Influence of Fallowing Practices on Soil Water and Precipitation Storage Efficiency in Semiarid Aragon (NE Spain)

D. Moret[*], J.L Arrúe, M.V., López and R. Gracia

Departamento de Edafología, Estación Experimental de Aula Dei, Consejo Superior de Investigaciones Científicas (CSIC), PO Box 202, 50080 Zaragoza, Spain

* Corresponding author.

Tel: (+34) 976 716095

Fax: (+34) 976 716145

E-mail address: david@eead.csic.es

Abstract

In semiarid drylands of Central Aragon, the cereal-fallow rotation, with mouldboard ploughing as main cultivation, is the most traditional farming system, in which a weed-free long fallow period (16-18 months) is practised to increase the amount of water available to the next crop. However, the ability of long fallowing for soil water conservation has been questioned in some dryland regions including Central Aragon. This research was aimed to quantify soil water losses (E), soil water storage (SWS) and precipitation storage efficiency (PSE) of long fallow under three management systems (conventional tillage, CT; reduced tillage, RT; no-tillage, NT). The PSE of long fallow relative to short fallow (5-6 months) was also evaluated. Over four experimental years (1999-2002), soil water balance for both short and long fallow periods was calculated from fallow seasonal precipitation and volumetric soil water content (0-70 cm depth). During long fallowing, primary tillage implemented in CT and RT plots induced significant E losses from the plough layer for the first 24 h after tillage. However, secondary tillage under CT and RT appeared to have a positive effect on soil water conservation at the end of fallow. Despite a different soil water dynamics among treatments, total E at the end of fallow was similar for the three fallow management systems. The partitioning of long fallow into three sub-periods showed that the early phase (July-November) was the most efficient in terms of SWS, having the lowest average daily evaporation rate (E_r) per day (0.65 mm day^{-1}). The overwinter period (December-May) and the late period (June-November) had greater E_r values (0.93 and 1.09 mm day^{-1}, respectively) and variable SWS as a function of rainfall pattern in those periods. In general, PSE, either for the fallow phases or the entire fallow period, increased when most of seasonal effective rainfalls ($\geq$ 10 mm day^{-1}) were received in the last two months of each period. Overall, long fallow PSE was small (11% on average). Neither SWS nor PSE were significantly affected by the tillage system. The average additional soil water at sowing after long fallow compared with short fallow was 20 mm.

Correspondingly, the average PSE of long fallow relative to short fallow was only 5.3%. These findings indicate that the use of long fallowing, as an agronomic practice to enhance soil water storage for the subsequent crop, should not longer be justified in semiarid Aragon.

Keywords: Soil water balance; Water conservation; Conservation tillage; Fallow efficiency; Dryland farming.

1. Introduction

Water is the main limiting factor for grain production in rainfed farming systems of many semiarid dryland regions, where cereal crops are frequently grown under a crop-fallow system (one crop every two years). This system generally involves a long-fallow period aimed to increase soil water storage and, thus, the amount of water available to the succeeding crop. With this widespread practice, no crop is grown during the fallow, weeds are controlled by repeated tillage or chemicals and, in general, the soil water recharge occurs during the overwinter fallow period when temperatures and evaporative demand are low and the precipitation is high. However, contradictory findings on the use of fallow for the purpose of enhancing soil water storage are found in the literature. Thus, for instance, whereas Bonfil et al. (1999) observed in the south of Israel that the fallow year was beneficial in terms of water storage, Farahani et al. (1998b) questioned this practice in semiarid Great Plains of the USA since, on average, only 20% of the seasonal fallow precipitation was stored in the soil profile.

Regarding soil management during fallow in semiarid dryland zones, conventional tillage management, with mouldboard ploughing as primary tillage followed by repeated shallow ploughing, has been found inefficient for soil water conservation (Aase and Siddoway, 1982; Dao, 1993). Therefore, fallow conservation tillage systems have been evaluated as an alternative to the traditional fallow management (Schillinger, 2001). However, the agronomic advantages of conservation tillage have also been questioned when soil water storage efficiency during and at the end of the fallow period is analysed. Whereas some authors did not observe differences in soil water storage between conventional and conservation tillage (Incerti et al., 1993; Dalrymple et al., 1993; Unger, 1994; Pannkuk et al., 1997; and Tanaka and Anderson, 1997), other researchers reported that no-tillage increases the fallow-precipitation storage efficiency (Schillinger and Bolton, 1993; O'Leary and Connor; 1997; Jones and Popham, 1997). On the other hand, in some regions (e.g., the Great Plains), fallow efficiency remains low even under modern tillage and residue management practices and, consequently, the original criticism of fallow still remains (Farahani et al., 1998a).

In the cereal growing areas of Central Aragon, a semiarid area in the central part of the Ebro River valley of Northeast Spain, fallowing (cultivo de año y vez or cereal-fallow rotation) is still widely practised. In these areas, the average annual precipitation is less than 400 mm and rainfall is sporadic and highly variable from year to year during both the fallow period and the growing season. The fallow period is 16-18 month long running from harvest (June-July) to sowing (November-December) in the following year. Farmers traditionally use mouldboard ploughing plus repeated secondary tillage cultivations for weed control during the long-fallow period. Despite the significance of fallowing for dryland cereal agriculture in Central Aragon and other semiarid areas of the Ebro River valley, the number of field measurements of water stored during the long fallow period and its corresponding storage efficiency is rather limited. López et al. (1996) reported that long fallowing, with either traditional or conservation tillage management, appears to be an inefficient practice for improving soil water storage at sowing when compared with continuous cropping. Similarly, Lampurlanés et al. (2002) found no differences in soil water storage between conventional and conservation tillage systems at the end of the long fallow period.

As part of a long-term tillage comparison experiment aimed to evaluate the feasibility of conservation tillage systems in a dryland cereal-growing area of Central Aragon, the objective of this study was to quantify and compare the effects of conventional tillage, reduced tillage and no-tillage on soil profile water storage and precipitation-storage efficiency during specific periods of the 16-18 month fallow in the cereal-fallow rotation. Soil water losses by evaporation immediately after primary and secondary tillage implementation were specifically evaluated. Finally, the precipitation-storage efficiency of the whole long fallow period under the three fallow tillage management systems was compared with that of the short summer fallow (5-6 month) in the continuous cropping system.

2. Material and methods

2.1. Site, fallow tillage systems and experimental design

The research was conducted at the dryland research farm of the Estación Experimental de Aula Dei (CSIC) in Peñaflor, Zaragoza province (latitude 41º 44'N; longitude 0º 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 ºC. Soil at the research site is a loam (fine-loamy, mixed thermic Xerollic Calciorthid) according to the USDA soil classification (Soil Survey Staff, 1975). Additional information on the site and soil characteristics can be found elsewhere (López et al., 1996).

The study was conducted on three adjacent large blocks of plots, which were set up on a nearly level area in 1990 (Field 1), 1991 (Field 2) and 1992 (Field 3), within a long-term conservation tillage experiment. Winter barley (Hordeum vulgare L.) was cultivated as continuous cropping (CC) in Field 1 (CC1) and under the traditional cereal–fallow rotation (CF) in Fields 2 (CF2) and 3 (CF3). The study was carried out when the three fields were in the fallow phase of their respective cropping system, which extends from harvest (June-July) to sowing (November-December) on the following year in the CF rotation (16-18 month long fallow) and on the same year in the CC system (5-6 month short fallow). Field measurements were made from harvest in June 1999 to sowing in November 2002 and comprised three consecutive long fallow seasons (1999-2000 season in field CF3, 2000-2001 season in field CF2 and 2001-2002 season again in field CF3) and three short fallow periods in field CC1 (Table 1). At the beginning of this study the tillage comparison experiment was in its 10th year of trial. The long fallow season was split into three well-differentiated phases or sub-periods: the first one from harvest to late fall (HF), the second from late fall to late spring (FS) and the third one from late spring to sowing (SS).

Three fallow management treatments were compared: conventional tillage (CT), reduced tillage (RT) and no-tillage (NT). The CT treatment consisted of mouldboard ploughing of fallow plots 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, primary tillage was chisel ploughing to a depth of 25-30 cm (non-inverting action), followed, as in CT, by a pass of sweep cultivator in late spring. Dates of both primary and secondary tillage operations were the same for the CT and RT treatments (Table 1). NT used exclusively herbicides for weed control throughout the fallow season.

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). Thus, three large blocks of ten plots were set up according to a split block design with tillage as the main plot and cropping system as the subplot. The size of the elemental 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 soil measurements at two observation points (one per treatment) separated by a distance of 5 m. To compare the effects of tillage treatments within each cropping system, analysis of variance (ANOVA) for incomplete block design was used (López and Arrúe, 1995). Duncan's multiple range test was used to compare among treatment means.

2.2. Field measurements and calculations

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 with a tipping bucket rain gauge (model ARG100, Campbell Scientific Inc.), air temperature and relative humidity were measured at 1.8 m with a combined sensor (model HMP35AC, Vaisala), wind speed and direction were measured at 2 m with a combined sensor (model 05103-5, Young) and solar radiation at 2 m with a pyranometer (model SP1110, Skye). All 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. As a measure of the natural atmospheric evaporative demand of the climate during the different phases of the fallow period, reference evapotranspiration ($\underline{ET_o}$) was calculated with the FAO Penman-Monteith equation from daily meteorological data (Allen et al., 1998). Since only actual evapotranspiration values were required, $\underline{ET_o}$ calculations were made without correction of weather data observed to reference, well-watered conditions (Allen et al., 1998).

2.2.2. Soil moisture measurements

During the experimental period, the volumetric soil water content ($\underline{\theta}$) content in the 0-10, 0-20, 0-40 and 0-70 cm soil layers was continuously monitored by Time Domain Reflectometry (TDR) on a weekly basis or as a function of rainfall events. For this purpose, four probes of two parallel stainless steel rods (diameter: 4 mm; length: 150, 250, 450 and 750 mm; spacing between rod centers: 50 mm) were inserted vertically into the soil at the observation point to a depth of 10, 20, 40 and 70 cm (Ferré and Topp, 2002). According to Dalton (1992), the protruding TDR electrode pair were connected to a cable tester (model 1502C, Tektronix) by means of a quick disconnect type interface housing a 50-200 Ω impedance matching pulse transformer. Waveforms were transferred to a laptop with a SP232 serial communication module and analysed using the software WinTDR'98 (Or et al., 1998). The model proposed by Topp et al. (1980), which proved to be suitable for our soil in a previous laboratory calibration experiment, was used to estimate θ for each soil depth. The multiple length probe method described by Miyamoto et al. (2001) was used afterwards to calculate θ for the 0-10, 10-20, 20-40 and 40-70 cm soil profile layers. Specifically, soil moisture measurements were taken just before and 24 h after primary and secondary tillage operations implemented in the CT and RT plots. The incomplete block design described above implied a total of 18 measurements of θ (6 per treatment) on each fallow field per soil depth and observation date.

2.3. Soil water balance and precipitation storage efficiency

Given the flat condition of the three experimental fields, runoff can be neglected. Thus, at a good first approximation, the soil water budget for a given fallow period or sub-period simplifies to:

$$P = E + SWS \qquad (1)$$

where P (mm) is the rainfall recorded over the time period in question, E (mm) is the sum of all water losses mainly by evaporation from the soil surface and drainage and SWS (mm) is the soil water storage in the soil profile (0-70 cm depth) calculated from the profile soil water at the end of the fallow period minus the profile soil water at the beginning.

The fallow precipitation storage efficiency (PSE) for specific or entire fallow periods was calculated as the percentage of precipitation that is stored at the soil (Farahani et al., 1998a) as:

$$PSE = (SWS / P) \times 100 \qquad (2)$$

The water storage efficiency of long fallow in the CF rotation with respect to the CC system (RPSE) was calculated using the equation

$$RPSE = (\Delta SWS / P_{TS}) \times 100 \quad (3)$$

where ΔSWS is the additional soil water (0-70 cm) at sowing after a long fallow compared with a short fallow and P_{TS} the rainfall received from the date of primary tillage in the CC system in autumn to sowing in both CC and CF cropping systems on the following year (López et al., 1996).

3. Results and discussion

3.1. Weather conditions

The experimental period (July 1999-November 2002) was drier than normal. Total precipitation received during the first (1999-2000), second (2000-2001) and third (2001-2002) long fallow periods was 4, 13, and 10% below the long-term average, respectively. Rainfall patterns, however, were much more contrasted among the three fallow periods and, particularly, among fallow sub-periods (Table 2). The precipitation in the early fallow sub-period, HF (July-November), was 20% and 39% below normal in the 1999-2000 and 2001-2002 fallows, respectively, and 28% above normal in the 2000-2001 fallow. In the second sub-period, FS (December-May), rainfall was 22, 15 and 3% below normal for the 1999-2000, 2000-2001 and 2001-2002 fallow periods, respectively. In the late fallow phase, SS (June-November), rainfall was 29 and 8% above normal in the 1999-2000 and 2001-2002 fallows, respectively, and 45% below normal in the 2001-2002 fallow. On the other hand, while the contribution of the SS rainfall to total seasonal precipitation was high in the 1999-2000 (48%) and 2001-2002 (43%) fallows, in the 2000-2001 fallow this fraction was much lower (23%).

Over the entire experimental period, about 50% of total precipitation was received in rainfalls of less than 10 mm. As can be seen in Table 2, the effective rainfall (here defined as the fraction of monthly precipitation received in days with a rainfall ≥ 10 mm) can be very low or even nil in almost every month. These features are consistent with those reported by McAneney and Arrúe (1993) analysing a 35-yr time series of monthly rainfall data from a different location within the study area. The small rainfall events during fallow tend to evaporate rapidly without making a significant contribution to soil water storage (SWS), which limits how much precipitation storage efficiency (PSE) can be improved in this harsh semiarid environment.

Rainfall registered during the CC1 short fallow (July-November) was 28 and 7% above normal for the years 2000 and 2002, respectively, and 39% below normal in 2001.

3.2. Soil water balance during fallow

Table 3 summarises the soil water loss (E), soil water storage (SWS) and precipitation storage efficiency (PSE) for the three experimental fallow periods. As discussed below, tillage management and rainfall pattern during the three sub-periods in which the long fallow was partitioned differently affected these fallow characteristics.

3.2.1. Soil water losses

Overall, during the first phase of fallow, HF, from harvest to late fall, E was small compared with that of the second and third fallow phases (Table 3). Even though the potential evaporation in the first part of HF (July-September) is high (6.5 mm day^{-1}) (Table 2), the reasons for a low E in the entire HF phase can be related to: i) a relatively higher crop residue cover (López et al., 2003), which reduces the evaporation by reflecting solar radiation and slowing the connective transport of vapour from the surface when the soil is wet (Pannkuk et al., 1997; O'Leary and Connor, 1997); ii) the presence of a dry and compacted layer at the soil surface with a variable thickness (i.e. soil crust), which acts as a surface resistance to soil evaporation (van de Griend and Owe, 1994); and iii) a low θ and rainfall after harvest (July-August), when ET_0 is high, and the evaporative demand at the end of the sub-period is low (Table 2). Over the three fallow periods, E was positively correlated with P received in the HF period (E = 0.541 P + 26.823; R^2 = 0.926). On the other hand, E was significantly affected by the tillage treatment only in the 2000-2001 fallow period, where a lower initial soil water stored under CT determined a lower soil water loss for this treatment.

Primary tillage implementation in the CT and RT plots during the second fallow phase, FS (late fall to late spring), induced significant changes in soil water content for the 0-40 cm layer (Fig. 1). Short-term tillage-induced effects on soil water flux under CT and RT resulted in soil water evaporation losses significantly larger than under NT (Fig. 2a). These important soil water losses immediately after tillage, also reported by Reicosky et al. (1999), may be related to an increment in soil surface roughness, which reduces the albedo and increases the potential evaporation by concentrating heat in the surface (Linden, 1982). In addition, soil roughness also increases the surface area of soil exposed to the atmosphere, thus allowing greater penetration of wind, which favours soil water evaporation from tilled soil (Jalota and Prihar, 1998). For instance, primary tillage implementation on 10 April 2001 in the 2000-2001 fallow was coincident with a WNW cierzo wind event that showed a mean daily wind speed of 5.3 and 7.8 m s^{-1} on 10 and 11 April 2001, respectively. Mean daily wind speed on the secondary tillage day (6 June 2001) in that fallow season was also significant (4.3 m s^{-1}). Overall, mouldboard ploughing with soil inversion up to 35-40 cm depth, induced in the CT plots a higher E compared with vertical chisel ploughing in RT (Fig. 2a). Over the three experimental years, the hourly soil water evaporation rate for the first 24 hours after tillage (E_h) averaged 0.59 and 0.46 mm h^{-1} for CT and RT, respectively, as compared with the 0.05 mm h^{-1} measured under NT. For the 2000-2001 and 2001-2002 fallow periods, E_h under RT (0.34 and 0.37 mm h^{-1}, respectively) was similar to the E_h reported by Reicosky et al. (1999) (≈ 0.35 mm h^{-1}). The highest E_h during the 1999-2000 fallow period (Fig. 2a) could be explained by a higher θ in the plough layer at the time of tillage as a consequence of the rainfall (32 mm) received in the 20-day period before tillage (Fig 3a) that favoured soil water loss immediately after tillage. The constancy of the differences in θ between tillage systems for a certain period after primary tillage (Fig. 3) proves the reliability of the water losses measured 24 hours after tillage in the CT and RT plots. The contribution of the different soil layers in the upper 40 cm to these water losses differed between CT and RT. Overall, whereas under CT (mouldboard ploughing) soil water loss from the 0-10, 10-20 and 20-40 cm represented respectively 18, 31 and 51% of the total E, soil water lost under RT (chiselling) was more homogeneously distributed with depth (32, 30 and 38% of E from the 0-10, 10-20 and 20-40 cm layers, respectively) (Fig. 1). Primary tillage operations appear to have a cumulative effect on E also in the medium term after tillage. In general, cumulative E varied in the order CT > RT > NT. For instance, in the 2000-2001 fallow period, the cumulative E for the 23-day period after primary tillage was higher under CT (29 mm) than under RT (20 mm) and NT (16 mm) (Fig. 4a). Most of these water losses mainly occurred, as explained above, on the first day after tillage. Afterwards, and compared with NT, a higher decrease in E_r was observed under CT and RT due to a higher water depletion in the plough layer immediately after tillage in these treatments. Thus, the average E_r under CT and RT for the 22-day period elapsed from DOY 107, 24 hours after tillage implementation, and DOY 129 was lower (0.57 and 0.59 mm day^{-1} for CT and RT, respectively) than under NT (0.67 mm day^{-1}). Globally, results also showed that mouldboard ploughing has a more sustained effect on soil water evaporation, which was reflected at the end of the FS phase in the three fallow periods by higher E values under CT (Table 3).

During the late fallow phase, SS (late spring to barley sowing), secondary tillage induced additional soil water losses under CT and RT, which mainly occurred from the upper 20 cm of soil. Overall, the average E for the first 24 hours after secondary tillage application was again greater under CT (4.2 mm) and RT (4.1 mm) than under NT (1.6 mm) (Fig. 2b). Hatfield et al. (2001) reported soil water evaporation fluxes from 10 to 12 mm for a 3-day period following a pass with a cultivator in spring and < 2 mm under NT over the same period. Although lower than the water lost immediately after primary tillage, $\underline{E}$ after secondary tillage can also be associated with an increment of both soil surface area and roughness (Jalota and Prihar, 1998). However, secondary tillage appears to have a positive effect on soil water conservation in the medium term. For instance, in the 2000-2001 fallow period, CT and RT showed the lowest $\underline{E_r}$ values 96 days after secondary tillage application (0.40, 0.46 and 0.64 mm day^{-1} for CT, RT and NT, respectively) (Fig. 4b). These results are in agreement with Jalota and Prihar (1998), who reported that while shortly after tillage $\underline{E_r}$ from tilled soil exceeds that from the untilled soil, after a certain time following the formation of a dry layer because of accelerated drying of the tilled surface soil, $\underline{E_r}$ from tilled soil lags behind $\underline{E_r}$ from untilled soil. This change in $\underline{E_r}$ can be explained by the breaking of capillary channels continuity from the subsoil to the soil surface after sweep plough tillage (Schillinger and Bolton, 1993; Jalota and Prihar, 1998). Since this cultivation was applied at the end of spring (Table 1), a loose structure and dryness of fine tilled soil could also have contributed to reduce $\underline{E_r}$ by providing thermal insulation in the topsoil that decreased thermally-induced upward both liquid and vapour flow from the subsoil (Papendick, 1987). Even though secondary tillage alters the dynamics of $\underline{E_r}$, this field operation did not induce significant differences among tillage systems in $\underline{E}$ at the end of the SS period (Table 3).

Overall, the early HF period had the lowest $\underline{E_r}$ (0.65 mm day^{-1}), followed by the overwinter FS and late SS periods with 0.93 and 1.09 mm day^{-1}, respectively. For the entire long-fallow period, $\underline{E}$ was not significantly affected by the fallow tillage system (Table 3). Although it has been shown how tillage implementation increases $\underline{E}$ in the short term, this effect is not reflected at the end of fallow. It appears that the rapid water depletion in the soil profile after tillage determines in the long-term a reduction of E_r in the tilled plots compared with the untilled plots, which, in the end, leads to a similar total E in the three tillage treatments.

3.2.2. Soil water storage and efficiency

Effects of seasonal fallow precipitation

Figure 5 shows the dynamics of the water stored in the 0-70 cm soil profile over the three experimental long fallow periods computed in reference to the start of each fallow period. Although the variation of SWS and PSE for a given fallow phase can be, in principle, related to the potential evaporation, this variation can sometimes be more closely associated to the rainfall received just before the fallow period (French, 1978; Jones and Popham, 1997). This would explain the negative values of SWS and PSE for the FS phase of the 2000-2001 fallow period and the SS phase of the 2001-2002 fallow (Table 3; Fig. 5). In contrast, positive values of SWS and PSE occurred when the soil profile was dry early in the sub-period and most of the rainfall was collected at the end, thus reducing soil water evaporation (i.e., SS phase in the 1999-2000 fallow and FS phase in the 2001-2002 fallow) (Fig. 5). Only the HF phase presented positive SWS and PSE values in the three experimental fallow seasons (Table 3). The positive relationship between SWS and P for this phase ($SWS = 0.454\ P + 26.821$; $R^2 = 0.889$) is explained by a dry profile at the beginning and both a relatively high number of rainy days and a low evaporative demand at the end (Table 2). This result is in good agreement with the positive correlation between P and simulated SWS to a depth of 100 cm found by Austin et al. (1998a) for the same fallow sub-period in the study area.

On the other hand, even though the FS phase in the 1999-2000 and 2001-2002 fallow periods was characterised by a comparable water storage at the beginning and a similar rainfall at the end (102 mm and 103 mm in April-May, respectively), SWS and PSE for this phase in the 2001-2002 fallow period were approximately two times greater than in the 1999-2000 fallow (Table 3). This difference was due to a greater effective precipitation (≥ 10 mm day^{-1}) in April-May in the 2001-2002 period (67%) compared to the 1999-2000 period (32%) (Table 2).

With regard to the entire fallow period, greatest SWS and PSE values were observed in the 1999-2000 fallow season (Table 3), which registered the highest effective precipitation in the last two months of fallow (Table 2). This result indicates that the rainfall received during the early and mid fallow has no effect on soil water storage at sowing, in agreement with Austin et al (1998a), who pointed out for the study area that rainfall during the last months of the long fallow is the principal determinant of the amount of water stored in the profile. However, French (1978) found in semiarid South Australia that fine-textured soils can significantly store additional water by sowing when rain occurs at the start of a 9-10 month fallow period. The SWS values were within the range measured by López et al. (1996) and estimated by Austin et al (1998a) in the Ebro River valley. In our study, the 16-18 month fallow period was characterised by an efficient early fallow phase for soil water storage (31-310% of the total SWS) and a variable SWS in the overwinter and late phases (Table 3). As observed in semiarid regions of the Northern Great Plains (Farahani et al., 1998b) and Pacific Northwest (Schillinger, 2001) of the USA, soil water storage efficiency, computed in reference to the start of fallow, decreased over the long fallow period (Fig. 6). At the end of fallow (sowing time), the average PSE value was low (11%) (Table 3) but comparable to figures reported in previous studies (French, 1978; Tanaka and Anderson, 1997; Pannkuk et al., 1997; Lampurlanés et al., 2002; Latta and O'Leary, 2003). The total amount of water stored in the soil profile (0-70 cm) for the following crop averaged 181, 128 and 137 mm for the 1999-2000, 2000-2001 and 2001-2002 fallow periods, respectively.

Effects of fallow tillage management

The distribution of water stored in the soil profile during fallow varied with the tillage treatments. In general, water content in the plough layer (0-40 cm depth) was greater under NT than under CT and RT (Fig. 3). This fact may be due to a higher soil water retention capacity measured at the topsoil under NT (Moret, 2004). On average, while water stored under NT in the 0-20, 20-40 and 40-70 cm soil layers represented respectively 29, 30 and 41% of the total SWS, under CT and RT these percentages were 21, 30 and 49%. These results agree with those obtained by Nyborg and Malhi (1989) in semiarid North-central Alberta and Chan and Heenan (1996) in Australia.

Despite this different soil water content distribution with depth between tilled and untilled plots, no significant differences in SWS and PSE among tillage systems were observed for the entire fallow period (Table 3), in agreement with other researchers (Lampurlanés et al., 2002; Latta and O'Leary, 2003). In semiarid environments of North-west Victoria, Australia, the greatest gains in soil water in 18-month long fallows were achieved on clay soils with stubble retention and no-tillage together (O'Leary and Connor, 1997). On the loamy soils in our study area, however, this alternative fallow management would not be beneficial for water conservation due to a low crop residue cover during most of the long-fallow period even under no-tillage conditions (López et al., 2003).

The additional soil water at sowing with a long fallow (16-18 months) compared with a short fallow (5-6 months) averaged 20 mm for the three experimental long fallow periods and the three tillage systems (Table 4). This figure is within the range of values (11-33 mm) given by Latta and O'Leary (2003) for a semiarid region of South-eastern Australia and comparable to the 19 and 27 mm predicted by Austin et al. (1998a, 1998b) for different locations in the Ebro River valley and the 28 mm measured by French (1978) in South Australia or the 12 mm given by López et al. (1996) for Central Aragon. Accordingly, the average precipitation storage efficiency of long fallow relative to short fallow (RPSE) was 5.3%, close to the mean value found by López et al. (1996) in Central Aragon (2.5%) and within the range of values obtained by Latta and O'Leary (2003) in South-eastern Australia (1-26%). Although the influence of tillage treatment on the additional water storage at the end of long fallow is not clear, RT appears to be the most efficient system to increase the water storage at sowing (Table 4).

4. Conclusions

In semiarid Central Aragon the type of fallow management in the cereal-fallow rotation may have a significant effect on the dynamics of soil water content during the long fallow period (16-18 months). Primary tillage implemented under conventional tillage (CT) and reduced tillage (RT) in late winter or early spring determines significant soil water losses from the plough layer immediately after tillage compared with no-tillage (NT). However, secondary tillage in the tilled treatments appears to have a positive effect on soil water conservation during the last fallow phase. Despite tillage operations imply a substantial and rapid water loss from the plough layer in the short-term, the total water lost measured for the entire fallow period was similar for CR, RT and NT. This result indicates that neither conventional tillage nor conservation tillage are able to improve soil water conservation in the crop-fallow rotation.

The partitioning of long fallow into three periods has shown that the early phase, from harvest to late fall, is in general the most efficient in terms of soil water storage (SWS), showing the lowest average daily evaporation rate (0.65 mm day^{-1}). The second period (late fall to early summer) and the third period (late spring to sowing), have greater daily evaporation rates (0.93 and 1.09 mm day^{-1}, respectively) and variable soil water storage as a function of the rainfall regime. Precipitation storage efficiency (PSE) for each fallow phase and also for the entire fallow period, increases when most of seasonal effective rainfalls (≥ 10 mm day^{-1}) are received in the last two months of each fallow period. Although a gain in water storage is achieved by fallowing, low PSE values (11% on average) indicate that this traditional practice is not efficient enough to substantially increase the amount of water available to the following crop.

Overall, neither SWS nor PSE of long fallowing was significantly affected by tillage. This would imply that conservation tillage systems could replace conventional tillage for soil management during fallow without adverse effects on soil water conservation. The average additional soil water at sowing after a long fallow period (16-18 months) compared with short-fallow (5-6 months) was 20 mm. Correspondingly, the average precipitation storage efficiency of long fallow relative to short fallow was only 5.3%. In conclusion, above results indicate that the benefits of long fallowing in terms of soil water storage are quite small. To improve the productivity and sustainability of dryland agrosystems in semiarid Aragon, further research is required to evaluate alternative fallow management practices either to improve fallow precipitation storage efficiency (i.e., delaying primary tillage till late fallow) or to benefit from the water currently being lost during fallow by evaporation through new crop rotations (i.e. use of a cover or pasture crop during the overwinter fallow phase).

Acknowledgements

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Figure captions

Figure 1. Soil water content profile measured under conventional tillage (CT), reduced tillage (RT) and no-tillage (NT) treatments before (continuous line) and after (broken line) primary tillage implementation on CT and RT plots in the 1999-2000, 2000-2001 and 2001-2002 fallow periods. Horizontal bars represent LSD ($P<0.05$) for comparison among tillage treatments, where significant differences were found.

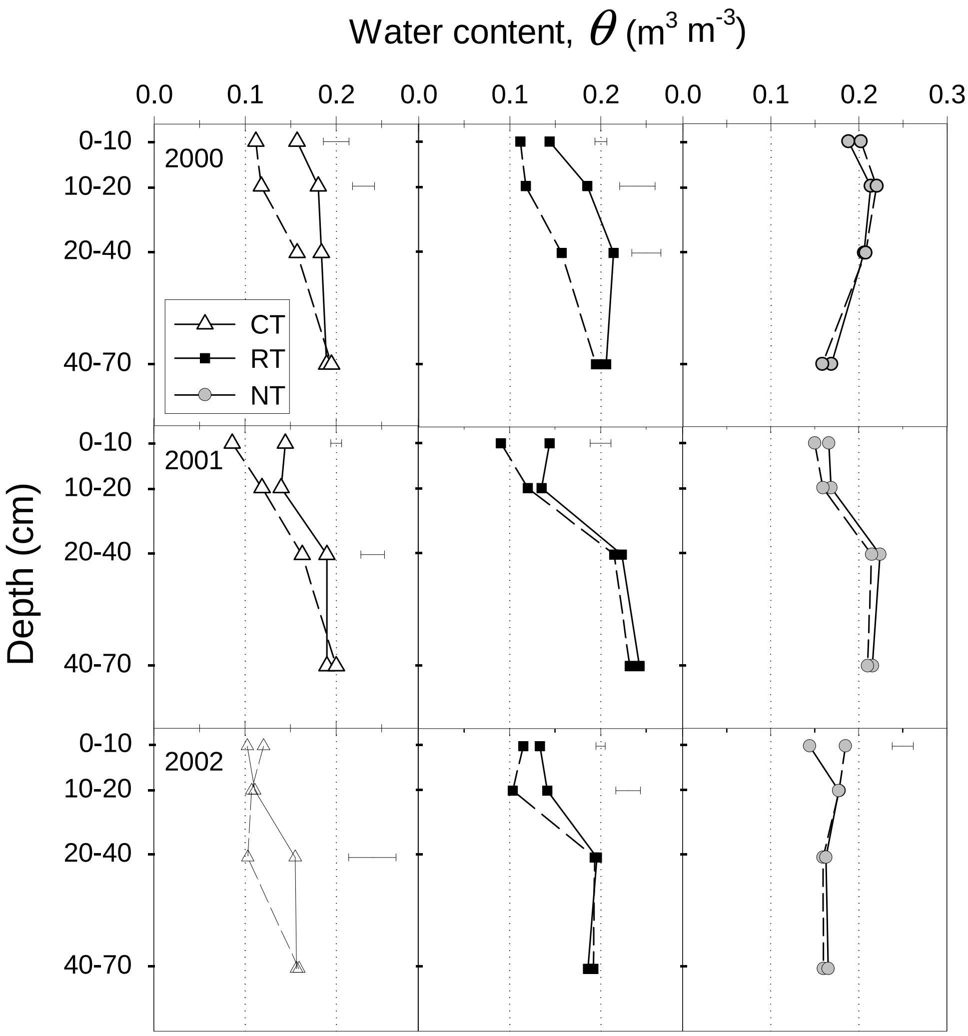
Figure 2. Cumulative water loss by evaporation under conventional tillage (CT), reduced tillage (RT) and no-tillage (NT) for the first 24 hours after tillage implementation on CT and RT plots in the 1999-2000, 2000-2001 and 2001-2002 fallow periods: (a) from the 0-40 cm soil layer after primary tillage; and (b) from the 0-20 cm soil layer after secondary tillage. Different letters above bars indicate significant differences at $P<0.05$.

Figure 3. Time course of rainfall and volumetric soil water content ($\underline{\theta}$) in the plough layer (0-40 cm depth) under conventional tillage (CT), reduced tillage (RT) and no-tillage (NT) following the implementation of primary tillage (**T**) on CT and RT plots in the second year of the 1999-2000 (a), 2000-2001 (b) and 2001-2002 (c) fallow periods. Bars represent LSD ($P<0.05$) for comparison among tillage treatments, where significant differences were found.

Figure 4. Cumulative water evaporation from the upper 40 cm of soil under conventional tillage (CT), reduced tillage (RT) and no-tillage (NT): (a) for a 23-day period after primary tillage and (b) for a 96-day period after secondary tillage in the 2000-2001 fallow season. **T** and **t** indicate primary and secondary tillage dates. Bars represent LSD ($P<0.05$) for comparison among tillage treatments, where significant differences were found.

Figure 5. (a) Daily precipitation (columns) and reference evapotranspiration ($\underline{ET_0}$) (continuous line) during the 1999-2000, 2000-2001 and 2001-2002 fallow periods. (b) Time course of water stored in the soil profile (0-70 cm) ($\underline{SWS}$) for the same fallow periods under conventional tillage (CT), reduced tillage (RT) and no-tillage (NT) treatments. **T** and **t** indicate primary and secondary tillage dates. Bars represent LSD ($P<0.05$) for comparison among tillage treatments, where significant differences were found. $\underline{SWS}$ values are computed in reference to the start of each fallow period. HF: harvest to late fall; FS: late fall to late spring; SS: late spring to sowing.

Figure 6. Soil water storage efficiency during the 1999-2000, 2000-2001 and 2001-2002 fallow periods under conventional tillage (CT), reduced tillage (RT) and no-tillage (NT) treatments. Bars represent LSD ($P<0.05$) for comparison among tillage treatments, where significant differences were found. (The efficiency values are computed in reference to the start of each fallow period).



Water content, θ (m3 m-3)
0.0
0.1
0.2
0.0
0.1
0.2
0.0
0.1
0.2
0.3
Depth (cm)
0-10
10-20
20-40
40-70
2000
2001
2002
CT
RT
NT

Fig.1

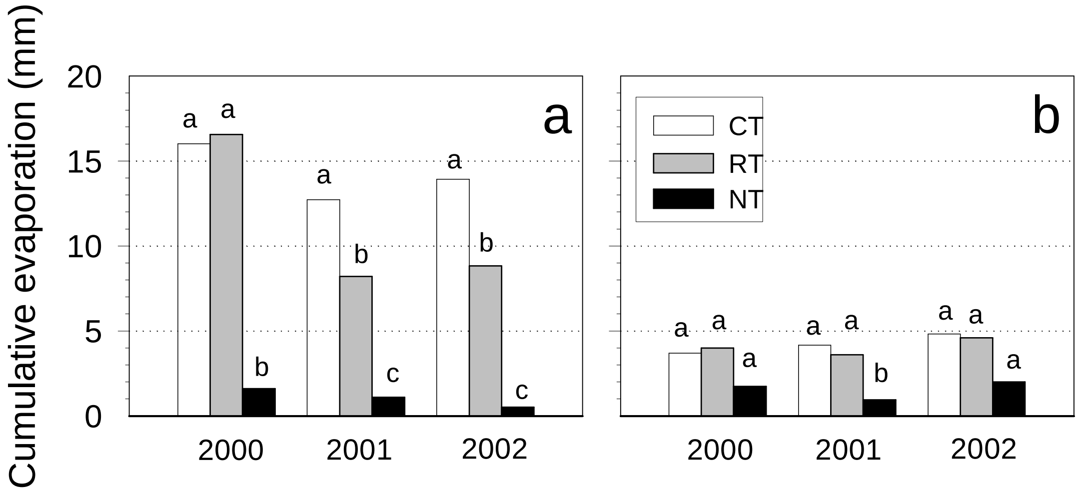
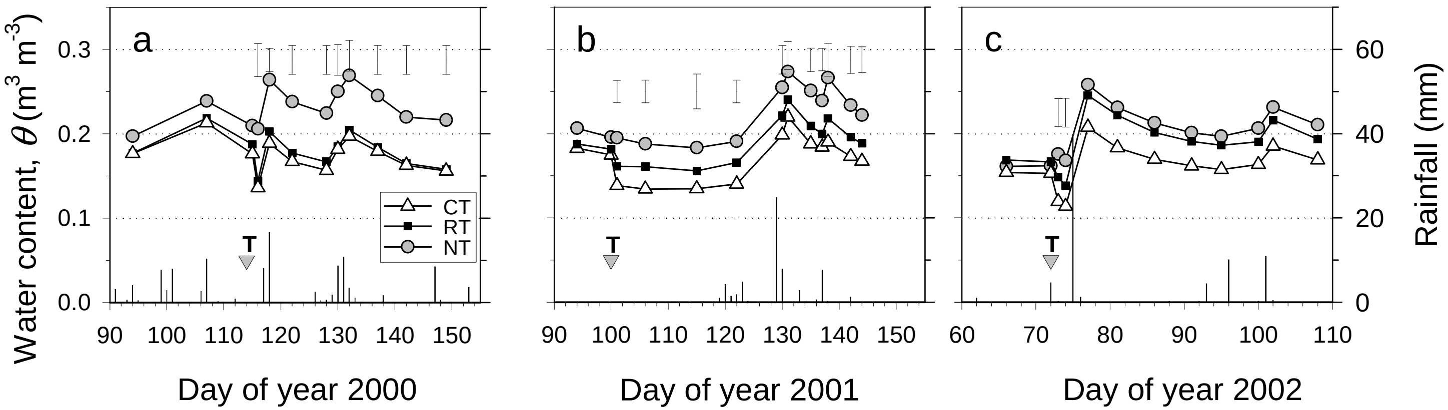
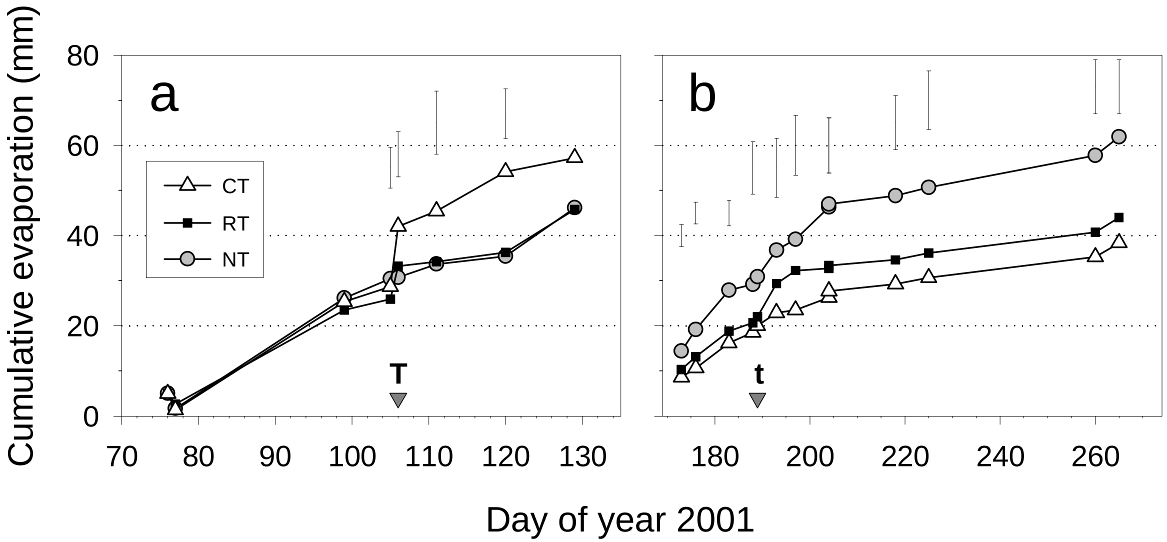

Cumulative evaporation (mm)
20
15
10
5
0
a
b
CT
RT
NT
2000
2001
2002
2000
2001
2002

Fig. 2



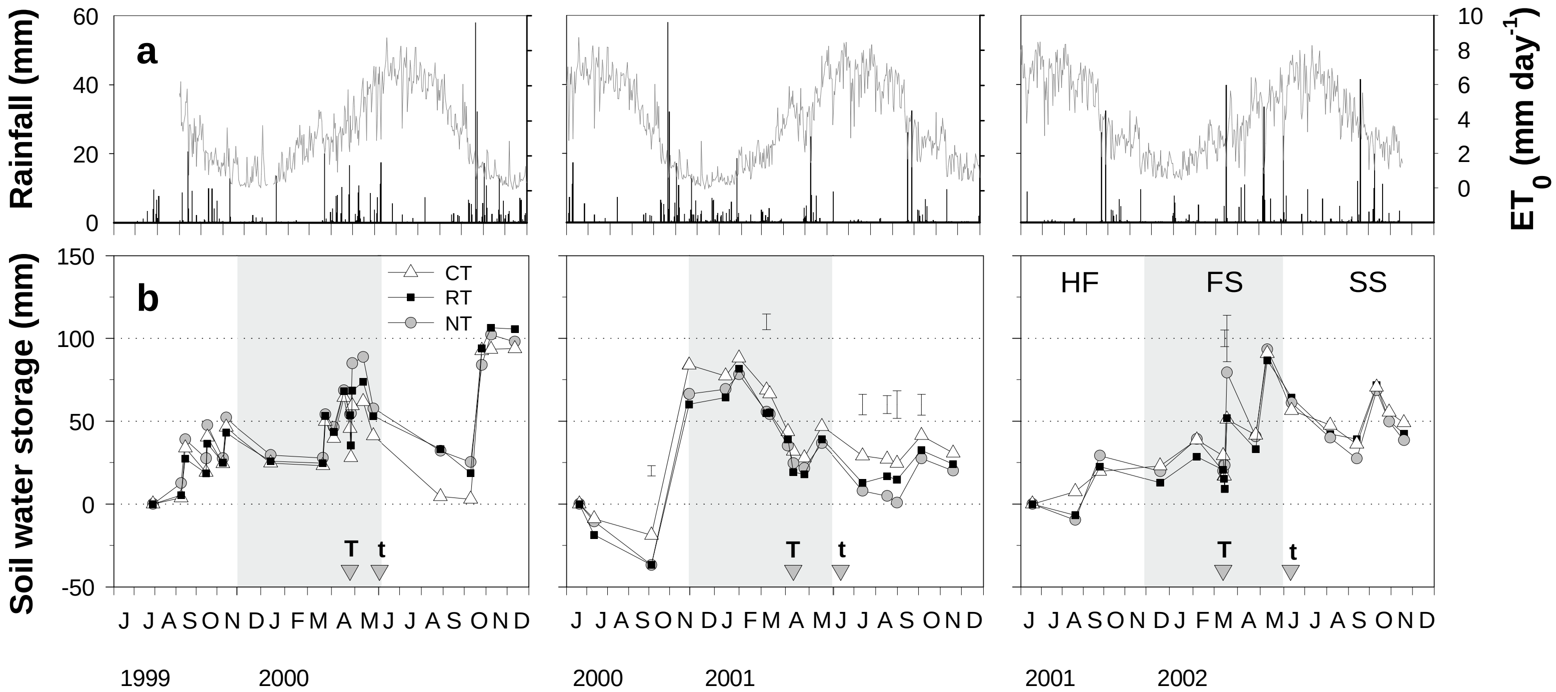
a
b
c
Water content, θ (m3 m-3)
Rainfall (mm)
CT
RT
NT
T
Day of year 2000
Day of year 2001
Day of year 2002

Fig. 3



Cumulative evaporation (mm)
80
60
40
20
0
a
b
CT
RT
NT
T
t
70
80
90
100
110
120
130
180
200
220
240
260
Day of year 2001

Fig. 4



a
b
Rainfall (mm)
Soil water storage (mm)
ET0 (mm day-1)
CT
RT
NT
HF
FS
SS
T
t
J J A S O N D J F M A M J J A S O N D
1999
2000
2001
2002

Fig. 5.

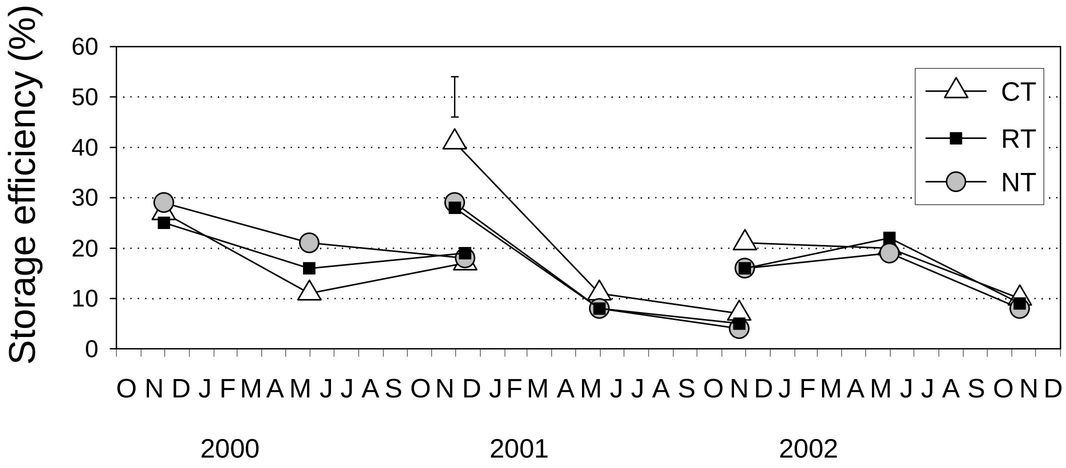

Storage efficiency (%)
60
50
40
30
20
10
0
CT
RT
NT
O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D
2000
2001
2002

Fig. 6

Table 1. Starting and ending dates for the experimental fallow periods and sub-periods and timing of tillage practices.

Fallow period	Field[†]	Fallow phase[‡]	Starting date (harvest)	Ending date (sowing)	Duration (days)	Primary tillage date	Secondary tillage date
			Long fallow period (16-18 months)				
1999-2000	CF3	HF	26 June 1999	30 Nov. 1999	158	25 April 2000	29 May 2000
		FS	1 Dec. 1999	31 May 2000	182		
		SS	1 June 2000	13 Dec. 2000	196		
2000-2001	CF2	HF	20 June 2000	30 Nov. 2000	164	10 April 2001	6 June 2001
		FS	1 Dec. 2000	31 May 2001	182		
		SS	1 June 2001	23 Nov. 2001	176		
2001-2002	CF3	HF	29 June 2001	30 Nov. 2001	155	13 March 2002	11 June 2002
		FS	1 Dec. 2001	31 May 2002	182		
		SS	1 June 2002	19 Nov. 2002	172		
			Short fallow period (5-6 months)				
2000	CC1		20 June 2000	13 Dec. 2000	177	22 Nov. 2000	12 Dec. 2000
2001	CC1		29 June 2001	23 Nov. 2001	148	1 Nov. 2001	22 Nov. 2001
2002	CC1		19 June 2002	19 Nov. 2002	154	2 Nov. 2002	18 Nov. 2002

[†] CC1: field 1 under continuous cropping; CF2, CF3: fields 2 and 3 under crop-fallow rotation.
[‡] HF: harvest to late fall; FS: late fall to early spring; SS: early spring to sowing.

Table 2. Monthly rainfall totals during the 1999-2000, 2000-2001 and 2001-2002 long-fallow seasons, with corresponding long-term averages (1954 - 2002), and mean monthly reference evaporation ($\underline{ET_0}$) for the 1999-2002 period at Peñaflor experimental site.

	Precipitation										$\underline{ET_0}$ [†]
	1999-2000			2000-2001			2001-2002			1954 - 2002 average	1999-2002 average
Month	Total	ER [‡]	NER [§]	Total	ER	NER	Total	ER	NER		
	mm										mm day^{-1}
July	27	0	27	4	0	4	3	0	3	17	6.6
August	9	0	9	7	0	7	2	0	2	24	6.3
September	46	21	25	9	0	9	60	58	2	41	4.2
October	33	0	33	122	90	32	25	0	25	40	2.4
November	15	13	2	66	39	27	10	0	10	41	1.9
December	7	0	7	36	0	36	3	0	3	28	1.0
January	14	13	1	44	19	23	22	0	22	27	1.0
February	1	0	1	4	0	4	6	0	6	23	2.1
March	25	20	5	21	0	21	48	40	8	28	2.9
April	62	27	35	5	0	5	27	20	7	36	3.9
May	40	11	30	54	25	29	76	49	27	50	4.8
June	48	28	20	9	0	9	40	25	15	36	6.5
July	4	0	4	3	0	3	17	0	17	17	6.6
August	7	0	7	2	0	2	9	0	9	24	6.3
September	9	0	9	60	58	2	60	53	7	41	4.2
October	122	90	32	25	0	25	54	31	13	40	2.4
November	66	39	27	10	0	10	35	0	35	41	1.9
17-mo total	535			481			497			554	

[†] Reference evapotranspiration calculated with the FAO Penman-Monteith equation (Allen et al., 1998).

[‡] ER: effective rainfall (fraction of monthly precipitation received in days with a precipitation ≥10 mm).

[§] NER: non-effective rainfall (fraction of monthly precipitation received in days with a precipitation <10 mm).

Table 3. Soil water loss (E), soil water storage (SWS) and precipitation storage efficiency (PSE) during specific phases of the 1999-2000, 2000-2001 and 2001-2002 long fallow seasons under conventional tillage (CT), reduced tillage (RT) and no-tillage (NT).

		Harvest to late fall				Late fall to late spring				Late spring to sowing				Entire fallow		
Fallow season	Tillage treatment	E[†] (mm)	SWS[‡] (mm)	% of total SWS	PSE[§] (%)	E (mm)	SWS (mm)	% of total SWS	PSE (%)	E (mm)	SWS (mm)	% of total SWS	PSE (%)	E (mm)	SWS (mm)	PSE (%)
1999-2000	CT	97	35	37	27	151	-2	-2	-1	203	62	65	23	451	95	17
	RT	99	33	31	25	136	13	12	9	205	60	57	22	440	106	19
	NT	94	38	39	29	129	20	20	13	224	40	41	15	448	98	18
	LSD[¶]	NS	NS		NS	15	15		NS	NS	NS		NS	NS	NS	NS
2000-2001	CT	126	87	272	41	210	-46	-144	-28	118	-9	-28	-9	454	32	7
	RT	153	60	250	28	193	-29	-121	-18	116	-7	-29	-7	462	24	5
	NT	151	62	327	29	197	-33	-174	-20	119	-10	-53	-9	467	19	4
	LSD	18	18		8	NS	NS		NS	NS	NS		NS	NS	NS	NS
2001-2002	CT	79	21	46	21	144	35	76	19	194	-10	-22	-5	417	46	10
	RT	84	16	37	16	134	45	105	25	202	-18	-42	-10	420	43	9
	NT	84	16	41	16	141	38	97	21	199	-15	-38	-8	424	39	8
	LSD	NS	NS		NS	NS	NS		NS	NS	NS		NS	NS	NS	NS

[†] E (for a given fallow period) = sum of water losses from the soil profile (0-70 cm) by evaporation and drainage.
[‡] SWS (for a given fallow period) = profile soil water at the end minus the profile soil water at the beginning of the fallow period. Percentage of SWS = (SWS during a given fallow period divided by total water stored during the entire fallow) x 100
[§] PSE (for a given fallow period) = (SWS divided by precipitation during that period) x 100
[¶] Least significant difference, $P < 0.05$. NS, not significant.

Table 4. Precipitation storage efficiency of long fallow relative to short fallow (RPSE) for the 1999-2000, 2000-2001 and 2001-2002 long fallow seasons as affected by conventional tillage (CT), reduced tillage (RT) and no-tillage (NT).

Fallow season	Tillage treatment	Rainfall (mm) †	Additional water stored in CF (mm)‡	RPSE (%)
1999-2000	CT	494	28	5.7
	RT		29	5.9
	NT		18	3.6
2000-2001	CT	301	1	0.3
	RT		37	12.3
	NT		25	8.3
2001-2002	CT	413	18	4.4
	RT		23	5.6
	NT		5	1.2

† Rainfall received during the long fallow period in the crop-fallow rotation (CF) from the time of primary tillage in the continuous cropping (CC) system in late fall to sowing in both systems on the following year (P_{TS}).

‡ Difference in soil water storage (0-70 cm) between the CF and the CC systems at sowing (ΔSWS).

§ RPSE = (ΔSWS / P_{TS}) x 100