In accordance with this sampling scheme, a total of 18 measurements (6 per treatment) were made. To compare the effects of the fallow tillage treatments within each cropping system, analysis of variance

(ANOVA) for the incomplete block design was used. To evaluate the cropping systems irrespective of the tillage treatment and tillage x cropping system interaction, ANOVA for the split block design with three replications was performed. Duncan's multiple range test was used to compare treatment means. The soil and crop parameters measured in BC in the three growing seasons were compared with those obtained in BF1 in 1999-2000 and 2001-2002 and in BF2 in 2000-2001.

2.2. Sampling and measurements

2.2.1. Weather

Daily meteorological observations were made at the experimental site over the whole experimental period using an automated weather station. Precipitation was measured at 1.5 m height using a tipping bucket rain gauge (model ARG100, Campbell Scientific Inc.); air temperature and relative humidity were measured at 1.8 m height with a combined sensor (model HMP35AC, Vaisala). The sensors were connected to a data-logger (model CR10, Campbell Scientific Inc.), which continuously recorded 60-min averages of data acquired at intervals of 10 s.

2.2.2. Soil water content

The volumetric soil water content (θ) in the soil profile (0-70 cm depth) at each observation point was monitored by Time Domain Reflectometry (TDR), using probes of two parallel stainless steel rods (diameter: 4 mm; length: 150, 250, 450 and 750 mm; spacing between rod centres: 50 mm). TDR probes were inserted vertically into the soil to a depth of 10, 20, 40 and 70 cm. The protruding pair of electrodes were connected to a cable tester (model 1502C, Tektronix), and the waveforms were transferred to a laptop to be analysed using the software WinTDR'98 (Or et al., 1998). The water content (θ) was estimated at 0-10, 10-20, 20-40 and

40-70 cm depth layers using the model proposed by Topp et al. (1980), which had proved to be suitable for our soil in a previous calibration experiment, and the multiple-length probe method described by Miyamoto et al. (2001). The soil water profile was monitored on a monthly basis at two observation points per plot in accordance with the incomplete block design. With this sampling scheme, a total 6 measurements per treatment were made on each field and observation date. The plant available soil water (PASW) was calculated as the difference between θ in the soil profile (0-70 cm) and θ at the permanent wilting point ($\psi = -1500$ kPa), previously determined in the laboratory for the three tillage systems (Moret et al., 2006).

2.2.3. Crop growth and yield

Crop establishment was determined as the percentage of seeds sown for which seeding emerged. The seed depth was estimated by measuring the length of white stem above the seed of 5 plants randomly sampled from each row (López and Arrúe, 1997). The crop growth was monitored from biomass samplings at selected growth stages according to the Zadoks scale (Zadoks et al., 1974). During the 1999-2000 growing season, plant samplings were made at early seeding growth (ZGS 11-12), flag leaf extending (ZGS 40), dough development (ZGS 80) and maturity (ZGS 99). During the 2000-2001 and 2001-2002 seasons, samplings were made at early seeding growth (ZGS 11-12), tillering (ZGS 22-28), anthesis (ZGS 60) and maturity (ZGS 99). An additional sampling was made at stem elongation (ZGS 32-38) in the 2001-2002 season. The last sampling date corresponded to the harvest day. Four 0.5 m-long rows per plot in accordance with the incomplete block design were selected for plant measurements at each sampling date. Immediately prior to harvest, all the plants from each 0.5 m-long row sampling were hand-harvested to determine the grain yield and yield components. The ears were counted and, after oven drying, threshed to determine the number of grains per

ear and the mean grain weight. The dry weight of above-ground plant material collected was determined after oven-drying at 65 °C for 48 h.

2.2.4. Water use and water use efficiency

By assuming negligible runoff and drainage below the root zone, crop water use (ET), including crop transpiration (T) and soil water evaporation (E), was calculated from seasonal rainfall (P) and the change in soil water content to a depth of 70 cm (ΔS) (i.e. $ET = \Delta S + P$).

On the basis of a constant transpiration efficiency (TE) for a cropping system (Tanner and Sinclair, 1983), the seasonal T was calculated directly from the above-ground dry matter (DM) as follows:

$$T = DM(e^* - e)/k \quad (1)$$

where $(e^* - e)$ is the mean daytime difference between the saturated (e^*) and the actual (e) vapour pressure and k is a crop-specific efficiency coefficient. The mean daytime vapour pressure deficit, $(e^* - e)$, was calculated for the period of active dry-matter DM accumulation (from ZGS 11-12 to ZGS 75-85), and k for barley was estimated to be 3.1 Pa (López and Arrúe, 1997). The soil water evaporation E was calculated by subtracting T from ET for the period from ZGS 00-09 to ZGS 75-85 (López and Arrúe, 1997).

The water use efficiency for both the total DM produced at harvest (WUE_b) and grain yield (WUE_g) was determined as the respective total biomass and yield weights divided by total ET and expressed in $kg\ ha^{-1}\ mm^{-1}$. The precipitation use efficiency index (PUE), defined as the grain yield divided by harvest-to-harvest water use (Jones and Popham, 1997) and expressed in $kg\ ha^{-1}\ mm^{-1}$, was also calculated for both BC and BF systems. Likewise, the fallow precipitation storage efficiency (PSE), defined as the percentage of fallow-season precipitation that is stored as soil water, was calculated for BF as

$$PSE = [(\theta_f - \theta_i)/P_F] \times 100 \quad (2)$$

where θ_f and θ_i are the volumetric water content in the soil profile (0-70 cm) (expressed in mm) at the end and the beginning of the 16-18-month fallow period, respectively, and P_F the precipitation during the fallow period.

3. Results

3.1. Seasonal rainfall and soil water storage

The average annual precipitation for the experimental period (1999-2002) was 362 mm. The total precipitation recorded from crop sowing to harvest during the 1999-2000 (205 mm), 2000-2001 (164 mm) and 2001-2002 (216 mm) crop-season periods was 24, 28 and 5% below the long-term average, respectively (Fig. 2a). Rainfall patterns among the growing seasons were contrasted with one another, with monthly totals irregularly distributed over each crop cycle period. Whereas the 1999-2000 and 2001-2002 seasons thus showed a dry autumn-winter period (November-March) (62 and 89 mm, respectively) and a wet spring (April-May) (107 and 95 mm, respectively), an opposite pattern characterised the 2000-2001 season (171 mm from November to March and 56 mm from April to May). Likewise, different amounts of effective rainfall ($\geq 10 \text{ mm day}^{-1}$) were observed among the experimental growing seasons. Whereas the 2000-2001 season showed the highest effective rainfall in the autumn-winter period, the effective rainfall in spring was significantly higher for the 2001-2002 season than the 1999-2000 and 2000-2001 seasons (Fig. 2a).

Figures 2b, 2c and 2d show the evolution of the water content in the soil profile (0-70 cm) over the entire experimental period for the different tillage and cropping systems. Whereas a dry autumn in 1999 and 2001 (Fig. 2a) caused low soil water content at seeding (Figs. 2b and 2c), a wet autumn in 2000 allowed an important water recharge (Figs. 2b and 2d). Tillage and crop rotations also affected soil water content. At seeding, the crop-fallow rotation (BF) on average stored 19 mm more water than the continuous cropping (BC) for conventional tillage

(CT), 32 mm more for reduced tillage (RT), and 17 mm more for no-tillage (NT) treatments (Fig. 2). Overall, CT proved to be the most inefficient system for storing water over the growing season. At harvest, a substantial depletion of water content in the soil profile was observed under both BC and BF systems (Fig. 3). The soil water profile was also affected by the different tillage systems. In the upper 20 cm θ was thus generally higher under NT than under CT and RT (Fig. 3).

3.2. Crop performance and water use

In our study, the vegetative growth of barley occurred from sowing to mid-March, while the reproductive period extended to late April. Table 1 summarises the percentage of crop emergence and seed depth as affected by tillage and crop systems for the three experimental growing seasons. The percentage of crop emergence during the period in 2000-2001 was significantly higher than in 1999-2000 and 2001-2002. While statistical differences in crop emergence were found at $P < 0.1$ between crop systems, no effect of tillage systems on crop emergence was observed. Seed depth was lower under NT than under the CT and RT treatments (Table 1). Figure 4 shows the seasonal changes in the above-ground dry-matter (DM) and the plant available soil water content (PASW) as affected by season, cropping system and tillage treatment. As can be observed, NT produced less DM than CT and RT. Table 2 presents the barley yields and harvest index as affected by season, cropping system and tillage management. The crop yield, which was not significantly affected by the tillage systems, was clearly influenced by the cropping system. The highest crop yield and harvest index values corresponded to the 2001-2002 season and the BF cropping system.

Figure 5 shows the total water use (ET) during the three growing seasons as influenced by tillage and cropping systems. Overall, 60% of the ET occurred by anthesis, and 40% took place from anthesis to maturity (Fig. 5). It was found that both seasonal precipitation and the

cropping system exerted a significant influence on $\underline{ET}$. Estimates of crop transpiration ($\underline{T}$), its contribution to $\underline{ET}$ and the transpiration efficiency for grain yield, $\underline{TE_g}$, are shown in Table 3. The partitioning of $\underline{ET}$ into its components showed that a large proportion of $\underline{ET}$ occurred as $\underline{E}$ and that $\underline{T}$ was greater under the BF rotation than under the BC system. Overall, the contribution of $\underline{E}$ to $\underline{ET}$ varied among the growing seasons, ranging from 31% of $\underline{ET}$ in 2001-2002 (wet spring) to 69% of $\underline{ET}$ in 1999-2000 (dry spring).

The water use efficiency for above-ground biomass at harvest ($\underline{WUE_b}$) and grain yield ($\underline{WUE_g}$) was affected by seasonal rainfall, the tillage treatment and the cropping system (Fig 6). The $\underline{WUE_b}$ values ranged between 6.1 and 32.2 kg ha⁻¹mm⁻¹, and the $\underline{WUE_g}$ values between 2.3 and 14.9 kg ha⁻¹ mm⁻¹. As water use efficiency is limited to the growing season, for comparison of cropping systems with fallow periods of different length, the precipitation use efficiency ($\underline{PUE}$) index of Jones and Popham (1997) was used (Table 4). Our results show that this index substantially increased when most of the effective rainfall occurred in the last months (March-May) of crop development (i.e. 2001-2002). Regardless the tillage systems, the average precipitation storage efficiency ($\underline{PSE}$) calculated for the BF rotation was 18, 5 and 9 kg ha⁻¹ mm⁻¹ for the 1999-2000, 2000-2001 and 2001-2002 growing seasons, respectively. No effect of tillage on the $\underline{PSE}$ index was observed.

4. Discussion

4.1 Seasonal rainfall influence on crop growth and yield

As found in previous studies (McAneney and Arrúe, 1993; Cantero-Martínez et al., 1995; Austin et al., 1998b; Díaz-Ambrona and Mínguez, 2001), barley growth and yield (Table 2) were dependent on seasonal rainfall, but also influenced to a large extent by the rainfall distribution over the crop-growing season (Smika, 1970).

1 In 1999-2000, the low plant available soil water (PASW) content between November 1999
2 and March 2000 (Fig. 4), due to a depleted soil water profile at seeding (Fig. 3) and the low
3 precipitation in that period (68 mm) (Fig. 2a), would explain the low ET (on average, 16%
4 lower than in 2000-2001 and 2001-2002) (Table 3) and DM (Fig. 4) values during the early
5 stages of crop development up to stem elongation, as well as the low WUE_b (Fig. 6) in this
6 season. The small differences between ET (Fig. 5) and the seasonal rainfall in this period
7 indicate that during the entire growing period the crop mostly used this rainfall. The low
8 effective rainfall recorded in April-May 2000 (38 mm) (Fig. 2a) was not enough to recharge
9 the soil water profile, which would explain the low DM production (226 g m⁻²) at harvest (Fig.
10 4). In 1999-2000, the low yields (Table 2) (61% lower than in 2001-2002 for a similar seasonal
11 rainfall) and low WUE_g values (Fig. 6) were associated with the low effective rainfall during
12 flowering (58 mm from March to May; Fig. 2a), which led to a lower number of ears per
13 square metre and a lower grain weight (Table 2). Similar results were observed by Amir et al.
14 (1991) and Day et al. (1987).

15 The extra water stored at the end of the 16-18 month fallow period in the 2000-2001
16 resulted in a better crop establishment (Table 1). The high average DM (433 g m⁻²) and high
17 ET measured up to anthesis (40% higher than the rainfall received in this period) was
18 connected with the high PASW in that period (November-March) (Fig. 4). As the high pre- to
19 post-anthesis ET ratio indicates, the low effective rainfall collected (25 mm) during the last
20 phases of crop development (April-May) stressed the crop during ear development, which
21 resulted in a decrease in the number of ears per square metre and, therefore, in low yields
22 (Table 2).

23 In 2001-2002, crop growth was markedly different between the autumn-winter season (41
24 mm of effective rainfall from November to the beginning of March), with low PASW and DM
25 values, and the spring period (109 mm of effective rainfall from March to May), with the most

vigorous crop growth from stem elongation to harvest (average DM equal to 597 g m^{-2}) (Fig. 4). The high yield (Table 2) and WUE_g (Fig. 6) values can be related to the large effective rainfall from March to May (Fig. 2a), which favoured ear and grain development. In general, the results are comparable to those reported by several authors (French, 1978; Amir et al., 1991; Cantero-Martínez et al., 1995), who observed that crop yield and harvest index were poorly correlated with soil water content at sowing but highly influenced by rainfall during the growing season.

4.2. Influence of cropping system on barley response

On average, the BF cropping system (barley-fallow rotation) produced 28% more DM (Fig.4) and used 15-26 mm more water (Fig. 5) than the BC system (continuous cropping). These differences, also observed in others studies (French, 1978; Carr et al., 2001; López-Bellido et al., 2000; Díaz-Ambrona and Mínguez, 2001; Lampurlanés et al., 2002, Latta and O'Leary, 2003), may be related to greater PASW values under BF, leading to better crop establishment and growth (Fig. 4). Although a consistent relationship between the extra water used by the BF crop and the additional water content at sowing was not found, the average ET is in line with the average 22 mm water gained at sowing by the BF system (Moret et al., 2006). The average T/ET ratio under BF (0.57) was 30% higher than under BC (0.44) (Table 3), similar to the 39% obtained by Amir et al (1991) in arid Israel. These differences can be attributed to the lower crop biomass under BC, which favoured soil water evaporation.

Overall, the grain yield in the BF rotation (1883 kg ha^{-1}) was 49 % greater than in the BC system (1261 kg ha^{-1}) (Table 2). This increased yield in BF is higher than the 25% measured by López and Arrúe (1997) and the 15% estimated by Austin et al. (1998a) in the same study area, but lower than the 63% obtained by Díaz-Ambrona and Mínguez (2001) in semiarid central Spain for barley. According to French (1978) in south Australia and López and Arrúe (1997) in

central Aragon, the higher yield under BF could be positively related to the extra water stored under BF. The mean yield gain in BF was 28 kg ha^{-1} per mm water conserved, which was greater than the 11 kg ha^{-1} per mm water conserved obtained by French (1978) and the 8 kg ha^{-1} per mm water conserved obtained by López and Arrúe (1997).

An interaction between the cropping system and rainfall distribution during the growing season was observed. Differences in the crop yield were small (16%) in 2000-2001 (wet autumn and dry spring) and more significant in 1999-2000 (95%) and 2001-2002 (54%) (dry autumn and wet spring in both cases). As Austin et al. (1998a) pointed out, these results suggest that in years with wet autumns (i.e. the 2000-2001 campaign), farmers could beneficially sow without long-fallowing (i.e. after the minimum 5-month fallow).

In line with data reported by French (1978) and with results by Cooper and Gregory (1987), Amir et al. (1991) and Latta and O'Leary (2003), in the present study the average values of both WUE_b and WUE_g were 26 and 29% greater, respectively, under the BF rotation than under the BC system. However, this difference between cropping systems was more significant in seasons with a dry autumn (1999-2000 and 2001-2002), in which the growing-season precipitation was low and not favourably distributed. Overall, the WUE_g (Fig. 6) was consistent with the values reported for barley in two areas of the Ebro river valley by Cantero-Martínez et al. (1995) and López and Arrúe (1997), which ranged from 5.9 to $9.5 \text{ kg ha}^{-1} \text{ mm}^{-1}$ in the first case, and from 0.7 to $17.0 \text{ kg ha}^{-1} \text{ mm}^{-1}$ in the second. Mrabet (2000) found WUE_g values from 2.5 to $10.7 \text{ kg ha}^{-1} \text{ mm}^{-1}$ in semiarid areas of Morocco.

Although no significant differences in PUE were observed between the BF and BC systems, the PUE tended to increase under BC (Table 4). This would indicate that the shorter fallow season in the BC system allows the use for crop transpiration of water that would otherwise be lost during long fallowing by soil water evaporation, runoff or deep percolation (Farahani et al., 1998). Thus, when grain production was adjusted to an annual basis including fallow time,

the BC system was more efficient at using precipitation, producing on average 34% more grain than the BF rotation.

Finally, the relationship between the precipitation fallow storage efficiency (PSE) of the BF rotation and crop yield was established for the three experimental years. The lack of correlation between PSE and yield ($R^2 = 0.06$) would indicate that under BF grain yield is mainly related to the amount of effective rainfall during the last months of crop development (March-May), rather than to the gain in soil water storage at sowing after a long 16-18 month period of fallow.

4.2. Fallow tillage effect on crop growth and yield

As observed by Chan and Heenan (1996), the greater water content in the NT topsoil at sowing (Fig. 3) did not induce significant differences in crop emergence among tillage systems (Table 1). The smallest seed depth was measured in NT plots, which should be associated with a more compacted soil surface under NT.

The NT treatment produced less DM than the CT and RT treatments (Fig. 4). As López et al. (1996) suggested, the crop growth under NT may have been limited by the more compacted NT topsoil that restricts root growth. Although no large differences in I were observed among the tillage treatments, high E values under NT resulted in a low PASW (Fig. 4). This could be attributed to the lower ground cover provided by the crop during crop growth (López and Arrúe, 1997) and the higher water content at the surface in the NT soil profile, which may enhance soil water evaporation in this treatment. These results are similar to those reported by Hamblin et al. (1982) in semiarid western Australia and López-Bellido et al. (2000) in southern Spain, but differ from results obtained in semiarid Morocco by Mrabet (2000), who found that the highest DM values were produced under NT.

Although small differences in grain yield were observed among tillage systems in the three experimental years, NT yielded 24 and 8 % less grain than CT and RT, respectively, as a result of the lower number of grains per unit of area (grains per ear $\times$ ears per m^2) (Table 2). A reduction of 53 and 43% in grain yield with NT compared to CT and RT was found by López and Arrúe (1997) in central Aragon after two years of trial. The lower grain production under NT could be related to the greater soil compaction at the surface horizons in this treatment, which restricts root growth and access to water and nutrients in deeper layers (López et al., 1996). These results differ from those found by Mrabet (2000) in semiarid Morocco and Lampurlanés et al. (2002) in north-eastern Spain, who reported a significant yield increase with NT compared to CT and RT treatments.

The average value of TE_g computed over the three experimental years ($13.6 \text{ kg ha}^{-1} \text{ mm}^{-1}$) was within the range found by López and Arrúe (1997) for barley ($7.4\text{-}23.8 \text{ kg ha}^{-1} \text{ mm}^{-1}$) and below the potential ratio ($16.7 \text{ kg ha}^{-1} \text{ mm}^{-1}$) estimated by McAneney and Arrúe (1993) for wheat in central Aragon. Although in general the tillage did not significantly affect water use efficiency, NT tended to show the lowest WUE values (Fig. 6) due to greater soil water evaporation losses under this treatment. This result differs from the one obtained in semiarid Morocco by Mrabet (2000), which showed higher WUE values under NT than under other tillage systems (e.g. chisel ploughing to a depth of 15-25 cm and disk ploughing to a depth of 25-35 cm) due to reduced evaporation in the NT treatment. In that study, however, there was little difference in WUE among treatments when averaged over years.

5. Conclusions

The results from three growing seasons showed that the growth, water use efficiency and yield of a winter barley crop were influenced by both the amount and distribution of seasonal precipitation and the cropping system. However, there were no clear differences in crop yield

among tillage treatments for the study period. This finding suggests that conventional tillage can be substituted by conservation tillage for fallow management in semiarid dryland cereal production areas in central Aragon.

Overall, the crop-fallow rotation (BF) provided the highest values of crop biomass and water use, yielding about 49% more grain than the continuous cropping (BC) system. Nevertheless, the BC system yielded 34% more grain than the BF rotation when the yields were adjusted to an annual basis. The results also showed that winter barley yields under BF were not dependent on the soil water stored at sowing after a long 16-18 month period of fallow. This means that the practice of long-fallowing to increase cereal crop yield in the study area is no longer recommendable. Further research on alternative crop rotations and cropping intensification to improve the efficient use of precipitation is needed for the sustainability of dryland agriculture in central Aragon.

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Figure captions

Figure 1. Diagram of agronomic practices (S, sowing; H, harvest) under continuous barley cropping (BC) and barley-fallow rotation in field 1 (BF1) and field 2 (BF2) during the 1999-2000, 2000-2001 and 2001-2002 cropping seasons.

Figure 2. Monthly rainfall for the experimental period (1999-2002) vs. long-term average (1954-2002) (a) and dynamics of soil water content (0-70 cm) for conventional tillage (CT), reduced tillage (RT) and no-tillage (NT) under continuous barley cropping (b) and barley-fallow rotation (c) and (d). S and H indicate sowing and harvest dates, respectively. Vertical bars indicate LSD ($P < 0.05$).

Figure 3. Soil water (θ) profiles at sowing and harvesting of barley as affected by tillage (CT, conventional tillage; RT, reduced tillage; NT, no-tillage) under continuous cropping (BC) and crop-fallow rotation (BF) in the 1999-2000, 2000-2001 and 2001-2002 growing seasons. Horizontal bars indicate LSD ($P < 0.05$).

Figure 4. Seasonal changes in total above-ground dry matter and plant available soil water content (PASW) (0-70 cm) as affected by tillage (CT, conventional tillage; RT, reduced tillage; NT, no-tillage) under continuous barley cropping (BC) and barely-fallow (BF) rotation during the 1999-2000, 2000-2001 and 2001-2002 growing seasons. Vertical bars indicate LSD ($P < 0.05$).

Figure 5. Crop water use (ET) during different phases of barley growth as affected by tillage (CT, conventional tillage; RT, reduced tillage; NT, no-tillage) and seasonal precipitation under continuous cropping (BC) and crop-fallow rotation (BF) during the 1999-2000, 2000-2001 and 2001-2002 growing seasons. ZGS indicates crop-development stages in the Zadoks scale (Zadoks et al., 1974) as follows: 22, crop tillering; 32, stem elongation; 40, flag leaf extending; 60, anthesis; 80, dough development; 99, crop maturity. An asterisk indicates significant differences among tillage treatments at $P < 0.05$ for a given development stage and cropping system.

Figure 6. Water use efficiency for above-ground biomass at harvest (WUE_b) and grain yield (WUE_g) of barley as affected by tillage (CT, conventional tillage; RT, reduced tillage; and NT, no-tillage) under continuous cropping (BC) and crop-fallow rotation (BF) in the 1999-2000, 2000-2001 and 2001-2002 growing seasons. Different letters above bars indicate significant differences at $p \leq 0.05$.

Table 1. Crop establishment of barley as affected by tillage (CT, conventional tillage; RT, reduced tillage; NT, no-tillage), and cropping system (BC, continuous cropping; BF, barely-fallow rotation) in the 1999-2000, 2000-2001 and 2001-2002 growing seasons.

Growing season	Cropping system	Tillage treatment	Emergence (%)	Seed depth (cm)
1999-2000	BC	CT	50.7a [†]	5.1a
		RT	45.8a	4.4a
		NT	62.9a	3.5b
	BF2	CT	67.1a	3.3a
		RT	67.1a	3.2a
		NT	66.8a	3.5a
2000-2001	BC	CT	79.5a	3.9a
		RT	83.3a	3.7a
		NT	82.3a	2.6a
	BF1	CT	79.1a	4.6a
		RT	81.9a	4.1a
		NT	93.3a	2.7a
2001-2002	BC	CT	47.5a	5.3a
		RT	55.9a	5.6a
		NT	65.2a	2.6b
	BF2	CT	61.3a	5.8a
		RT	69.4a	4.4b
		NT	67.9a	1.8c

[†] Different letters within a column indicate significant differences at $p < 0.05$

Table 2. Grain yield and yield components of barley as affected by tillage (CT, conventional tillage; RT, reduced tillage; NT, no-tillage), and cropping system (BC, continuous cropping; BF, barley-fallow rotation) in the 1999-2000, 2000-2001 and 2001-2002 growing seasons.

Growing season	Cropping system	Tillage treatment	Grain yield (kg ha ⁻¹)	Ears per M ²	Grains per ear	Grain weight (mg)	Harvest index
1999-2000	BC	CT	859a [†]	183.4a	17.4a	27.8a	0.43a
		RT	457c	122.6a	14.4a	27.5a	0.36b
		NT	633b	145.0a	16.3a	27.8a	0.35b
	BF2	CT	1442a	255.9a	18.6b	31.2a	0.50a
		RT	1693a	239.2a	21.2a	32.3a	0.49a
		NT	839a	210.8a	14.5c	28.9a	0.36a
2000-2001	BC	CT	1409a	246.6a	13.9a	37.5a	0.28a
		RT	1188a	236.8a	13.6a	35.2a	0.28a
		NT	902a	148.7a	20.4a	31.5a	0.27a
	BF1	CT	1475a	284.6a	14.1a	44.8a	0.25a
		RT	1347a	224.5a	16.7a	33.4a	0.24a
		NT	1242a	236.1a	20.9a	26.7a	0.26a
2001-2002	BC	CT	2599a	457.7a	17.2a	33.6a	0.39a
		RT	1782a	350.5a	14.9a	33.2a	0.39a
		NT	1386a	263.0a	17.1a	28.1a	0.32a
	BF2	CT	3096a	528.2a	15.6b	34.5a	0.40b
		RT	3021a	374.8a	22.1a	36.7a	0.43b
		NT	3578a	570.7a	17.7b	36.1a	0.56a

[†] Different letters within a column indicate significant differences at $p < 0.05$

Table 3. Crop transpiration ($\underline{T}$), its contribution to water use ($\underline{T/ET}$) and transpiration efficiency for grain yield ($\underline{TE_g}$) of barley, estimated from vapour pressure deficit ($\underline{e^* - e}$) and above-ground dry matter ($\underline{DM}$) under conventional tillage (CT), reduced tillage (RT) and no-tillage (NT) in the continuous cropping (BC) and barley-fallow (BF) rotation in the 1999-2000, 2000-2001 and 2001-2002 growing seasons.

growing season	Cropping system	Tillage treatment	$\underline{(e^* - e)}$ (Pa)	$\underline{ET}$ (mm)	$\underline{DM}$ (g m ⁻²)	$\underline{T}$ (mm)	$\underline{T/ET}$ (%)	$\underline{TE_g}$ (kg ha ⁻¹ mm ⁻¹)
1999-2000	BC	CT	850	187a [†]	202a	56.0a	28.6a	15.7a
		RT		190a	121a	33.1b	16.6b	13.3b
		NT		178a	178a	48.7a	26.0a	12.9b
	BF2	CT	850	199a	303a	86.0a	41.4a	17.8a
		RT		202a	340a	93.1a	45.8a	17.7a
		NT		200a	212a	58.0a	29.1a	13.1a
2000-2001	BC	CT	858	219a	453a	125.7a	57.2a	10.1a
		RT		225a	398a	110.2a	48.7b	10.0a
		NT		228a	329a	91.1a	40.0c	9.8a
	BF1	CT	858	253a	510a	137.6a	58.9a	10.0a
		RT		237a	512a	142.0a	59.6a	8.8a
		NT		233a	397a	109.9a	47.8a	10.0a
2001-2002	BC	CT	805	214ab	661a	171.7a	80.5a	15.0a
		RT		223a	440b	114.3a	51.0b	15.0a
		NT		206b	370b	96.0a	46.2b	12.2a
	BF2	CT	805	235a	754a	196.0a	82.9a	15.2b
		RT		243a	710a	184.4a	75.7a	16.4b
		NT		241a	649a	169.2a	70.2a	21.7a

[†] Different letters within a column indicate significant differences at $p < 0.05$

Table 4. Precipitation use efficiency (PUE) of barley (grain yield divided by harvest-to-harvest crop water use) as affected by tillage (CT, conventional tillage; RT, reduced tillage; NT, no-tillage), and cropping system (CC, continuous cropping; CF, barley-fallow rotation) in the 1999-2000, 2000-2001 and 2001-2002 growing seasons

Growing season	Cropping system	Tillage treatment	Rainfall [†] (mm)	ET [‡] (mm)	<u>PUE</u> (kg ha ⁻¹ mm ⁻¹)
1999-2000	BC	CT	335	335	2.6a [§]
		RT		360	1.3b
		NT		316	2.0ab
	BF2	CT	620	619	2.3a
		RT		611	2.6a
		NT		611	1.4a
2000-2001	BC	CT	386	383	3.7a
		RT		378	3.1a
		NT		415	2.2a
	BF1	CT	721	723	2.0a
		RT		718	1.9a
		NT		716	1.7a
2001-2002	BC	CT	320	304	8.5a
		RT		321	5.6a
		NT		290	5.1a
		LSD			NS
	BF2	CT	706	708	4.4a
		RT		720	3.8a
		NT		715	4.5a

[†] Harvest to harvest precipitation

[‡] Harvest to harvest crop water use

[§] Different letters within a column indicate significant differences at $p < 0.05$

Fig. 1

Fig. 3

Fig. 4

Fig. 5

Fig. 6