Water Balance Simulation of a Dryland Soil during Fallow under Conventional and Conservation Tillage in Semiarid Aragon, Northeast Spain

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Abstract

In Central Aragon, winter cereal is sown in the autumn (November-December), commonly after a 16-18 month fallow period aimed at conserving soil water. This paper uses the Simple Soil-Plant-Atmosphere Transfer (SiSPAT) model, in conjunction with field data, to study the effect of long fallowing on the soil water balance under three tillage management systems (conventional tillage, CT; reduced tillage, RT; and no-tillage, NT). This was on the assumption that soil properties would remain unchanged during the entire fallow season. Once the model was validated with data obtained before primary tillage implementation, the differences between simulated and observed soil water losses for the CT and RT treatments could be interpreted as the direct effect of the soil tillage system. The model was calibrated and validated in a long-term tillage experiment using data from three contrasting long-fallow seasons over the period 1999-2002, where special attention was paid to predicting soil hydraulic properties in the pre-tillage conditions. The capacity of the model to simulate the soil water balance and its components over long fallowing was demonstrated. Both the fallow rainfall pattern and the tillage management system affected the soil water budget and components predicted by the model. The model predicted that about 81% of fallow seasonal rainfall is lost by evaporation in long-fallow periods with both a dry autumn in the first year of fallow and a rainfall above normal in spring. Whereas, when the fallow season is characterised by a wet autumn during the first year of fallow the model predicted a decrease in soil water evaporation and an increase in water storage and deep drainage components. In this case, the predicted water lost by evaporation was higher under NT (64%) than under RT (56%) and CT (44%). The comparison between measured and simulated soil water loss showed that the practice of tillage decreased soil water conservation in the short term. The long-term analysis of the soil water balance showed that, in fallow periods with a wet autumn during the first year of fallow, the soil water loss measured under CT and RT was moderately greater than that predicted by the model.

Keywords: Water balance; Modelling; Soil water conservation; Tillage management; Long-fallowing.

1. Introduction

In the rainfed arable land of Central Aragon (NE Spain), the most common cropping system is the traditional cereal/fallow rotation (one crop in 2 yr), which extends over about 430,000 ha, in areas with an average annual rainfall of less than 400 mm, and involves a long-fallow period of about 16 to 18 months (López et al., 2003). The traditional practice of long-fallowing is aimed, among other things, at increasing the total stored water at the time of sowing for efficient use by the following crop. However, a low rainfall regime, with high between-year variability, along with a high evaporative demand (Herrero and Snyder, 1997), imposes significant constraints on agricultural production in Central Aragon (McAneney and Arrúe, 1993). Although mouldboard ploughing, followed by repeated shallow tillage operations, remains the commonest form of fallow management for controlling weeds during the fallow period, this traditional tillage practice is slowly being replaced by conservation tillage systems due to the lower labour, fuel, and machinery costs of these systems. Moret et al. (2004) studied the effect of conventional and conservation tillage systems on soil water conservation during the fallow period in semiarid Central Aragon and found that different tillage practices had no effect on long-term precipitation storage efficiency. On the other hand and regardless of tillage practices, field measurements by López et al. (1996) and Moret et al. (2004) and calculations by Austin et al. (1998) suggested that the benefits from water storage during fallow are quite small.

Although field experiments have been the traditional approach used in many semiarid rainfed farming regions to evaluate the influence of fallowing practices on soil water storage during the fallow period, few of them are long enough in duration to take into account the long-term effects of treatments that change slowly with time. Field data can be used in conjunction with model simulation data, however, to achieve a better understanding of the processes controlling soil water balance and storage during fallow.

As reviewed by Connolly (1998), many simulation models have been used to simulate the water balance in soil-crop systems, but few of them have been applied specifically to the study of soil water changes during the fallow period. Fischer et al. (1990) used a simulation model to predict the effect of fallow and of new tillage systems on the total available soil water at sowing in New South Wales, Australia. In Spain, Austin et al. (1998) developed a functional, physically based simulation model to estimate water storage in the soil profile during fallow in Central Aragon, similar to that proposed by López and Giráldez (1992) for the climatic conditions of southern Spain. The mechanistic SiSPAT (Simple Soil-Plant-Atmosphere Transfer) model (Braud et al., 1995), which gives a physically based representation of the processes involved in the soil-plant-atmosphere continuum, has been successfully used to study the mechanisms of soil water evaporation on fallow land in arid Niger (Braud et al., 1997) and semiarid Central Spain (Boulet et al., 1997).

The objective of this study was to further assess the applicability of the SiSPAT model for simulating the soil water balance during the long fallow period in Central Aragon under three fallow management systems (conventional tillage, CT; reduced tillage, RT; and no-tillage, NT) using a complete data set collected during the 1999-2002 period. The simulations were conducted under the assumption that the soil hydraulic properties remained unchanged during the entire fallow period. This hypothesis was fully justified for the no-tillage treatment. For the CT and RT treatments, we assumed that the hypothesis can be taken as valid in the long-term and that in the short-term the differences between simulated and observed water losses can be interpreted in terms of a direct tillage effect on soil water loss resulting from a modification of the soil hydraulic properties. Once confidence in the simulation was established by comparing the simulated soil water losses with the observations, we used model simulations of components of the soil water balance (evaporation and drainage, not accessible from the observations) to compare the effect of different tillage practices on the short- and long-term soil water losses.

2. Material and methods

2.1. Model description

This study was conducted using the original Simple Soil-Plant-Atmosphere Transfer (SiSPAT) model (Braud et al., 1995). A detailed description of the model can be found in Braud (2000). SiSPAT is a vertical 1D model of heat and water exchanges within the soil-plant-atmosphere continuum, forced at a reference level with a series of measured climatic data. We here used the bare-soil version of the model. Equations modelling coupled heat and water transfer in the soil are solved for both the liquid and vapour phase (Milly, 1982). The model deals with vertically heterogeneous soils. Initial and boundary conditions must be provided for the soil temperature and matrix potential profiles. We used gravitational mass flux and sinusoidal temperature for the bottom boundary condition. The soil–atmosphere interface is modelled using an electrical analogy, allowing the surface fluxes of heat and water to be derived using a two-equations system (surface energy balance and continuity of the mass flux at the soil surface).

Regardless of the type of fallow management system, at the experimental site the degree of soil cover by cereal crop residues was very low (< 30-40%) during the specific fallow periods considered in the study, as reported by López et al. (2003). Consequently, possible mulch effects on the water and energy budget of the field were not considered in the experimental set-up. Accordingly, the original version of SiSPAT was used instead of the SiSPAT-mulch version (González-Sosa et al., 1999), which explicitly takes into account the heat and water transfers within a plant-residue mulch layer.

2.2. Field data set

2.2.1. Experimental site and fallow management systems

The site is located at the dryland research farm of the Estación Experimental de Aula Dei (CSIC) in the province of Zaragoza (latitude 41º 44'N; longitude 0º 46'W; altitude 270 m). The climate is semiarid with an annual rainfall of 390 mm and an average annual air temperature of 14.5 ºC. Field research was carried out on two adjacent large blocks of ten plots, which were set up on a nearly level area in 1991 (Field 1) and 1992 (Field 2) as part of a long-term conservation tillage experiment initiated in 1989. The soil (fine-loamy, mixed thermic Xerollic Calciorthid) has a dominant clay loam texture along the soil profile, with the exception of Field 2, where a textural discontinuity is present at a depth of 40 cm, with some plots showing a sandy loam texture (Fig. 1). A more detailed description of the soil and crop management is given by López et al. (1996). The study was conducted when the fields were in the fallow phase of a winter barley (Hordeum vulgare L.)-fallow rotation, which extends from harvest (June-July) to sowing (November-December) the following year. Field measurements were made during three fallow seasons: 1999-2000 (26 June 1999 – 13 December 2000) and 2001-2002 (29 June 2001 – 19 November 2002) in Field 2, after 8 and 10 years of trial, and 2000-2001 (20 June 2000 – 23 November 2001) in Field 1, after 10 years of trial.

Three different fallow management treatments were compared: conventional tillage (CT), reduced tillage (RT) and no tillage (NT). 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 early summer. In the RT treatment, the primary tillage was chisel ploughing to a depth of 25-30 cm (non-inverting action), followed as in CT by a pass of the sweep cultivator in early summer. The primary tillage operations in the CT and RT plots were implemented on 25 April 2000, 10 April 2001, and 13 March 2002, and the secondary tillage on

26 May 2000, 5 June 2001, and 11 June 2002. No tillage operations were used in the NT treatment, in which weeds were controlled with herbicides.

The tillage treatments 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). The size of the elemental plot was 33.5 m x 10 m, with a separation of 1 m between plots.

2.2.2. Climatic variables

Hourly meteorological observations were made at the experimental site over the entire experimental period using an automatic weather station. The air temperature and humidity measured at a height of 1.8 m and the wind speed at 2 m were used for running the model. A tipping bucket rain gauge was used to measure the rainfall. Incoming short-wave solar radiation was measured using a pyranometer sensor at a height of 2 m. During the third fallow period, the net short-wave radiation (Rn) was recorded at 1 m above the soil surface on a NT plot using a net radiometer. All the sensors were connected to a data-logger, which continuously recorded 60-min averages of data acquired at intervals of 10 s. The long-wave incoming radiation was calculated using the expression proposed by Brutsaert (1975) (cited by Braud et al., 1995) for clear sky conditions.

Overall, the 1999-2002 experimental period was drier than normal. The total rainfall received during the first (1999-2000), second (2000-2001) and third (2001-2002) long-fallow periods was 3, 13, and 10%, respectively, below the long-term average (554 mm). The rainfall patterns were contrasted among the three fallow periods, with monthly totals found to be irregularly distributed over each fallow period (Table 1). The 2000-2001 fallow was characterised by a high rainfall (62% above normal) in the autumn (September-November) of the first year of fallow, and a dry spring (30% below normal), with only 17% of the total fallow rainfall occurring in the March-May period. In contrast, the 1999-2000 and 2001-2002 fallows had a low rainfall (about 22%

below normal in both cases) in autumn (19% of the total fallow rainfall) and a rainfall 11 and 33% above normal, respectively, in spring (24 and 30% of the total fallow rainfall) (Table 1).

2.2.3. Soil parameters

For the initialisation and validation of the model, the soil temperature (T_{soil}) was measured using thermistors horizontally inserted at depths of 2, 6 and 10 cm on one plot per tillage treatment during the three fallow periods. The soil temperature was additionally measured at 20 cm during the 2000-2001 fallow period and at 20, 50 and 70 cm during the 2001-2002 fallow period. The soil thermistors were connected to a data-logger, and data signals were acquired every 10 s and averaged over 60-min intervals. Soil temperature measurements gathered during periods with slow changes in soil water content were used to calculate the soil heat flux at the surface (G) for the three fallow seasons and tillage systems by using the "zero flux method" or calorimetric method (Sauer, 2002).

The volumetric water content of soil (θ) in the top 70 cm was monitored on a daily basis or as a function of rainfall events over the three experimental fallow periods using the Time Domain Reflectometry (TDR) technique. Probes consisting of two parallel stainless steel rods were vertically inserted into the soil to a depth of 10, 20, 40 and 70 cm, and θ was calculated using the model proposed by Topp et al. (1980). Two measurements of θ were made per experimental plot, which in accordance with the incomplete block design used gave a total of 18 measurements (6 per tillage treatment) on each fallow field per sampling depth and observation date.

The system of fallow tillage management affected the soil water dynamics during the three fallow periods. Figure 2 provides an example of the variation in θ for the 0-10, 10-20, 20-40 and 40-70 cm layers measured by TDR in Field 2 under CT, RT and NT treatments from 21 September 1999 to 12 December 2000 (first long-fallow period). Compared to CT and RT, the soil water stored under NT tends to be higher in the surface horizons and lower in the deeper ones. This behaviour is more marked during rainy periods, as occurred at the beginning and the end of the period (Fig. 2), reflecting the rainfall events in September-November 1999 and March-April 2000, respectively (Table 1).

The soil dry bulk density, ρ_b, hydraulic conductivity, K, and water retention curve, $\theta(h)$, were measured in situ in the 1-10 cm and 40-50 cm soil layers for the different tillage systems. In the three fallow periods, measurements of soil properties were made between January and March, just before primary tillage operations. Two samplings were performed per experimental plot, fallow period and sampling depth. The soil bulk density, ρ_b, was determined by the core method. The hydraulic conductivity, K, was measured at -14, -4, -1, and 0 cm soil pressure head (h) using a tension disc infiltrometer (Perroux and White, 1988) and calculated according to the multiple-head method (Ankeny et al., 1991). The volumetric water content of soil beneath the infiltrometer disc was determined by TDR at the end of each infiltration measurement. For this purpose, and prior to the infiltration measurements, a three-rod TDR probe was installed horizontally into the soil at a depth of 3-4 cm. The water content / matric potential relationship, $\theta(h)$, during draining was only measured during the 2001-2002 fallow period on Field 2. For the 0 to –30 kPa range, simultaneous field measurements of θ, using three-rod TDR probes, and h, using microtensiometers, were performed. Additionally, soil water retention at -100, -500 and -1500 kPa was measured in the laboratory on 2 mm sieved soil samples using a pressure membrane extractor. The $\theta(h)$ curve for Field 1 was estimated from soil water retention data given by López (1993). Likewise, the hydraulic conductivity of the surface crust (K_c) (0-1 cm depth) was determined at saturation (h = 0 cm) according to Vandervaere et al. (1997). The bulk density of the surface crust was measured by the clod method (Grossman and Reinsch, 2002) using paraffin wax as a coating agent.

2.2.4. Field water balance

Assuming a negligible runoff from the nearly level experimental plots in both Field 1 and Field 2 (0-2 % slope), the soil water budget for a given fallow period simplifies to:

$$E + D = P + \Delta\theta \quad (1)$$

where E (mm) is the water loss by evaporation from the soil surface, D is the deep percolation, P (mm) is the rainfall recorded over the time period in question, and $\Delta\theta$ is the change in soil water storage (0-70 cm depth) calculated using the volumetric moisture content profiles.

2.2.5. Modelling strategy

The measured soil and climate parameters were directly introduced into the model. For the soil horizons that were characterised in the field (0-1 cm; 1-10 cm; and 40-50 cm), the total soil porosity, ξ, was calculated from the soil dry bulk density ρ_b and the soil particle density ρ_s (ρ_s = 2.65 Mg m^{-3}), through $\xi = 1 - (\rho_b / \rho_s)$. The soil water retention curve was obtained by fitting the measured (h, θ) values to the van Genuchten (1980) model

$$\frac{\theta - \theta_r}{\theta_{sat} - \theta_r} = \left[1 + \left(\frac{h}{h_g}\right)^n\right]^{-m} \quad (2)$$

where n is the shape factor and m = 1-(2/n) (Braud, 2000). In this equation, θ_{sat} and θ_r are the saturated and residual volumetric water contents, respectively, and h_g is the scale factor. In our case, θ_{sat} is the water content below the disc infiltrometer at the end of the infiltration measurement at saturation, and θ_r was estimated from the soil textural properties (Kosugi et al., 2002). The hydraulic conductivity curve $K(\theta)$ was fitted using the Brooks and Corey (1964) model:

$$K(\theta) = K_{sat} (\theta / \theta_{sat})^{\beta} \quad (3)$$

where $\underline{K_{sat}}$ is the saturated hydraulic conductivity, $\underline{\beta}$ a shape factor estimated from the measured $\underline{K}(\underline{h})$ relationship, and $\underline{\theta}$ is the soil water content below the infiltrometer disc at the end of each tension infiltration measurement.

The values for all the above soil parameters are given in Table 2. On average, the values of $\underline{K_{sat}}$, $\underline{n}$, $\underline{h_g}$ and $\underline{\theta_{sat}}$ measured under NT in the 1-10 cm soil layer were significantly lower than those measured under the CT and RT treatments. In contrast, $\underline{\rho_b}$ was significantly greater under NT than under CT and RT. These results indicate that long-term NT management (after 8-10 years of trial) compacted the topsoil, which in turn affected the soil hydraulic properties. In general, the spatial variability of the soil parameters was low, as indicated by the low values of the coefficient of variation (CV) (Table 3). The interannual variability of $\underline{K_{sat}}$ for the 0-10 cm depth soil layer under NT (CV= 45%) was lower than that observed for the CT (CV = 50%) and RT (CV = 52%) treatments. The mean value of the surface crust hydraulic conductivity at saturation was 1.0 x 10^{-5} m s^{-1}, with no significant differences among fallow periods and tillage treatments. The bulk density of the soil's surface crust (measurements taken in the 2000-2001 fallow period) was 1.28 Mg m^{-3}, with no significant differences among tillage treatments (CV = 5.3%).

The soil depth was fixed at 0.7 m and, according to tillage management (e.g., ploughing depth) and soil crusting characteristics, divided into five horizons (0-1 cm; 1-10 cm; 10-20 cm; 20-40 cm; and 40-70 cm). The values of the soil parameters measured in the 1-10 and 40-50 cm layers were extended to the 10-20 and 40-70 cm horizons, respectively. Intermediate calibrated values were taken for the 20-40 cm horizon (data not shown).

Since the SiSPAT model also requires the specification of the thermal conductivity $\underline{\lambda}$, this parameter was derived using the Van de Griend and O'Neil model (Braud, 2000) as the option most appropriate to our experimental set-up, where only the soil texture is known and no measurements of the soil thermal properties are available. Other non-measured surface parameters that must be prescribed are the bare soil albedo, α, and the roughness length for the momentum, z_{om}. The Passerat de Silans model (Braud, 2000), calibrated for a loam soil, was used to calculate α, and z_{om} was set to 0.004 m (M.V. López, personal communication).

Given the soil and climate data sets available for the three fallow periods, we used the split-sample technique for the calibration and validation of the model. The measurements of θ, T_{soil}, G and R_n gathered in Field 2 from 29 November 2001 to 19 November 2002 during the 2001-2002 fallow period were used to calibrate the model. Calibration consisted of fitting the β parameter for the 0-10 and 40-70 cm soil layers, and estimating the soil hydrophysical parameters for the 10-20 cm and 20-40 cm soil horizons. The measurements of θ, T_{soil} and G from 21 September 1999 to 13 December 2000 (1999-2000 fallow season) and from 7 October 2000 to 23 November 2001 (2000-2001 fallow season) were used to validate the model. Whereas the complete data sets were used for the calibration and validation of SiSPAT under NT conditions, only data subsets from until the primary tillage dates (e.g., 25 April 2000, 10 April 2001 and 13 March 2002) were considered for the CT and RT treatments.

To draw a comparison between the variables observed, $\underline{Var}(\underline{obs})$, and the variables calculated using the model, $\underline{Var}(\underline{mod})$, regressions of the form $\underline{Var}(\underline{mod}) = \underline{Slope} \times \underline{Var}(\underline{obs}) + \underline{Intercept}$ were performed. The root mean square error (RMSE) was also calculated by

$$RMSE = \left[\frac{1}{N} \sum_{i=1}^{N} \left(Var_i(\mathrm{mod}) - Var_i(obs) \right)^2 \right]^{1/2} \quad (4)$$

where $\underline{N}$ is the number of pairs available.

Finally, in order to assess the efficiency of the three tillage practices, a simulation of the soil water balance under the three tillage management systems was performed for the entire fallow periods on the assumption that the measured soil parameters would remain unchanged until the end of the fallow season. This assumption was obviously justified for the NT treatment. Its validity for the CT and RT treatment will be discussed by comparing the simulation results of soil water loss with the observations.

3. Results and discussion

3.1. Model performance

The results gathered during the calibration phase are summarised in Table 3. Overall, there is a satisfactory agreement between measured and modelled soil and surface flux variables. The determination coefficient (R^2) and slope of the regressions for the different fallow tillage management systems are in most cases close to one, with relatively small intercept values. The soil temperature at different depths is well predicted by the model, with an average RMSE value of 2.7 ºC. This deviation could be due to an overestimation of the thermal amplitude by the model. The small RMSE found for $\underline{\theta}$ at all soil depths indicates that the model predicts the soil water dynamics reasonably well. In the case of the soil heat flux $\underline{G}$, the deviation between observed and predicted values can be related to an overestimation of the values of $\underline{G}$ during night-time. However, given the limitations and uncertainties associated with the calorimetric method used to calculate $\underline{G}$ (Sauer, 2002), the RMSE values obtained for this variable (average of 44.5 W m^{-2}) can be considered acceptable. The statistics (R^2, slope, intercept and RMSE) for the regressions between observed and modelled values of the soil temperature ($\underline{T_{soil}}$), volumetric soil water content ($\underline{\theta}$), net radiation ($\underline{Rn}$) and soil heat flux ($\underline{G}$) were similar to those found in previous SiSPAT assessment studies (Braud et al., 1997; Boulet et al., 1997; Gonzalez-Sosa et al., 1999; Gonzalez-Sosa et al., 2001).

Table 4 summarises, for the different tillage systems, the comparison between predicted and measured values of $\underline{T_{soil}}$, $\underline{\theta}$ and $\underline{G}$ used to validate the model during the 1999-2000 and 2000-2001 fallow periods. Generally, the model tends to underestimate the soil temperature, as shown by the negative values of the regression intercept. However, the observed difference of about 1 ºC can be considered negligible. As regards the soil moisture, except for $\underline{\theta_{0\text{-}70\ cm}}$ under CT and RT in the 1999-2000 fallow period, the model proved able to simulate the dynamics of the soil water content in the soil profile (0-70 cm depth). The $\underline{G}$ values predicted by the model agree with the observed values, as indicated by high determination coefficients, slopes close to one, and small intercepts (Table 4). Figure 3 shows an example of the correlations between the measured and simulated soil water content for the 0-70 cm depth soil profile (Tables 4 and 5) for the three tillage management systems and fallow periods.

3.2. Comparison between measured and simulated soil water loss

To begin by focusing on the long-term analysis, Figure 4 shows a comparison between the simulated and measured cumulative soil water loss (i.e., $\underline{E+D}$) from the 0-70 cm soil profile for the three tillage systems and fallow periods. In general, the soil water loss measured during the entire fallow periods for NT and before tillage operations for CT and RT agreed with that simulated by SiSPAT.

The comparison between the simulated, $(\underline{E}+\underline{D})_S$, and measured, $(\underline{E}+\underline{D})_M$, total soil water lost from the 0-70 cm soil profile at the end of fallow allowed us to quantify the long-term influence of tillage practices on soil water storage and conservation (Fig. 5). While for the 1999-2000 and 2001-2002 fallows both values of water loss were very similar, $(\underline{E}+\underline{D})_S$ under both CT and RT for the 2000-2001 fallow period was lower than $(\underline{E}+\underline{D})_M$ (35 and 26 mm lower, respectively) (Fig. 5). This may indicate that both mouldboard and chisel ploughing had a negative influence on the total soil water conservation in fallow periods with a very wet autumn during the first year of fallow. As the hypothesis in the simulation is that soil hydraulic properties are not modified by tillage practices, and given the good results provided by the model when this hypothesis is justified (NT treatment), it can be assumed that the differences between simulated and observed soil water losses are due to a modification of the soil hydraulic properties caused by tillage.

Consequently, it might be concluded that eliminating primary tillage operations in fallows with high soil water recharge during the autumn of the first year of fallow might increase the amount of water stored in the soil profile at sowing time. However, this conclusion should be taken with caution, and further experimental work should be done to validate it.

Figure 6 shows the time course of the measured and modelled $\underline{\theta}$ for the plough layer (0-40 cm depth) under the CT, RT and NT treatments over the 1999-2000 fallow period and clearly illustrates the effect that tillage operations had on the soil water content. It can be observed that the agreement between measured and simulated $\underline{\theta}$ under NT for the entire period decreases under the CT and RT treatments, particularly under CT, from the date of primary tillage implementation on (shaded area).

In order to evaluate the short-term effects of primary tillage on soil water storage, the time course of the water loss measured from the 0-70 cm soil profile, $(\underline{E} + \underline{D})_M$ was compared with the values simulated by SiSPAT, $(\underline{E} + \underline{D})_S$. This comparison is best illustrated by the results from the 2000-2001 fallow season since a relatively long dry period followed primary tillage on DAY 100 (Fig. 7). Assuming a negligible deep drainage on the day of tillage (Fig. 4), SiSPAT correctly simulated the cumulative evaporation loss under NT for the post-tillage period. By contrast, there were clear differences in the tilled treatments between observed and calculated evaporation immediately after tillage (Fig. 7). This discrepancy can be explained by the fact that the model did not take into account the soil loosening caused by tillage and its effects on the water transmission properties at the soil surface. The soil loosening produced by tillage increases surface roughness, which increases potential evaporation by concentrating heat in the surface layers and allowing greater wind penetration into the soil (Jalota and Prihar, 1990). In our case, the soil water loss for the 24 h after tillage was 12.7 and 8.3 mm under CT and RT, respectively, as opposed to only 1.2 mm under NT (Fig. 7).

3.3. Simulation of the soil water balance and components during fallow

The objective of this section is to compare the soil water losses between years, according to the rainfall regime, and between treatments. Results from SiSPAT simulations are also used to evaluate in which situations water losses are likely to be caused by evaporation and in which situations drainage below 70 cm is the dominant process.

Figure 4 shows the water balance predicted by SiSPAT for the three experimental fallow periods and distinct tillage management systems on the assumption that the soil parameters for the CT and RT remain constant through the whole fallow period. The results show that the components of the soil water budget for each fallow season were influenced by the fallow rainfall pattern. On average, the soil water evaporation estimated by the model for the 1999-2000, 2000-2001 and 2001-2002 fallow periods represented 71, 55 and 91% of the total rainfall, respectively, while the deep drainage estimated by the model represented 18, 28 and 5% of the total rainfall in the respective periods. Table 5 shows the total water balance and its components simulated by SiSPAT at the end of the three fallow periods under the three tillage management treatments. These results indicate that if most of the fallow season rainfall is received during the autumn-winter period of the first year of the fallow, when the evaporative demand is low, water storage in the soil profile is possible even below 70 cm depth. As a result, the water stored deep in the soil is kept protected against evaporation during late spring and summer, and might consequently be partially used by the following crop. On the other hand, the model simulation also showed that long-fallow periods characterised by a dry winter and a wet spring have no significant effects on soil water storage and percolation. Thus, the large rainfall registered in the spring of the 1999-2000 and 2001-2002 fallow periods was mostly lost by evaporation from the soil surface, probably due to a concurrent high evaporative demand that prevented the water from flowing to deep soil layers.

The components of the soil water balance estimated by SiSPAT also varied with the fallow tillage treatment, presumably because the soil hydraulic properties in the pre-tillage period differ significantly among treatments due to the long-term effect of tillage on soil properties (see section 2.2.5). This effect was most evident in the 2000-2001 fallow period, with a rainfall above normal in the autumn of the first year of fallow. For this period, the estimated soil water losses by evaporation under NT (64%) were higher than those estimated under CT and RT (44 and 56%, respectively). Conversely, model estimates of the drainage component showed that 21, 25 and 38% of the total rainfall received during the 2000-2001 fallow period drained below 70 cm depth under NT, RT and CT, respectively. These differences among tillage systems could be related to differences in soil hydraulic properties. Thus, high topsoil water content under NT (Fig. 2) could have enhanced soil water evaporation during the following spring and summer fallow periods in this treatment.

In fallow seasons with a dry autumn in the first year of fallow and a wet spring (e.g., the 1999-2000 and 2001-2002 fallows), the differences in the components of the soil water balance among the tillage systems were much smaller. In these cases, the evaporative demand during a rainy spring period appears to be the main factor regulating the soil water fluxes.

4. Conclusions

The SiSPAT (Simple Soil-Plant-Atmosphere Transfer) model was used to simulate on a long-term basis the water budget of a loamy dryland soil during the fallow period of a semiarid rainfed winter barley-fallow rotation managed with three different tillage systems (conventional tillage, CT; reduced tillage, RT; and no-tillage, NT). The model's performance was evaluated by comparing numerical results and field data covering specific sub-periods of three 17-18 month fallow seasons. On the assumption that the soil properties under the different tillage systems remained unchanged over the whole fallow period, the model showed that about 81% of fallow seasonal rainfall was lost by evaporation in fallow periods having both a dry autumn in the first year of fallow and a wet spring. In contrast, if the long-fallow period was characterised by a wet autumn during the first year of fallow the model predicted an increase in water storage and deep drainage and a decrease in soil water evaporation. In this case, the soil water evaporation under NT was about 14% higher than that estimated under CT and RT.

The comparison between measured (0-70 cm depth) and simulated soil water loss showed that tillage operations have a null or a negative effect on the amount of soil water stored at the end of fallow. This indicates that the traditional primary tillage in early spring of the second year of fallow could be eliminated. However, taking into account that the simulated soil water loss in the tilled soils (CT and RT) was lower than in the NT soils due to the actual modification of the soil hydrophysical properties as a result of tillage, further research should be conducted in order to ascertain whether alternative fallow management practices, such as the delaying of primary tillage until the end of fallow, might improve soil water storage at sowing in semiarid Central Aragon.

Finally, further effort should be made to improve the SiSPAT model by including a specific submodel describing the dynamics of soil hydrophysical properties following tillage. This would allow a better simulation of the water balance during fallow and thus make it possible to define the optimum timing of tillage operations.

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Figure captions

Figure 1. Textural triangle showing the soil texture classes in the experimental plots of Field 1 (white points) and Field 2 (gray points) at the 0-10 cm depth (circles) and the 40-50 cm depth (triangles). CT, RT and NT indicate plots under conventional tillage, reduced tillage, and no-tillage, respectively.

Figure 2. Time course of rainfall and volumetric soil water content ($\underline{\theta}$) in the 0-10 cm, 10-20 cm, 20-40 cm and 40-70 cm layers measured in Field 2 under conventional tillage (CT), reduced tillage (RT) and no-tillage (NT) during the 1999-2000 fallow season from 21 September 1999 to 13 December 2000. **T** and **t** indicate primary and secondary tillage dates.

Figure 3. Correlations between measured and simulated soil water content for the 0-70 cm soil profile during the 1999-2000, 2000-2001 and 2001-2002 long-fallow periods under conventional tillage (CT), reduced tillage (RT) and no-tillage (NT).

Figure 4. Cumulative rainfall received during the 1999-2000, 2000-2001 and 2001-2002 long-fallow periods, cumulative total soil water loss measured from the soil profile (0-70 cm depth) and corresponding cumulative water losses by evaporation and deep drainage predicted by SiSPAT under conventional tillage (CT), reduced tillage (RT) and no-tillage (NT).

Figure 5. Relationship between total soil water loss (evaporation plus deep drainage) measured and predicted by the SiSPAT model at the end of the 1999-2000, 2000-2001

and 2001-2002 fallow periods under conventional tillage (CT), reduced tillage (RT) and no-tillage (NT).

Figure 6. Comparison of simulated (continuous line) volumetric soil water content ($\underline{\theta}$) for the 0-40 cm horizon with observations (symbols) from TDR measurements in Field 2 under conventional tillage (CT), reduced tillage (RT) and no-tillage (NT) during the 1999-2000 fallow season from 21 September 1999 to 13 December 2000 (**T**, primary tillage; **t**, secondary tillage).

Figure 7. Cumulative soil water loss (evaporation plus deep drainage) measured (symbols) and predicted by SiSPAT (continuous line) under conventional tillage (CT), reduced tillage (RT) and no-tillage (NT) from the upper 70 cm of soil following primary tillage (**T**) in the 2000-2001 long fallow period. Bars indicate rainfall events.

Table 1. Monthly rainfall (mm) during the 1999-2000, 2000-2001 and 2001-2002 long-fallow seasons compared with long-term monthly totals (1954-2002 average) at the experimental site.

Month	1999-2000	2000-2001	2001-2002	49-yr avg.
July	27	4	3	17
August	9	7	2	24
September	46	9	60	41
October	33	122	25	40
November	15	66	10	41
December	7	36	3	28
January	14	44	22	27
February	1	4	6	23
March	25	21	48	28
April	62	5	27	36
May	40	54	76	50
June	48	9	40	36
July	4	3	17	17
August	7	2	9	24
September	9	60	60	41
October	122	25	54	40
November	66	10	35	41
17-mo total	535	481	497	554

Table 2. Average values of soil parameters† measured in the 1-10 and 40-50 cm soil horizons in Field 1 and Field 2 during the 1999-2000, 2000-2001 and 2001-2002 fallow periods under conventional tillage (CT), reduced tillage (RT) and no-tillage (NT) treatments.

Soil layer	Tillage treatment	ρ_b ($Mg\ m^{-3}$)	ξ	θ_{sat} ($m^3\ m^{-3}$)	h_g (m)	n	K_{sat} ($m\ s^{-1}$)
				1999-2000 fallow period			
Horizon 2 (1-10 cm)	CT	1.22 (2)‡	0.54	0.50 (5)	-	-	$2.3\ 10^{-5}$ (46)
	RT	1.14 (3)	0.57	0.51 (4)	-	-	$2.1\ 10^{-5}$ (51)
	NT	1.30 (3)	0.51	0.41 (4)	-	-	$1.1\ 10^{-5}$ (46)
	LSD§	0.08		0.04	-	-	$0.8\ 10^{-5}$
Horizon 3 (40-50 cm)	CT	1.32 (6)	0.50	0.39 (3)	-	-	$1.8\ 10^{-5}$ (48)
	RT	1.35 (4)	0.49	0.40 (6)	-	-	$1.5\ 10^{-5}$ (70)
	NT	1.30 (4)	0.51	0.38 (3)	-	-	$1.9\ 10^{-5}$ (48)
	LSD	NS		NS	-	-	NS
				2000-2001 fallow period			
Horizon 2 (1-10 cm)	CT	1.29 (9)	0.51	0.49 (4)	0.10 ¶	2.25 ¶	$3.0\ 10^{-5}$ (59)
	RT	1.24 (7)	0.53	0.49 (6)	0.11	2.24	$2.1\ 10^{-5}$ (55)
	NT	1.37 (5)	0.48	0.42 (3)	0.30	2.21	$1.2\ 10^{-5}$ (39)
	LSD	0.07		0.04	-	-	$0.8\ 10^{-5}$
Horizon 3 (40-50 cm)	CT	1.52 (8)	0.43	0.41 (7)	0.25 ¶	2.19 ¶	$1.7\ 10^{-5}$ (57)
	RT	1.51 (1)	0.40	0.42 (3)	0.25	2.20	$1.2\ 10^{-5}$ (17)
	NT	1.60 (3)	0.40	0.39 (3)	0.23	2.22	$1.7\ 10^{-5}$ (77)
	LSD	NS		NS	-	-	NS
				2001-2002 fallow period			
Horizon 2 (1-10 cm)	CT	1.25 (3)	0.53	0.48 (3)	0.11 (32)	2.24 (1)	$2.6\ 10^{-5}$ (46)
	RT	1.17 (2)	0.54	0.49 (2)	0.14 (13)	2.25 (1)	$2.9\ 10^{-5}$ (44)
	NT	1.38 (1)	0.48	0.42 (6)	0.28 (62)	2.22 (1)	$1.0\ 10^{-5}$ (49)
	LSD	0.19		0.03	0.14	0.02	$1.5\ 10^{-5}$
Horizon 3 (40-50 cm)	CT	1.42 (10)	0.46	0.40 (4)	0.13 (136)	2.26 (6)	$1.4\ 10^{-5}$ (22)
	RT	1.37 (10)	0.48	0.41 (6)	0.11 (65)	2.19 (5)	$1.7\ 10^{-5}$ (26)
	NT	1.36 (11)	0.49	0.39 (6)	0.14 (44)	2.27 (5)	$2.2\ 10^{-5}$ (54)
	LSD	NS		NS	NS	NS	NS

† ρ_b, soil dry bulk density; ε, total soil porosity; θ_{sat}, saturated volumetric soil water content; h_g and n are the scale and shape factors in the van Genuchten (1980) model for the water retention curve; K_{sat}, saturated hydraulic conductivity; β; shape factor in the Brooks and Corey (1964) model for the hydraulic conductivity curve.

‡ Figures in parenthesis are coefficient of variation in %.

§ Least significant difference, $P < 0.05$. NS, not significant.

¶ Values estimated from data reported by López (1993).

Table 3. Coefficient of determination R^2, slope and intercept of the regressions Var(mod) = Slope x Var(obs) + Intercept and RMSE obtained during model calibration under conventional tillage (CT), reduced tillage (RT) and no-tillage (NT) treatments during the 2001-2002 fallow period (calibration period).

Model variable	CT					RT					NT				
	N†	R^2	Slope	Intercept ‡	RMSE ‡	N	R^2	Slope	Intercept	RMSE	N	R^2	Slope	Intercept	RMSE
$T_{soil\_2\ cm}$	1480	0.94	1.17	-4.6	3.9	1480	0.97	1.09	-2.8	4.2	7514	0.97	1.11	-3.7	2.5
$T_{soil\_6\ cm}$	1480	0.96	1.09	-3.0	3.8	1480	0.95	0.98	-0.6	3.3	7514	0.96	1.01	-1.6	1.9
$T_{soil\_10\ cm}$	1480	0.96	1.15	-3.8	3.3	1480	0.96	1.13	-3.7	2.7	7514	0.97	1.07	-2.8	2.0
$T_{soil\_20\ cm}$	1480	0.97	1.18	-4.4	3.7	1480	0.97	1.07	-2.4	2.2	7514	0.97	1.06	-2.1	1.7
$T_{soil\_50\ cm}$	1480	0.94	0.89	1.9	5.1	1480	0.98	0.98	-0.2	1.0	7514	0.94	0.83	3.3	1.1
$T_{soil\ 70\ cm}$	1480	0.97	0.92	1.2	4.7	1480	0.97	0.83	3.2	1.1	7514	0.93	0.88	2.5	1.4
$\theta_{0\text{-}10\ cm}$	22	0.89	0.71	0.057	0.032	22	0.86	0.62	0.054	0.039	85	0.75	0.66	0.084	0.027
$\theta_{0\text{-}20\ cm}$	22	0.85	0.72	0.061	0.034	22	0.88	0.65	0.068	0.033	85	0.77	0.72	0.064	0.018
$\theta_{0\text{-}40\ cm}$	22	0.86	0.97	0.006	0.034	22	0.93	1.01	0.002	0.036	85	0.79	0.83	0.037	0.012
$\theta_{0\text{-}70\ cm}$	22	0.76	1.00	0.007	0.034	22	0.68	0.90	0.014	0.036	85	0.85	0.80	0.032	0.013
Rn											7514	0.96	1.00	-37.2	52.2
G	430	0.78	0.93	-2.0	36.7	430	0.80	1.00	-3.6	55.1	2150	0.90	0.88	14.1	41.8

† Number of pairs available.

‡ Intercept and RMSE are given in ºC for soil temperature (T_{soil}), in m^3m^{-3} for volumetric soil water content (θ) and in Wm^{-2} for soil heat flux (G) and net radiation (Rn).

Table 4. Coefficient of determination R^2, slope and intercept of the regressions Var(mod) = Slope x Var(obs) + Intercept and RMSE obtained during model validation under conventional tillage (CT), reduced tillage (RT) and no-tillage (NT) treatments during the 1999-2000 and 2000-2001 fallow periods (validation period).

Model variable	CT					RT					NT				
	N†	R^2	Slope	Intercept ‡	RMSE ‡		R^2	Slope	Intercept	RMSE	**N**	R^2	Slope	Intercept	RMSE
1999-2000 fallow															
$T_{soil\ 2\ cm}$	5200	0.92	0.97	-0.6	4.0	5200	0.92	1.00	-1.9	2.9	10130	0.98	1.01	-1.2	1.9
$T_{soil\ 6\ cm}$	5200	0.78	0.91	-0.6	4.5	5200	0.81	0.98	-1.5	3.3	10130	0.89	0.88	1.1	2.5
$T_{soil\ 10\ cm}$	1100	0.67	0.94	-0.5	4.3	1100	0.66	0.86	-0.6	2.6	6005	0.86	0.96	0.1	2.3
$\theta_{0\text{-}10\ cm}$	51	0.85	0.68	0.051	0.025	51	0.84	0.74	0.054	0.030	106	0.89	0.75	0.056	0.016
$\theta_{0\text{-}20\ cm}$	51	0.87	0.73	0.045	0.022	51	0.84	0.78	0.047	0.026	106	0.85	0.73	0.060	0.015
$\theta_{0\text{-}40\ cm}$	51	0.76	0.74	0.040	0.023	51	0.66	0.63	0.065	0.026	106	0.87	0.71	0.054	0.013
$\theta_{0\text{-}70\ cm}$	51	0.60	0.53	0.074	0.023	51	0.65	0.48	0.081	0.026	106	0.88	0.76	0.045	0.010
G	150	0.96	0.89	-4.6	23.5	150	0.85	0.96	5.7	40.2	2260	0.94	0.77	11.7	48.2
2000-2001 fallow															
$T_{soil\ 2\ cm}$	4350	0.87	1.23	-2.7	2.5	4350	0.92	1.12	-3.4	2.9	8157	0.98	1.06	-2.1	2.1
$T_{soil\ 6\ cm}$	4350	0.69	0.90	-0.8	2.7	4350	0.72	0.89	-0.6	3.2	8157	0.90	0.91	0.2	3.0
$T_{soil\ 10\ cm}$	4350	0.88	1.15	-2.2	2.2	4350	0.83	1.04	-2.1	2.9	8157	0.95	1.02	-1.7	2.5
$T_{soil\ 20\ cm}$	4350	0.78	1.02	0.2	1.9	4350	0.87	1.06	-1.6	2.3	8157	0.97	0.97	-0.7	1.8
$\theta_{0\text{-}10\ cm}$	42	0.89	0.95	0.002	0.037	42	0.94	0.86	0.019	0.054	86	0.95	0.81	0.040	0.019
$\theta_{0\text{-}20\ cm}$	42	0.94	0.89	0.014	0.039	42	0.96	0.85	0.031	0.053	86	0.95	0.87	0.032	0.013
$\theta_{0\text{-}40\ cm}$	42	0.97	0.86	0.009	0.041	42	0.99	0.91	0.008	0.048	86	0.95	0.91	0.010	0.014
$\theta_{0\text{-}70\ cm}$	42	0.98	0.93	0.004	0.032	42	0.94	0.98	0.004	0.049	86	0.91	0.98	0.009	0.011
G	900	0.85	1.02	6.86	44.8	800	0.89	0.87	4.2	49.2	4350	0.87	0.77	7.4	55.3

† Number of pairs available.

‡ Intercept and RMSE are given in ºC for soil temperature (T_{soil}), in m^3m^{-3} for volumetric soil water content (θ) and in Wm^{-2} for soil heat flux (G).

Table 5. Total rainfall, and soil water evaporation, deep drainage and deep drainage plus water evaporation from the 0-70 cm depth simulated by the model SiSPAT during the 1999-2000, 2000-2001 and 2001-2002 long-fallow periods under conventional tillage (CT), reduced tillage (RT) and no-tillage (NT).

Field	Fallow period	Tillage system	Rainfall	Evaporation	Deep drainage	Deep drainage + Evaporation
			mm			
Field 2	1999-2000	CT	463.2	334.7	77.3	412.0
		RT		328.2	80.9	409.1
		NT		317.5	96.0	413.5
Field 1	2000-2001	CT	459.5	202.6	174.5	377.1
		RT		257.7	117.1	374.8
		NT		295.9	96.5	392.4
Field 2	2001-2002	CT	362.4	327.5	9.8	337.3
		RT		332.8	13.1	345.9
		NT		325.6	27.4	353.0

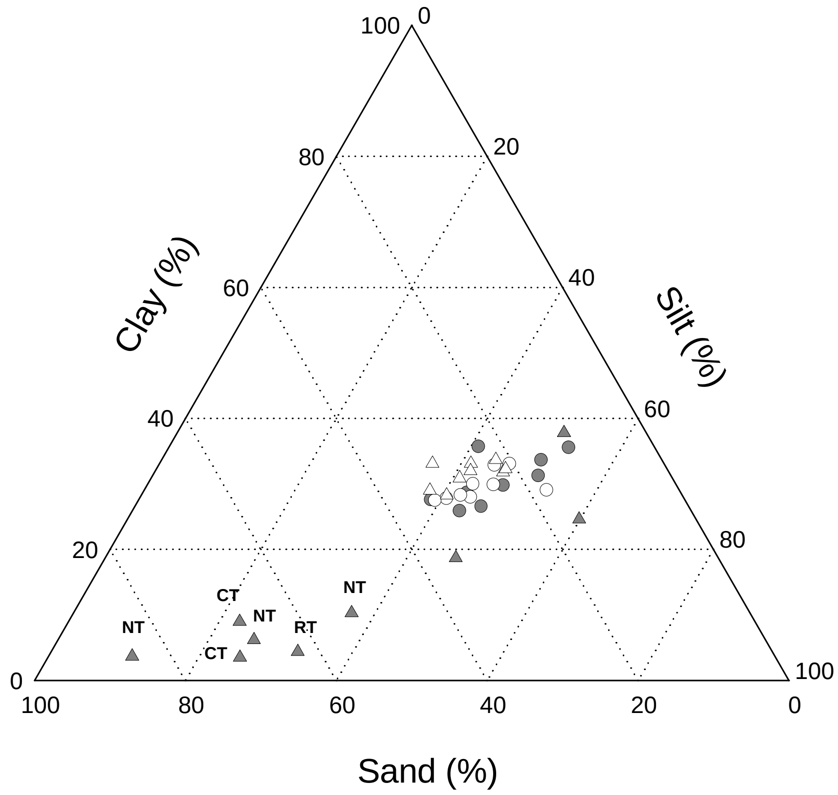

100
0
80
20
60
40
40
60
20
80
0
100
100
80
60
40
20
0
Clay (%)
Silt (%)
Sand (%)
CT
NT
NT
RT
NT
CT

Fig. 1

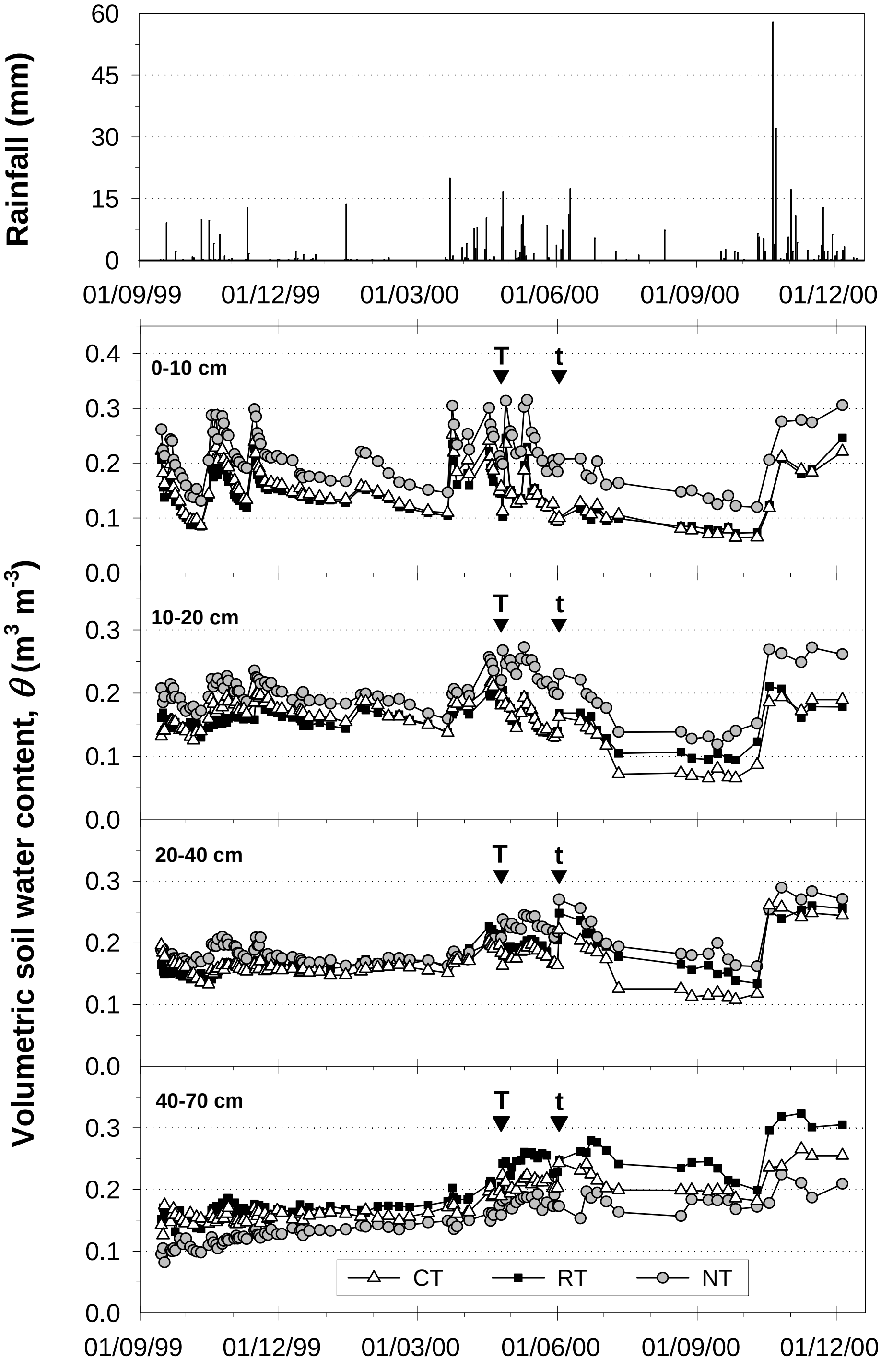
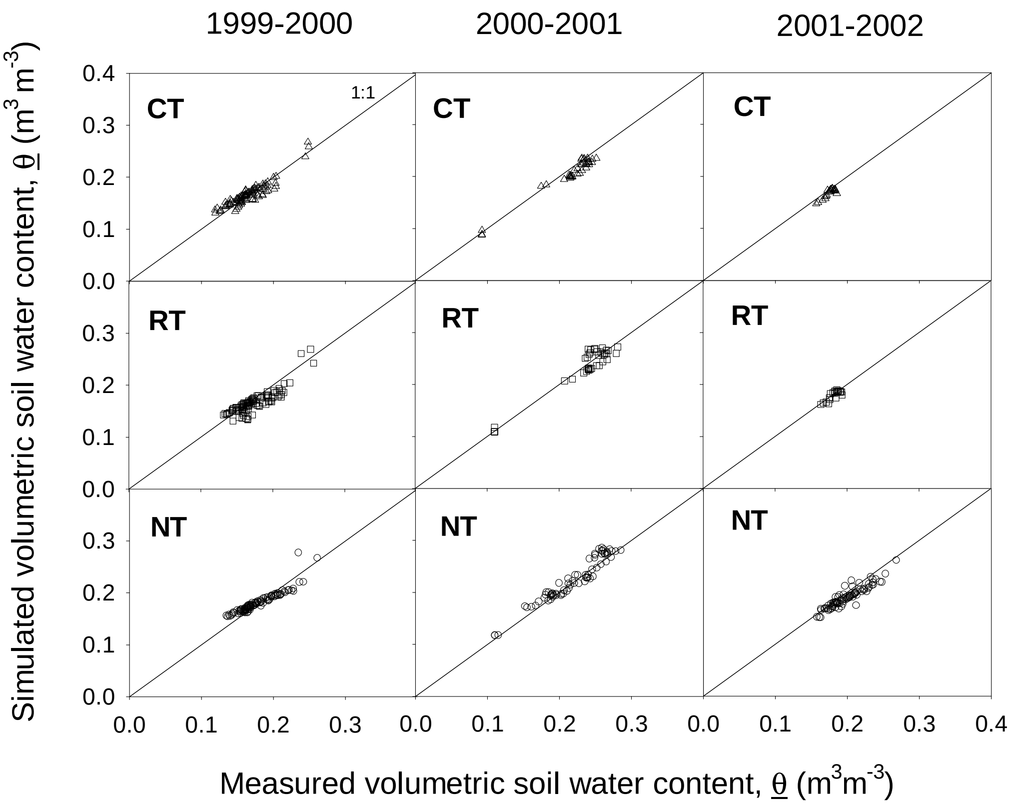
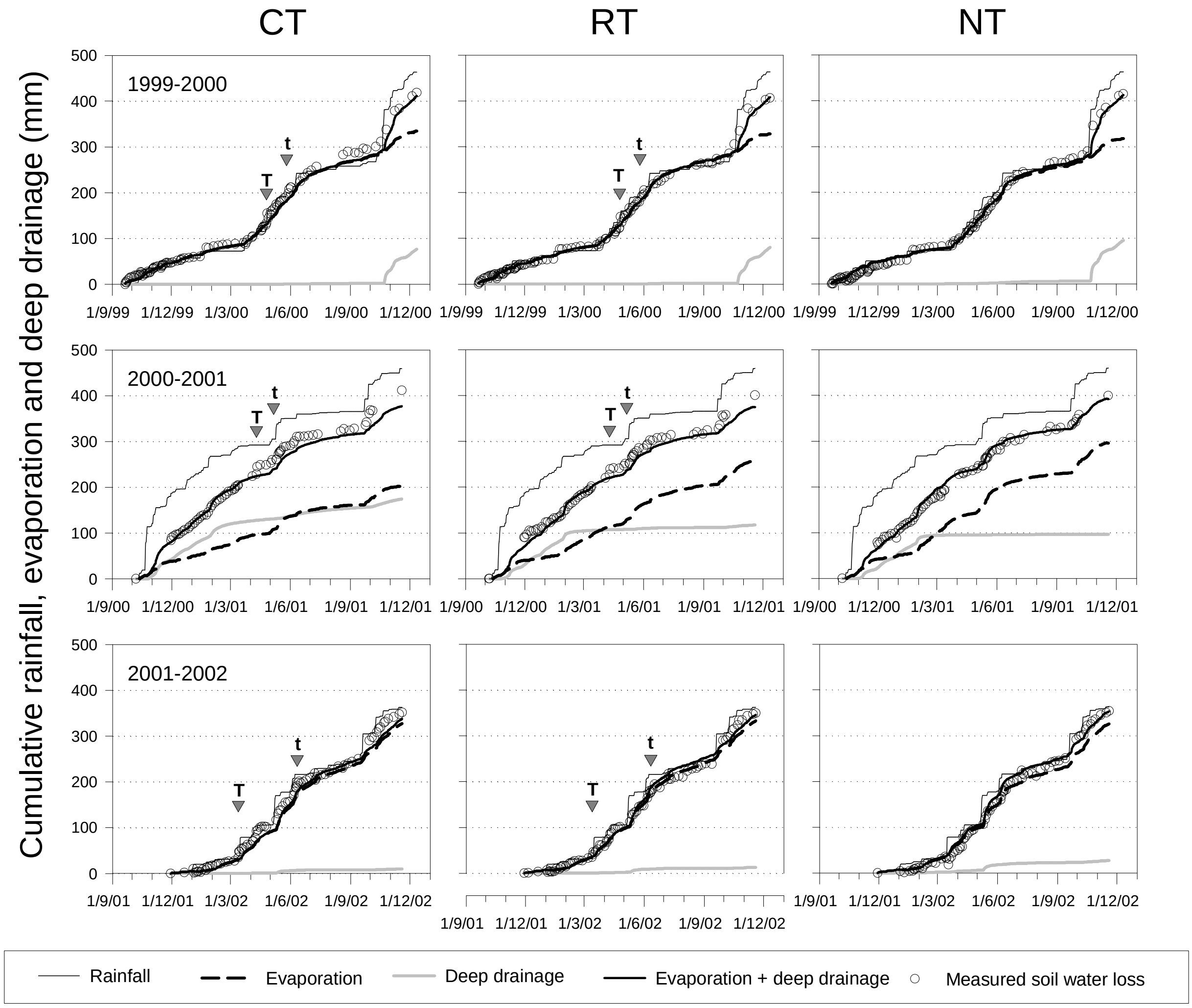

Rainfall (mm)
60
45
30
15
0
01/09/99
01/12/99
01/03/00
01/06/00
01/09/00
01/12/00
Volumetric soil water content, θ (m3 m-3)
0-10 cm
10-20 cm
20-40 cm
40-70 cm
T
t
0.4
0.3
0.2
0.1
0.0
CT
RT
NT

Fig. 2



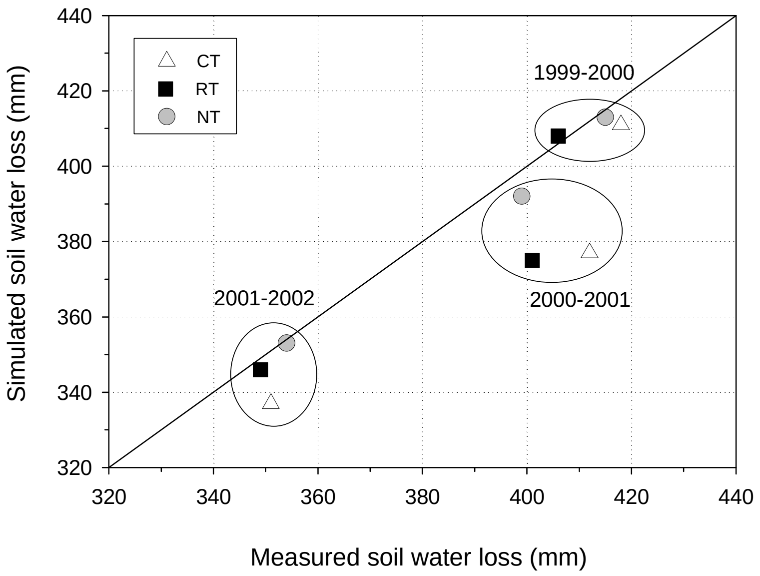
1999-2000
2000-2001
2001-2002
Simulated volumetric soil water content, θ (m3 m-3)
CT
CT
CT
RT
RT
RT
NT
NT
NT
1:1
0.0
0.1
0.2
0.3
0.4
Measured volumetric soil water content, θ (m3m-3)

Fig. 3



CT
RT
NT
Cumulative rainfall, evaporation and deep drainage (mm)
1999-2000
2000-2001
2001-2002
T
t
Rainfall
Evaporation
Deep drainage
Evaporation + deep drainage
Measured soil water loss

Fig. 4



Simulated soil water loss (mm)
440
420
400
380
360
340
320
CT
RT
NT
1999-2000
2000-2001
2001-2002
320
340
360
380
400
420
440
Measured soil water loss (mm)

Fig. 5

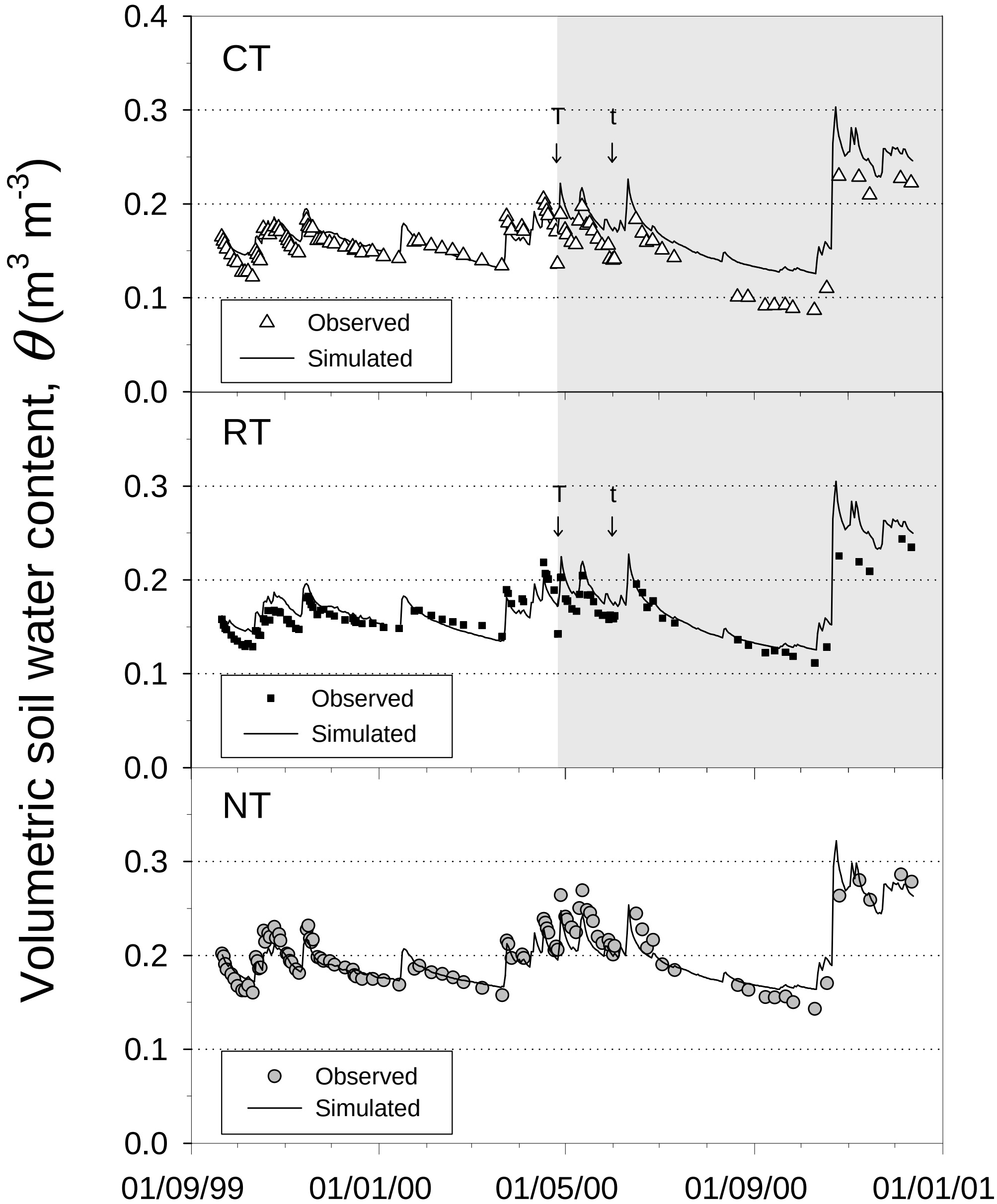
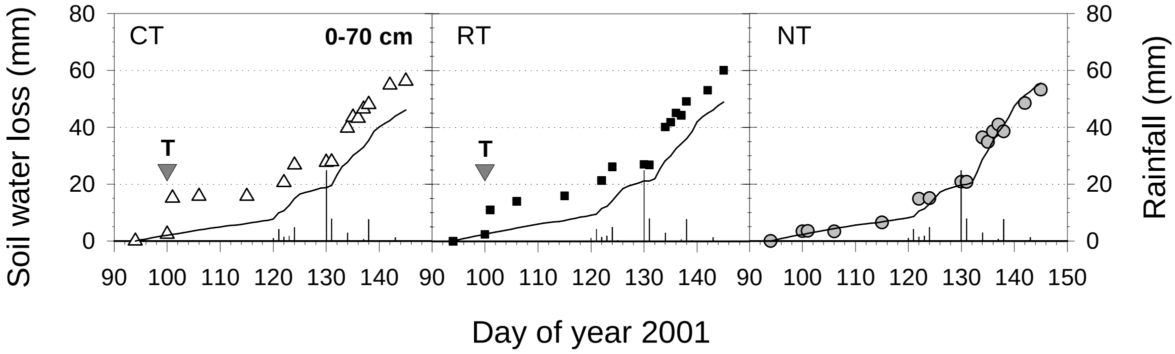

Volumetric soil water content, θ (m³ m⁻³)
CT
RT
NT
T
t
Observed
Simulated
0.0
0.1
0.2
0.3
0.4
01/09/99
01/01/00
01/05/00
01/09/00
01/01/01

Fig. 6



CT
0-70 cm
RT
NT
T
T
Soil water loss (mm)
Rainfall (mm)
0
20
40
60
80
90
100
110
120
130
140
150
Day of year 2001

Fig. 7