2004

Tesis Doctoral

David Moret Fernández

Efectos del laboreo sobre las propiedades hidrofísicas y balance hídrico del suelo durante el periodo de barbecho de una rotación cebada-barbecho en condiciones de secano semiárido del centro de Aragón

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Estación Experimental de Aula Dei

Departamento de Edafología

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Este trabajo de investigación ha sido realizado gracias a una beca del Plan Nacional de Formación de Personal Investigador (Ministerio de Ciencia y Tecnología) adscrita al Proyecto de Investigación AGF98-0261-CO2-02.

José Luís Arrúe Ugarte, Investigador Científico del Consejo Superior de Investigaciones Científicas (CSIC) en la Estación Experimental de Aula Dei (EEAD),

CERTIFICA:

Que Don David Moret Fernández ha realizado bajo mi dirección el trabajo que, para optar al grado de Doctor Ingeniero Agrónomo, presenta con el título:

Efectos del laboreo sobre las propiedades hidrofísicas y balance hídrico del suelo durante el periodo de barbecho de una rotación cebada-barbecho en condiciones de secano semiárido del centro de Aragón.

Y para que así conste, firmo la presente Certificación en Zaragoza a veinticuatro de octubre de dos mil tres.

Carlos Cantero Martínez, Profesor Titular de Universidad en la Escuela Técnica Superior de Ingeniería Agraria de la Universidad de Lleida

CERTIFICA:

Que Don David Moret Fernández ha realizado bajo mi tutela, como ponente en el Departamento de Producción Vegetal y Ciencias Forestales de la Universidad de Lleida, el trabajo que, para optar al grado de Doctor Ingeniero Agrónomo, presenta con el título:

Efectos del laboreo sobre las propiedades hidrofísicas y balance hídrico del suelo durante el periodo de barbecho de una rotación cebada-barbecho en condiciones de secano semiárido del centro de Aragón.

Y para que así conste, firmo la presente Certificación en Lleida a veinticuatro de octubre de dos mil tres.

Agradecimientos

Después de cinco años viviendo y trabajando en Zaragoza quiero expresar mi más sincero agradecimiento a todas aquellas personas que de una manera u otra han intervenido en la Tesis o con quienes he compartido muy agradables momentos durante su realización.

En primer lugar, al Dr. José Luis Arrúe Ugarte como director de esta Tesis por haberme permitido desarrollar las ideas surgidas a lo largo de la misma, así como su entera disponibilidad y constante ayuda y estímulo.

Agradecer a mis compañeros de grupo de investigación, Ricardo, Mariví, Pepa y Jorge, por la ayuda siempre disponible en todo momento. Gracias también al resto de compañeros del Departamento de Edafología, Maribel, Tere López y Tere Guillamon, Mabel, Ana y Javier con quienes he compartido muy agradables ratos y unas excelentes costilladas y calçotadas.

A todas las personas de la Estación Experimental de Aula Dei con quienes he compartido buenos momentos y han ofrecido su ayuda desinteresadamente. Agradecer en especial al personal de mantenimiento (David, Enrique, Javier, Manolo y Tomás) por sus consejos prácticos a la hora de desarrollar las ideas surgidas a lo largo de la Tesis. Al personal de la casa de labor (José Andrés, Adolfo, Jesús, Miguel Ángel, Fernando y Andrés) por su colaboración en los trabajos de campo y al personal de administración (Marisa, Mª Pilar, Lola, Gonzalo, Armando…) por su simpatía siempre presente en todo momento. Agradecer también a los becarios del centro (Marías, Loreto, Jorge, Raquel, Ana, Sofía…) y demás personas (Aurora, Piluca, Carmen, Conchita……..) con quienes he compartido muy agradables ratos durante los cafés.

Agradecer también su compañía y amistad a los becarios del campus de Aula Dei (Yoli, Santi, Olga, Noe, Pili, entre otros).

A mis compañeros de los sucesivos pisos en los que he estado viviendo durante mi estancia en Zaragoza (Manu, Houssem, Yoana e Ichie) y en especial a las chicas

de la Casa Rosa (Ana, Viki, Carmen, Mabel, Piasca y Mareke) con quienes sigo viviendo muy a gusto.

A toda la gente que he ido conociendo durante mi estancia en Zaragoza: la gente del Comité, los compañeros del MRG, de la Vía, y un sinfín de personas que no nombro porque la lista sería interminable.

Finalmente, a mi familia por su cariño y su incondicional apoyo durante estos años.

Resum

L’objectiu del present treball ha estat investigar l’efecte del sistema de conreu i del guaret sobre les propietats hidrofísiques i el balanç d’aigua durant el període de guaret de la rotació cereal-guaret, en un secà semiàrid del centre d’Aragó, dintre d’un experiment a llarg termini. El sòl del camp experimental és franc (Xerollic Calciorthid) i té una profunditat útil de 70 cm. La precipitació mitjana anual és de 390 mm. Es va disposar de tres blocs de parcel·les, una amb conreu continuat (CC) amb ordi, i dues amb rotació ordi-guaret (CF), i es van comparar tres sistemes de conreu (conreu convencional, CT; conreu reduit (RT); i no conreu, NT) durant tres cicles de cultiu i guaret (1999-2000, 2000-2001 i 2001-2002) en ambdós sistemes de cultiu. Durant el període de guaret en CF es van realitzar mesures de densitat aparent (r_b), conductivitat hidràulica (K) y corba de retenció d’aigua al sòl a 2 i 40 cm de profunditat. Per les mesures de K, es va desenvolupar un infiltròmetre de disc que incorpora un sistema de Reflectometria de Domini Temporal (TDR) que permet una lectura automàtica de la infiltració. En el experiment es va utilitzar un sistema experimental de blocs incomplets. En total, durant el guaret de CF es van realitzar quatre mesures de propietat hidrofísiques: abans i després de les operacions primàries de conreu, després del conreu i les primeres pluges, i al final de guaret. El perfil d’humitat del sòl es va mesurar amb la tècnica TDR. Durant els períodes de cultiu es va també determinar la biomassa i el rendiment. Després de 8-10 anys d’assaig, r_b amb NT va ser més gran que l’observada amb CT i RT a 2 cm de profunditat. NT va presentar una més baixa humitat a saturació i aigua disponible per a les plantes, i una més baixa K degut a un menor número de macropors i mesopors. Les operacions primàries de conreu amb CT i RT van reduir la r_b, augmentant la porositat d’aireació i reduint l’aigua disponible per les plantes. Es va observar també una reducció del tamany de por representatiu i un augment del nombre de pors transmissors d’aigua, i per tant una més alta K. Les pluges després de les operacions de conreu van augmentar r_b de CT i RT en la superfície, lo que va reduir la porositat d’aireació i la K, a través de un més baix nombre de pors transmissors d’aigua. Les operacions primàries de conreu van augmentar de manera notable la tassa de evaporació d’aigua del sòl durant les primeres 24 h després del conreu. Les operacions secundàries de conreu van afavorir la conservació de l’aigua del sòl al reduir la tassa de evaporació en relació amb NT. L’eficiència del guaret per l’acumulació d’aigua al sòl (*PSE*) va ser baixa (11%), augmentant en aquells períodes quan la pluja era important en els últims dos mesos del guaret. El sistema de CF va conservar al final del guaret 22 mm més d’aigua que el sistema CC. Per una altra banda, el sistema de conreu no va tenir cap efecte sobre el *PSE*. L’aplicació del model de simulació SiSPAT per estimar el balanç d’aigua del període de guaret va permetre observar que, sense operacions de conreu durant el guaret, el sòl amb NT tendeix a evaporar més aigua que amb CT i RT, els quals afavoreixen el drenatge profund. Comparant la *PSE* mesurada al camp amb l’estimada mitjançant el model, es va observar que en anys amb una primera fase de guaret molt plujosa, les operacions de conreu afavoreixen les pèrdues d’aigua, reduint la *PSE*. El rendiment de l’ordi va ser més gran en els anys amb més abundants pluges efectives en primavera, essent, en conjunt, un 49% mes gran en CF que en CC. Per una altra banda, CC va tenir un rendiment 34% més gran que CF quan la producció de gra es va ajustar a una base anual considerant la precipitació entre dos collites consecutives i la duració del període de guaret en cada sistema. El sistema de conreu no va tenir cap efecte sobre el rendiment.

Resumen

El objetivo principal del presente trabajo ha sido evaluar el efecto del sistema de laboreo sobre las propiedades hidrofísicas y el balance de agua durante el periodo de barbecho de la rotación cereal-barbecho (cultivo de “año y vez”) en un secano semiárido del centro de Aragón como parte de un experimento de laboreo de larga duración. En el sitio experimental, el suelo, de textura franca (Xerollic Calciorthid), tiene una profundidad útil de 70 cm y la precipitación media anual es de 390 mm. Se dispusieron tres bloques de parcelas, uno con cultivo continuo (CC) de cebada y dos, contiguos a éste, en rotación “año y vez” (CF), y se compararon tres sistemas de laboreo (laboreo convencional, CT; laboreo reducido, RT; y no-laboreo, NT) durante tres ciclos de barbecho y cultivo (1999-2000, 2000-2001 y 2001-2002) en ambos sistemas de cultivo. Durante el periodo de barbecho en CF se efectuaron medidas de densidad aparente (r_b), conductividad hidráulica (K) y curva de retención de agua del suelo a 2 y 40 cm de profundidad. Para la medida de K se desarrolló un infiltrómetro de discos que incorpora un sistema de Reflectometría de Dominio Temporal (TDR) y permite la lectura automática de la infiltración. Las determinaciones, siguiendo un diseño de bloques incompletos, se efectuaron en cuatro momentos del barbecho: antes de labores primarias, inmediatamente después de estas labores, tras las primeras lluvias después de labores y al final del barbecho. El perfil de humedad del suelo (0-70 cm) se monitorizó durante el periodo experimental por TDR. Durante los periodos de cultivo, se determinó la biomasa y el rendimiento. Tras 8-10 años de ensayo, r_b en NT fue mayor que en CT y RT a 2 cm. NT presentó también a esa profundidad una menor humedad a saturación y agua disponible para las plantas, y una menor K debido a un menor número de macroporos y mesoporos. Las labores primarias aplicadas en CT (vertedera) y RT (chisel) redujeron r_b, aumentando la porosidad de aireación y reduciendo el agua disponible para las plantas. También se observó una reducción del tamaño del poro representativo y un aumento del número de poros transmisores de agua, y con ello una K más elevada. Las lluvias tras labores primarias aumentaron r_b en la superficie en CT y RT, lo que redujo la porosidad de aireación y la K, a través de un menor número de poros transmisores de agua. Las labores primarias incrementaron de manera notable la tasa de evaporación durante las primeras 24 horas tras labores. Sin embargo, las labores secundarias favorecieron la conservación del agua del suelo a medio plazo al reducir la tasa de evaporación con relación a NT. La eficiencia del barbecho para acumular agua en el suelo (*PSE*) fue baja (11 %), siendo mayor en periodos de barbecho con elevada pluviometría en los tres últimos meses del barbecho. Como promedio, el sistema CF almacenó al final del barbecho 22 mm más agua que el sistema CC. Por otro lado, el sistema de laboreo no tuvo efectos significativos sobre la eficiencia del barbecho. La aplicación del modelo SiSPAT para simular el balance de agua durante el barbecho permitió observar que, en ausencia de labores durante el barbecho, el suelo bajo NT tiende a evaporar más agua que en CT y RT, los cuales favorecen el drenaje profundo. Comparando la *PSE* medida en campo con la estimada por el modelo se observó que en años con una primera fase de barbecho muy lluviosa las labores favorecen las pérdidas de agua por evaporación, reduciéndose la *PSE*. El rendimiento de cebada fue mayor en años con abundantes lluvias efectivas en primavera, siendo, en conjunto, un 49% mayor en CF que en CC. Sin embargo, CC rindió un 34% más que CF cuando la producción de grano se ajustó a una base anual considerando la precipitación entre dos cosechas consecutivas y la duración del periodo de barbecho en cada sistema. El sistema de laboreo no tuvo ningún efecto significativo sobre el rendimiento.

Abstract

The main objectives of this research, as part of long-term tillage experiment, were: i) to evaluate the effects of three fallow tillage management systems (conventional tillage, CT, reduced tillage, RT, and no-tillage, NT) on soil hydrophysical properties and water balance during three long fallow periods (1999-2000, 2000-2001 and 2001-2002) in a dryland cereal-growing area of Central Aragon; and ii) to investigate the influence of those effects on the response of a winter barley crop in terms of growth, yield and water use efficiency. Soil at the research site, with an average annual precipitation of 390 mm, is a loam (fine-loamy, mixed thermic Xerollic Calciorthid). The study was conducted on three adjacent large blocks of plots, one under continuous cropping (CC) and two under a cereal-fallow (CF) rotation. Soil bulk density, r_b, soil water retention curve, $q(y)$, and soil hydraulic conductivity, $K(y)$, at –14, -4, -1 and 0 cm pressure head, and related hydraulic parameters were measured at 2 and 40 cm depth before and immediately after primary tillage, after post-tillage rains and at the end of fallow, according to an incomplet block design. An automated tension disc infiltrometer that measures the water level changes in the Mariotte-type supply reservoir via time domain reflectometry (TDR) was developed for measuring *K*. The soil water profile (0-70 cm) was monitored over the entire experimental period by TDR. During the growing seasons, crop above-ground biomas at different stages and yield were measured. After 8-10 years of trial, and compared with CT and RT, NT plots presented a more compacted topsoil, which resulted in a lower water content at saturation and a lower available water-holding capacity. Although a larger macropore size was observed under NT, *K* under this treatment was significantly lower than under CT and RT due to a lower number of water transmitting pores per unit area. In the short term, soil loosening by tillage increased the aeration porosity (pores > 300 μm) and decreased available water retention micropores (30-0.2 μm pores). Tillage also increased the number of water conducting mesopores, which increased *K*. The rainfall after primary tillage under CT and RT, increased the surface r_b, which reduced the aeration porosity and *K*, though out a decrease of number of water conducting pores. Primary tillage implemented in CT (mouldboard ploughing) and RT (chiselling) 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 storage (*SWS*) at the end of fallow. Overall, fallow precipitation storage efficiency (*PSE*) was low (11% on average) and increased when most of fallow seasonal precipitation occurred in the last three months of the fallow period. Neither *SWS* nor *PSE* under CF were significantly affected by the tillage system. The application of the SiSPAT model to simulate the water balance during long fallow allowed to observe that the NT soil tends to evaporate more water than the CT and RT soils. The comparison between measured and estimated *SWS* at the end of a wet-autumn fallow showed that *PSE* under CT and RT was about half of the efficiency predicted by the model. On the assumption that soil properties measured under the three tillage treatments do not change over the whole fallow period, the SiSPAT model estimated that about 80% of fallow seasonal precipitation 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. On average, and regardless of tillage, CF yielded 49% more grain than CC. However, CC yielded 34% more grain than the CF rotation when yields were adjusted to an annual basis including the length of fallow. No differences in crop yield were observed among tillage treatments in the study period.

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Lista de símbolos y abreviaturas

AWHC	Contenido de agua disponible para las plantas (m^3 m^{-3})
c	Velocidad de propagación de la luz en el vacío (3 x 10^8 m s^{-1})
C_0	Radio máximo de poro para una tensión y determinada (mm)
CC	Sistema de cultivo anual
CF	Sistema de cultivo de “año y vez”
CT	Sistema de laboreo convencional
DM	Biomasa del cultivo (g m^{-2})
(e^*-e)	Déficit de presión de vapor medio diurno (Pa)
E	Pérdidas de agua del suelo (mm)
E_h	Evaporación acumulada 24 horas después de las labores (mm)
E_r	Tasa diaria de pérdidas de agua del suelo (mm día^{-1})
EDP	Diámetro de poro equivalente (μm)
ER	Lluvia efectiva (> 10 mm día^{-1})
ET	Evapotranspiración o agua utilizada por el cultivo (mm)
ET_0	Evapotranspiración de referencia (mm)
FS	Segunda fase del periodo de barbecho largo (16-18 meses) (desde finales de otoño hasta principios de verano)
g	Aceleración debida a la fuerza de la gravedad (9.8 m s^{-2})
G	Flujo de calor del suelo (W m^{-2})
h	Tensión de agua en el suelo (kPa, cm)
h_g	Factor de escala en le modelo de van Genuchten de curva de retención de agua en el suelo (m)
HF	Primera fase del periodo de barbecho largo (16-18 meses) (desde cosecha hasta finales de otoño)
I	Infiltración acumulada de agua en el suelo (mm)
k	Coeficiente de eficiencia del cultivo (Pa)
K	Conductividad hidráulica del suelo (mm s^{-1}, cm s^{-1})
K_i, K_{sat}	Conductividad hidráulica del suelo a tensión *i* y a saturación, respectivamente (mm s^{-1}, cm s^{-1})
K_c	Conductividad hidráulica a saturación de la costra superficial del suelo (mm s^{-1}, cm s^{-1})
L	Longitud de una sonda TDR (m)
m	Factor de forma en el modelo de van Genuchten (1980) de curva de retención de agua en el suelo (-)
n	Factor de forma en el modelo de van Genuchten (1980) de curva de retención de agua en el suelo (-)
N_{WL}	Número de poros efectivos de transmisión de agua por unidad de superficie de suelo según Watson y Luxmoore (1986) (poros m^{-2})
N_y	Número de poros efectivos de transmisión de agua de radio l_y por unidad de superficie de suelo (poros m^{-2})
N_{Dy}	Número de poros efectivos de transmisión de agua de radio l_{Dy} por unidad de superficie de suelo (poros m^{-2})
NER	Lluvia no efectiva (< 10 mm día^{-1})
NT	Sistema de no-laboreo o siembra directa
P	Precipitación (mm)
P_F	Precipitación registrada durante el periodo de barbecho (mm)

P_{TS}	Precipitación desde la fecha de labores primarias en el sistema de cultivo continuo hasta la siembra del año siguiente (mm)
PASW	Agua del suelo disponible para las plantas (mm)
PUE	Eficiencia de uso de la precipitación (kg ha^{-1} mm^{-1})
PSE	Eficiencia de almacenamiento de agua de lluvia durante el periodo de barbecho (%)
PT	Transductores de presión
Q	Caudal de infiltración de agua en el suelo (cm^3 s^{-1})
Rn	Radiación neta (W m^{-2})
RPSE	Eficiencia de almacenamiento de agua de lluvia durante el barbecho largo (16-18 meses) en relación al barbecho corto (5-6 meses) (%)
RT	Sistema de laboreo reducido
S	Sortividad del suelo (mm $s^{-0.5}$)
S_0	Sortividad del suelo a saturación (mm $s^{-0.5}$)
SiSPAT	Simple-Soil-Plant-Atmosphere-Transfer model
SS	Tercera fase del periodo de barbecho largo (16-18 meses) (desde principios de verano hasta siembra)
SWS	Almacenamiento de agua en el suelo (mm)
t	Fecha de labores secundarias
t	Tiempo (h, s)
T	Transpiración del cultivo (mm)
T	Fecha de labores primarias.
T_{soil}	Temperatura del suelo (°C)
TE	Eficiencia de transpiración (kg ha^{-1} m^{-1})
TDR	Reflectometría de Dominio Temporal.
v	Velocidad de propagación de una onda electromagnética en un medio dieléctrico (m s^{-1})
WSE	Eficiencia de almacenamiento de agua en el suelo (%)
WSE_M,, WSE_M,	Eficiencia de almacenamiento de agua en el suelo medida y simulada por el modelo SISPAT, respectivamente (%)
WUE_b	Eficiencia de uso de agua del cultivo para la producción de biomasa (kg ha^{-1} mm^{-1})
WUE_g	Eficiencia de uso de agua del cultivo para la producción de grano (kg ha^{-1} mm^{-1})
z_{om}	Longitud de rugosidad (m)
a	Albedo del suelo desnudo (-)
$\bar{a}_{x,y}$	Pendiente del tramo lineal entre las tensiones *x* e *y* en el modelo exponencial de conductividad hidráulica de Reynolds y Elrick (1991)
b	Factor de forma en el modelo de Brooks y Corey (1964) de curva de conductividad hidráulica del suelo (-)
DS	Cambios en el contenido de humedad en el perfil del suelo (mm)
DSWS	Agua adicional almacenada en el suelo durante el periodo de barbecho largo (16-18 meses) con respecto al barbecho corto (5-6 meses) (mm)
e	Constante dieléctrica de un medio (+)
e_{air}	Constante dieléctrica del aire (1)
e_{TDR}	Constante dieléctrica medida por TDR (+)
e_{water}	Constante dieléctrica del agua (81 a 25 °C)
f	Potencial de flujo mátrico del suelo (cm^2 s^{-1})

j	Contribución de diferentes clases de tamaño de poros del suelo al flujo de agua a saturación (%)
l	Conductividad térmica aparente del suelo (W m^{-1} K^{-1})
l_y	Tamaño de poro representativo de transmisión de agua a tensión y (mm)
l_{Dy}	Tamaño de poro representativo de transmisión de agua para dos tensiones consecutivas (mm)
m	Viscosidad dinámica del agua (g cm^{-1} s^{-1})
r	Densidad (g cm^{-3})
r_b	Densidad aparente del suelo (g cm^{-3})
r_s	Densidad real del suelo (2.65 g cm^{-3})
s	Tensión superficial del agua (g s^{-2})
q	Contenido volumétrico de humedad del suelo (m^3 m^{-3})
q_r	Contenido volumétrico de humedad residual del suelo (m^3 m^{-3})
q_{sat}	Contenido volumétrico de humedad del suelo a saturación (m^3 m^{-3})
q_{FC}	Contenido volumétrico de humedad del suelo a capacidad de campo (y = -10 kPa) (m^3 m^{-3})
q_{PWP}	Contenido volumétrico de humedad del suelo a punto de marchitez permanente (y = -1500 kPa) (m^3 m^{-3})
q_{WL}	Porosidad efectiva de transmisión de agua en el suelo para dos tensiones consecutivas según Watson y Luxmoore (1986) (m^3 m^{-3})
q_x	Porosidad efectiva de transmisión de agua en el suelo para dos tensiones consecutivas (m^3 m^{-3})
y	Tensión de agua en el suelo (kPa, cm)
x	Porosidad total del suelo (m^3 m^{-3})

Capítulo 1

Introducción general

Introducción general

1. Los secanos semiáridos de la zona centro del valle del Ebro.

En Aragón, donde la superficie cultivada en secano representa aproximadamente el 75 % de la superficie agrícola total (Gobierno de Aragón, 2001), gran parte de los cultivos herbáceos se realizan en zonas de clima árido o semiárido, con una pluviometría media anual inferior a 500 mm. La escasa precipitación y la irregular distribución de ésta a lo largo del año constituyen los principales factores limitantes de la producción agrícola de secano, cuyas consecuencias son bajos rendimientos y alta variabilidad interanual (McAneney y Arrúe, 1993).

La cebada, con una superficie cultivada de aproximadamente el 30 % (380.000 ha) de la superficie total agrícola de Aragón, es el cultivo más extendido en esta comunidad (Gobierno de Aragón, 2001). El rendimiento medio en grano de este cultivo en las zonas de secano semiárido oscila entre los 1500 y 2000 kg ha^{-1}. El sistema de cultivo tradicional en estas condiciones es la rotación cebada-barbecho, o cultivo de "año y vez", que incluye un largo periodo de barbecho de 16 a 18 meses de duración y que transcurre desde la cosecha (junio-julio) hasta la siembra (noviembre-diciembre) del año siguiente. Los principales motivos para la utilización de este tipo de barbecho son el aumento del agua disponible para el cultivo al final del mismo, la mejora de la fertilidad de suelo y la reducción de la incidencia de malas hierbas, plagas y enfermedades que puedan afectar al siguiente cultivo. A esta justificación agronómica del uso del barbecho, hay que añadir la relacionada con el cumplimiento de las directivas de la Política Agraria Comunitaria (PAC), que ha hecho renacer el "interés" por esta práctica en los últimos años.

En los secanos semiáridos del centro del valle del Ebro, la aplicación de un pase con arado de vertedera, como labor primaria, seguido por varios pases de cultivador, como labores secundarias, sigue siendo el sistema convencional de manejo del suelo durante el periodo de barbecho en el sistema de cultivo de "año y vez". Este manejo viene justificado porque, en principio, mejora la infiltración del agua de lluvia tras las labores, elimina malas hierbas y favorece la mineralización de la materia orgánica del suelo. Sin embargo, el uso del laboreo tradicional en los secanos del valle del Ebro ha experimentado en las últimas décadas una progresiva regresión, a consecuencia de la disminución del precio del grano y del aumento de los costes de combustible y otros insumos. Ello ha propiciado la búsqueda de prácticas alternativas de manejo de suelo encaminadas a aumentar los rendimientos de cosecha y a reducir los costes de producción. En este sentido, es a principios de los años 90 del pasado siglo cuando comienza a considerarse la posibilidad de sustituir, en los sistemas de cultivo de "año y vez" de los secanos semiáridos de la zona centro del valle del Ebro, el laboreo convencional por prácticas de laboreo de conservación (mínimo laboreo y no laboreo) que reducen el número de labores previas a la siembra y permiten un mayor ahorro energético (Arrúe y López, 1991). A esta consideración de índole económica habría que añadir el cumplimiento de las medidas agroambientales de la PAC, orientadas a la protección del suelo a través de la sustitución de los sistemas tradicionales de laboreo, que favorecen las pérdidas de suelo por erosión hídrica y eólica, por prácticas agrícolas respetuosas con el medio ambiente como es el caso del laboreo de conservación.

2. Limitaciones de los sistemas tradicionales de cultivo

Dada la importancia que el sistema de cultivo tradicional de "año y vez" tiene en el centro del valle del Ebro, se ha planteado la necesidad de comprobar si esta rotación es un sistema agronómicamente sustentable en relación con la rentabilidad de las explotaciones agrícolas de secano, el aprovechamiento del agua de lluvia o la mejora de la fertilidad física y química del suelo. De los resultados obtenidos en los escasos estudios realizados hasta el presente sobre esta problemática (McAneney y Arrúe, 1993;, López et al.,1996; Austin et al., 1998a; Austin et al., 1998b) puede concluirse que la práctica del barbecho en la rotación cereal-barbecho es ineficiente desde el punto de vista de la conservación del agua del suelo cuando se compara con un sistema anual de monocultivo, aún cuando las estimaciones indican que el rendimiento en grano de una rotación de cebada-barbecho puede ser, por término medio, un 15 % superior al obtenido con un cultivo continuo de cebada (Austin et al., 1998a). Este incremento potencial, debido principalmente al incremento del agua almacenada en el suelo en el sistema de "año y vez" (un 6.2% con respecto al cultivo anual), supondría un aumento de unos10 kg ha^{-1} de grano por mm de agua conservada (Austin et al., 1998b). Según estos autores, la decisión de utilizar la rotación cereal-barbecho o un cultivo continuo vendría definida principalmente por la lluvia recibida en los tres últimos meses del barbecho, de modo que en años con otoños lluviosos, un cultivo con un barbecho corto (5-6 meses tras la cosecha) podría resultar viable, al igual que en años con otoños secos, donde existiría un alto riesgo de fallos de siembra, un barbecho largo podría favorecer el almacenamiento de agua en el suelo en el momento de la siembra, lo que reduciría dichos riesgos (Austin et al., 1998a). Así, pues, de acuerdo con los resultados mencionados, la viabilidad económica del sistema de cultivo de "año y vez" continúa siendo cuestionable, ya que, además, para que fuera rentable, en sentido estricto, los rendimientos del mismo deberían doblar como mínimo los obtenidos con un sistema de cultivo continuo (Austin et al., 1998a).

Ante esta disyuntiva, una posible solución para mejorar la eficiencia en el uso de la precipitación recibida durante el periodo de barbecho podría encontrarse en una intensificación de los actuales sistemas de cultivos extensivos de secano incluyendo nuevas rotaciones, tal como se ha planteado en otras regiones semiáridas (Farahani et al., 1998 López-Bellido et al., 2000; Díaz-Ambrona and Mínguez, 2001;). Sin embargo, la eficiencia del barbecho para conservar agua no sólo depende del tipo de suelo y del régimen pluviométrico sino también del manejo del suelo (Lampurlanés et al., 2002). Así, pues, el laboreo, práctica de manejo de suelo que altera las propiedades de retención y transmisión de agua en el suelo, interviene directamente sobre los componentes del balance del agua (almacenamiento, evaporación y drenaje) (Singh et al., 1996) y, por tanto, sobre la economía del agua durante el barbecho. Sin embargo, aunque un incremento en la porosidad y en la continuidad de los poros aumenta el flujo y la capacidad de almacenamiento de agua en el suelo, también puede favorecer la evaporación del agua acumulada en profundidad (Baunmhardt and Jones, 2002). Por ello, un conocimiento adecuado del comportamiento de las propiedades hidrofísicas del suelo resulta imprescindible si queremos determinar qué prácticas de laboreo durante el barbecho pueden conducir a unas condiciones óptimas de crecimiento y desarrollo del cultivo.

Hasta la fecha son escasas las investigaciones realizadas en las zonas semiáridas del valle del Ebro en las que se hayan cuantificado los efectos de diferentes sistemas de laboreo sobre las propiedades físicas del suelo y su repercusión en los componentes del balance del agua. A este respecto, López (1993), en uno de los primeros estudios de comparación de sistemas de laboreo realizados en la zona, observó que tras dos años de ensayo, el sistema de no-laboreo aumentaba la resistencia a la penetración del suelo frente al laboreo reducido y el laboreo tradicional. Similares resultados obtuvo Lampurlanés (2000) al comprobar que la densidad aparente del suelo bajo no-laboreo era mayor que en tratamientos de mínimo laboreo y subsolado. Estas diferencias de compactación entre suelos labrados y no labrados se deben a la modificación de la estructura del suelo por efecto de las labores anuales. Ello supone un aumento inicial de la porosidad, que posteriormente se reduce y estabiliza debido a la reconsolidación del suelo que tiene lugar por la acción de las lluvias y los consiguientes ciclos de humectación y desecación del suelo (Green et al., 2003). Los cambios de porosidad del suelo afectan, a su vez, a la retención humedad y a la tasa de infiltración y movimiento del agua en el suelo. Así, mientras López (1993) no observó, tras dos años de ensayo, un empeoramiento en la conductividad hidráulica del suelo a saturación bajo no-laboreo con respecto a sistemas de laboreo reducido y convencional, Lampurlanés (2000) si encontró en siembra directa, con una mayor compactación del suelo, una menor conductividad hidráulica que bajo mínimo laboreo y que el incremento de ésta tras las labores se reducía progresivamente durante el barbecho por el efecto de la lluvia. En cuanto a la influencia de los diferentes sistemas laboreo sobre la capacidad de retención de agua en el suelo, aún no se ha realizado ningún estudio en el centro de Aragón sobre este particular aspecto, siendo escasos los llevados a cabo en otras regiones. Según el trabajo de Evett et al. (1999), en las Grandes Llanuras de Estados Unidos, frente a sistemas de laboreo convencionales, la siembra directa tiende a reducir la retención de agua en condiciones próximas a saturación y a incrementar la misma a tensiones inferiores a 7 kPa.

Así, pues, a tenor de los efectos potenciales que los sistemas de laboreo tienen sobre el régimen hídrico del suelo y de las exigencias de una agricultura moderna y sostenible en cuanto a reducción de costes de producción y mejora de la calidad del suelo, se ha planteado la necesidad de evaluar las ventajas que los sistemas de laboreo de conservación presentan frente al laboreo convencional, para la conservación del agua en el suelo durante el barbecho. Por otro lado, y tal como se ha indicado, los estudios de campo realizados en el centro de Aragón han sido hasta la fecha escasos e insuficientes. López et al. (1996) observaron, comparando sistemas de laboreo convencional y laboreo de conservación, que mientras los sistemas de labranza con vertedera y chisel conservaban al final del barbecho cantidades similares de agua, los efectos del sistema de siembra directa resultaron inconsistentes. Por su parte, Lampurlanés et al. (2002) observaron, en otra zona semiárida del valle del Ebro, que el sistema de no-laboreo, sin eliminación de los residuos superficiales de post-cosecha, era potencialmente el más eficiente en la conservación del agua del suelo al final del periodo de barbecho. Por otra parte, y al margen del efecto beneficioso sobre la conservación del agua del suelo, el laboreo tiene también repercusiones sobre los rendimientos del cultivo. Así, pues, López y Arrúe (1997) concluyeron que el laboreo reducido era la mejor alternativa al laboreo convencional para mantener la producción en los secanos semiáridos de la zona centro del valle del Ebro. Similares resultados obtuvieron Angás (2001) y Lampurlanés et al. (2002), quienes observaron que el laboreo de conservación aplicado en sistemas agrícolas de secano en condiciones semiáridas de la zona oriental del valle del Ebro mejoraba el rendimiento del cultivo de cebada, especialmente en años secos, en los que el laboreo convencional tenía un comportamiento negativo.

3. Objetivos y estructura del trabajo

Partiendo de la base de que el agua es el principal factor limitante de la producción agrícola en las zonas semiáridas de secano, como es el caso del centro de Aragón, resulta esencial investigar aquellas prácticas agronómicas que puedan reducir las pérdidas de agua del suelo por evaporación. Así, pues, el objetivo general del presente trabajo ha sido evaluar, en las condiciones de secano semárido del centro de Aragón, los efectos del laboreo convencional (CT) y del laboreo de conservación -mínimo laboreo (RT) y no-laboreo (NT)- sobre las propiedades hidrofísicas y el balance de agua del suelo a lo largo del periodo de barbecho que caracteriza el sistema de cultivo de “año y vez”, así como las repercusiones de dichos efectos sobre el crecimiento y rendimiento de un cultivo de cebada, tanto bajo cultivo continuo como en la rotación cebada-barbecho.

El trabajo de campo del presente estudio se ha llevado a cabo entre agosto de 1999 y noviembre de 2002. En este periodo, que incluye tres ciclos de cultivo con sus respectivos periodos de barbecho, se han desarrollado cuatro objetivos particulares según se detalla a continuación.

Con el fin de interpretar el efecto de los diferentes sistemas de laboreo sobre la dinámica del agua en el suelo a lo largo del periodo de barbecho en el sistema de “año y vez”, el primer objetivo ha consistido en estudiar para cada uno de los tratamientos la evolución de las principales propiedades hidráulicas del suelo (conductividad hidráulica y curva de retención de humedad del suelo) a lo largo del periodo de barbecho (***Capítulo 4***). En el caso de las medidas *in situ* de la conductividad hidráulica del suelo, éstas se han realizado mediante un nuevo sistema de medida de infiltración desarrollado al efecto y compuesto por un infiltrómetro de disco asociado a un sistema TDR (Reflectometría de Dominio Temporal), que permite automatizar las lecturas y eliminar errores de medida (***Capítulo 2***). Asimismo, y dado que las labores reducen la resistencia del suelo a la penetración por un mayor esponjamiento del mismo, se ha estudiado el efecto del peso del infiltrómetro sobre las medidas de conductividad hidráulica del suelo, a fin de valorar los posibles errores cometidos en dichas medidas en suelos recientemente labrados (***Capítulo 3***).

Un segundo objetivo ha sido estudiar el efecto del sistema de laboreo sobre la dinámica del contenido de agua del suelo a lo largo del periodo de barbecho en el sistema de cultivo de “año y vez” y evaluar, frente al sistema de cultivo continuo, la eficiencia del barbecho en la rotación cebada – barbecho en el almacenamiento de agua (***Capítulo 5***).

A partir de los datos agrometeorológicos y de las medidas de propiedades hidrofísicas registradas a lo largo de los tres periodos de barbecho “año y vez” caracterizados, se ha calibrado y validado el modelo de simulación SiSPAT (Braud et al., 1995), para lo cual se han utilizado también los datos de humedad, temperatura y flujo de calor del suelo registrados durante los tres años experimentales. La posterior aplicación del modelo SiSPAT a los datos de campo tuvo como objetivo estimar las pérdidas potenciales de agua por evaporación y drenaje profundo que pueden tener lugar durante el barbecho en el caso hipotético de que, durante dicho periodo, no se realice ningún tipo de labor agrícola y valorar nuevas alternativas a los sistemas tradicionales de laboreo, tales como el retraso de las labores o la alternancia de sistemas de laboreo en función de la pluviometría (***Capítulo 6***).

Finalmente, tras examinar el efecto de los diferentes sistemas de cultivo y tratamientos de laboreo sobre la conservación del agua en el suelo al final de los periodos de barbecho, el último objetivo ha consistido en evaluar la influencia de las diferentes prácticas de cultivo sobre el crecimiento, rendimiento y eficiencia en el uso del agua del cultivo de cebada en condiciones semiáridas de secano semiárido en la zona centro del valle del Ebro (***Capítulo 7***). En la sección final de Conclusiones generales se resumen los principales resultados obtenidos en la Tesis.

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Capítulo 2

TDR Application for Automated Water Level Measurement from Mariotte Reservoirs in Tension Disc Infiltrometers

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Submitted to: *Journal of Hydrology*

TDR Application for Automated Water Level Measurement from Mariotte Reservoirs in Tension Disc Infiltrometers

ABSTRACT

This paper describes the use of an automated method of measuring water level changes in Mariotte-type reservoirs via time domain reflectometry (TDR) and demonstrates its field application for measurements of soil hydraulic properties. The method is based on the assumption that the travel time of a TDR pulse propagating along a transmission line immersed in an air-water medium is the summation of the pulse travel times in the air and water phases. A TDR cable tester generates a pulse that propagates through a three-rod probe traversing the centre of the Mariotte reservoir from top to bottom. The reflection of the pulse is automatically transferred to a computer for waveform analysis with the water level being a simple function of probe length and the air, water, and air-water medium dielectric constants as measured by the cable tester. Water level measurements obtained with the TDR technique showed close agreement with those obtained using visual and pressure transducer procedures. The advantages of this TDR method over more traditional methods was demonstrated in a field experiment using a tension disc infiltrometer. The new approach allows for automated water level measurements and is simple, accurate and easy to implement. Moreover, it allows for simultaneous TDR measurements of both water flow and volumetric water content of soil below the infiltrometer disc.

1. Introduction

Accurate characterisation of soil hydraulic properties is crucial to solving many hydrological, engineering, and environmental issues linked to soil water storage and transport in the vadose zone. In practice, this is achieved using field determinations of transient and steady-state infiltration rates of water into the soil, either under positive or negative head conditions (Angulo-Jaramillo et al., 2000). Both methods involve measuring the change of water level in a water-supply reservoir. Generally, this is done by visually noting the water level drop in a Mariotte column. However, this practice requires constant vigilance since visual readings have to be made at constant intervals and sometimes over long periods of time as in the case of slowly permeable clay soils. In other situations, when using early-time transient flow to infer soil hydraulic properties (Vandervaere et al., 1997), initial infiltration rates can be too rapid to be recorded with the required precision.

Over the last decade, the tension disc infiltrometer (Perroux and White, 1988) has become a popular tool in the study of saturated and near saturated soil water flows (Angulo-Jaramillo et al., 2000). To overcome the limitations of the standard visual technique, automated tension infiltrometers have been configured with either two gage transducers (Ankeny et al., 1988) or a single differential transducer (Casey and Derby, 2002). Though these infiltrometers are capable of providing accurate water level measurements, they depend upon accurate calibration.

When estimating soil hydraulic properties from disc infiltrometer measurements, determination of the initial and final soil volumetric water content below the infiltrometer disc is also required. This is usually done by extracting soil cores, an exacting and laborious task but one that could also be achieved using time domain reflectometry (TDR), a relatively new and highly accurate technique now widely used in many soil science and hydrology laboratories (Jones et al., 2002). Some studies have already explored the combined use of tension disc infiltrometry and TDR measurements of soil water content (Vogeler et al., 1996; Schwartz and Evett, 2002). The present study further develops this idea more fully in exploiting TDR for the infiltration measurements themselves.

TDR technology has also been used to measure the elevation of ground water table depths (O’Connor and Dowding, 1999) and the water level in tanks collecting surface runoff from erosion field plots (Thomsen et al., 2000). In these and other applications, such as the “guided microwave” devices commercially available for level measurement of fluids in industrial containers, the measurement principle is the location of the TDR voltage reflection at the air-medium interface. However, errors are possible if the operator does not correctly identify such reflections, as can happen when TDR signatures are visually analysed to locate the air-water interface in piezometric tubes (O’Connor and Dowding, 1999). In contrast, the standard TDR method for automated measurement of soil water content considers the travel time of the TDR pulse along the whole length of the transmission line. We develop a similar approach here for the measurement of water level changes in order to calculate infiltration rates from a disc infiltrometer.

The objectives of this research were twofold: firstly, to test the use of TDR for automated, unattended measurement of water level changes in Mariotte-type reservoirs, and secondly, to demonstrate its field use with a tension disc infiltrometer to provide simultaneous TDR measurements of both water flow and soil water content.

2. Materials and methods

2.1. Theory

TDR relies on the determination of the propagation velocity of electromagnetic waves along parallel metallic probes embedded in the medium of interest. The fundamental physical property affecting the pulse transit time is the dielectric property of the medium with the propagation velocity (n) expressed as :

$$v = \frac{c}{\sqrt{e}} \tag{2.1}$$

where c is the velocity of light in free space (3 x 10^8 m s^{-1}) and e is the relative dielectric constant of the medium (Topp et al., 1980). By definition, the propagation velocity (n) along a TDR probe of length L is given in terms of the pulse transit time, t, and the path length, $2L$ (Dalton, 1992) as

$$v = \frac{2L}{t} \tag{2.2}$$

Equating Equation (2.1) and Equation (2.2) and solving for the transit time gives

$$t = \frac{2L\sqrt{e}}{c} \tag{2.3}$$

In the case of a TDR probe vertically inserted in a stratified medium with different phases the measured total travel time of the TDR pulse is a summation of the travel times in the different phases (Ferré et al., 1996):

$$t = \Sigma_i t_i \tag{2.4}$$

where the subscripts refer to the different phases. In the case of a TDR probe of length L traversing from the top to the bottom of a Mariotte reservoir of height L partially filled with water (Fig. 2.1) we obtain

$$t = \frac{2L\sqrt{e_{TDR}}}{c} = \frac{2x\sqrt{e_{air}}}{c} + \frac{2(L-x)\sqrt{e_{water}}}{c} \tag{2.5}$$

where e_{TDR} is the apparent dielectric constant measured by the TDR cable tester; e_{air} and e_{water} are the relative dielectric constants of air and water measured previously with the same probe; and x is the probe length above water level.

Solving the equality (2.5) for x we obtain

$$x = L\frac{\sqrt{e_{TDR}} - \sqrt{e_{water}}}{\sqrt{e_{air}} - \sqrt{e_{water}}} \tag{2.6}$$

2.2. TDR-based water level sensing set-up: probe design and waveform analysis

On the basis of the above theoretical considerations, this paper presents a new system for automated water level measurements in a Mariotte column (e.g. the water- supply reservoir of a tension disc infiltrometer using TDR (Fig. 2.1). This

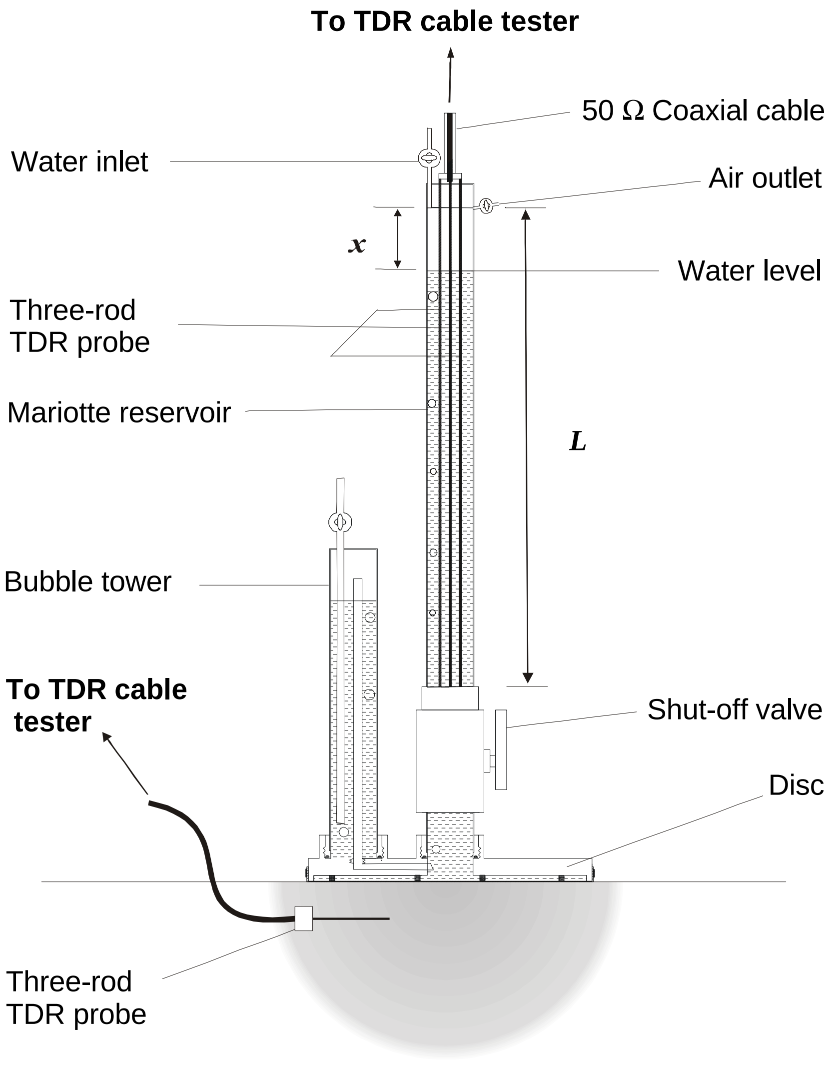

Figure 2.1. Cross section of a tension disc infiltrometer configured with a TDR probe inside the water-supply reservoir

application comprises a three-rod coaxial TDR probe placed in the centre of the water reservoir and connected to a TDR pulser (Tektronix 1502C Metallic Time Domain Reflectometer) equipped with a SP232 serial communication port. The probe is firmly fixed to the water reservoir by means of an epoxy casing at the top and a PVC rod of 12 mm of diameter traversing the reservoir at the bottom. The cable tester generates electromagnetic pulses at predetermined intervals that propagate through the water reservoir along the probe. Reflections of the pulse propagate back to the receiving unit in the TDR pulser. The waveform is then transferred to the computer and automatically analysed using the software WinTDR'98 (Or et al., 1998).

The waveform characteristics of several three-wire TDR probe designs with different wire material (steel, tin and copper) and geometrical configurations were investigated before choosing copper rods with a diameter of 1.6 mm and a separation of 10 mm for the outermost rods.

To reduce conductive losses and improve the quality of the TDR waveforms and their analysis by using the double-reflection procedure (Heimovaara, 1993), probe rods were insulated with polyolefin heat-shrink tubing having a wall thickness of 0.5 mm. Figure 2.2 shows the effect of this type of coating. For a Mariotte reservoir full of water and with a probe without coating, the signature of the second reflection is poorly defined (Fig. 2.2a). By contrast, the definition substantially improves when the same probe is coated (Fig. 2.2b, waveform III). This improvement, which is maintained as the water reservoir empties (Fig. 2.2b), substantively improves the accuracy in finding the second reflection point on the wave trace by using the tangent lines procedure with either the classical sloped line method or the flat line method as designed in WinTDR'98 for well defined waveforms (Or et al., 1998). Once the apparent dielectric constant of the air - water medium within the water reservoir, e_{TDR} , is obtained via Equation (2.3), the water level height $(L\text{-}x)$ is calculated from Equation (2.6). Values of e_{air} and e_{water} are measured with the

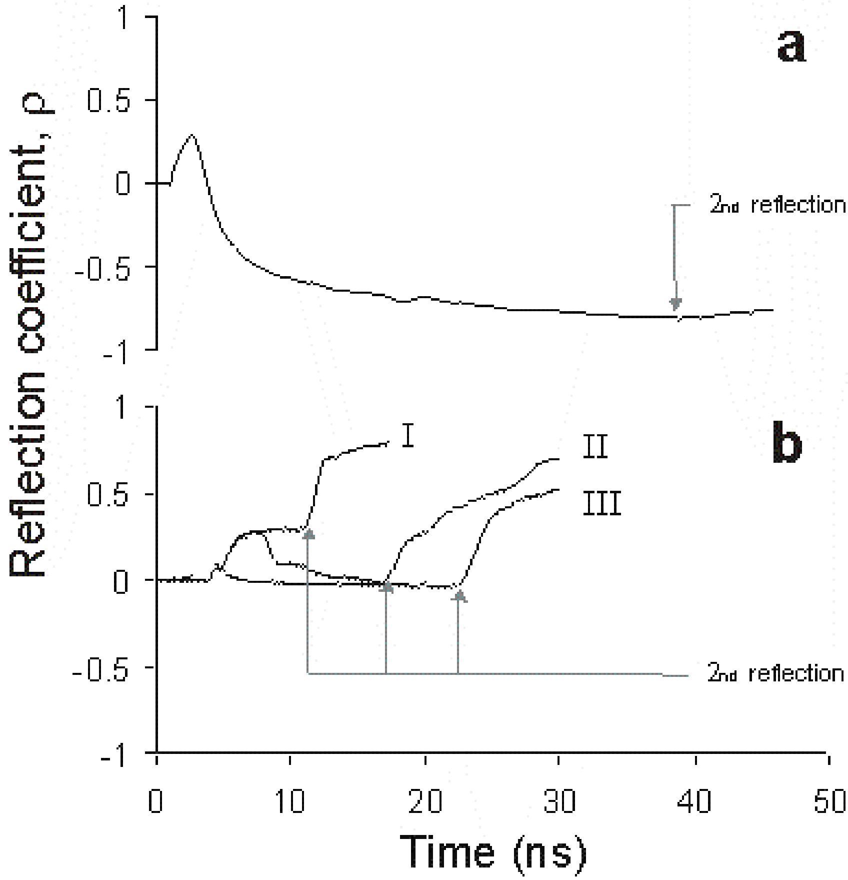

Figure 2.2. Comparison of TDR signatures for the three-rod probe developed to measure water level changes in a Mariotte reservoir: (a) probe with uncoated rods and reservoir full of water; (b) probe with rods coated with polyolefin tubing and reservoir empty (I), half-full of water (II) and full of water (III).

reservoir empty and full of water, respectively, immediately prior to the experimental runs.

2.3. Performance and field application

In order to evaluate the capability of the new TDR-based water level sensing technique for in situ automated water flow measurement by tension disc infiltrometry, two experiments were conducted. In both tap water with an electrical conductivity of 1.14 dS m^{-1} was used.

The first experiment was undertaken in the laboratory to test the performance and precision of the proposed TDR application under ideal conditions for measuring the water level in Mariotte reservoirs. TDR was compared with the standard visual technique, with readings made to the nearest millimetre, and a single differential pressure transducer. To this end, a vertical water reservoir, consisting of a 90 cm tube made of clear methacrylate plastic with 4.2 cm of internal diameter, was equipped with a coated three-wire TDR probe 86.5 cm long similar to that described previously (Fig. 2.1). A differential pressure transducer (model 26PCDFA6D, Microswitch, Honeywell) was installed at the bottom of the reservoir and calibrated as described by Casey and Derby (2002). A transparent calibrated measuring tape was externally attached to the reservoir wall for visual water level measurements. To allow for stationary water level measurements, the reservoir was closed at the bottom by means of a rubber stopper having a PVC stopcock. Simultaneous visual, pressure transducer and TDR-based depth measurements were made at intervals of approximately 5-10 cm, from 0 cm (reservoir full of water) down to 86.5 cm (reservoir full of air). This procedure was repeated twice.

A second experiment to demonstrate the field use of the new TDR application was also carried out. It consisted of measuring the infiltration rate of a recently tilled loamy soil at a water pressure head (y) of 0 cm using a 0.25 m diameter tension disc infiltrometer (Perroux and White, 1988). In this case, the TDR instrumented Mariotte column used in the laboratory experiment acted as the water-supply reservoir. As in the laboratory, it was also equipped with a measuring tape and a calibrated single differential transducer. Prior to the infiltration measurements, the reservoir was filled with water in situ by closing both the air-inlet stopcock at the bubbling tower and the valve between the reservoir and the base of the disc (Fig. 2.1). Then, opening the air-outlet and water-inlet stopcocks at the top the reservoir allows air to evacuate while water is poured in to rapidly fill the Mariotte reservoir. The base of the disc was covered with a nylon cloth of 20-μm mesh and a thin layer of commercial sand (80-160 μm grain size) poured onto the soil surface to ensure good contact between the disc and the soil.

For the imposed tension, and taking into account the infiltration surface area and the cross sectional area of the reservoir tube and that of the probe rods, the cumulative infiltration was calculated from water-level drop in the reservoir every 30 seconds by the visual, pressure transducer and TDR methods.

Prior to the infiltration test, a TDR probe of three stainless steel rods (diameter: 2 mm; length: 100 mm; spacing for the outermost rods: 25 mm) was carefully inserted horizontally into the soil beneath the infiltrometer disc at a depth of 4 cm to monitor the volumetric water content of soil (q) (Fig. 2.1).

Six additional infiltration tests were performed also at $y = 0$ mm with the aim of testing the suitability of the TDR technique against the more common gravimetric method of obtaining the final water content of soil below the infiltrometer. At the completion of each test (steady-state infiltration rate), the volumetric water content of a surface soil core (50 mm in diameter by 50 mm height) was determined gravimetrically.

TDR measurements of both cumulative infiltration and q were synchronously and automatically made every 30 seconds using WinTDR’98 (Or et al., 1998). To this end, the two TDR probes were connected to a multiplexer (model SDMX50, Campbell Scientific Inc.).

3. Results and discussion

Figure 2.3 shows the results of the laboratory experiment. There was an excellent correlation between visual measurements of water level height (h_{VIS}) in the Mariotte column and simultaneous measurements obtained using either the pressure transducer (PT) ($h_{PT} = 0.994\ h_{VIS}$ - 0.578, $r^2 = 0.998$) or TDR ($h_{TDR} = 1.006\ h_{VIS} - 0.279$, $r^2 = 0.999$).

The variability observed among TDR water level readings for a given height was very low, as reflected by an average coefficient of variation of 0.11% obtained in an

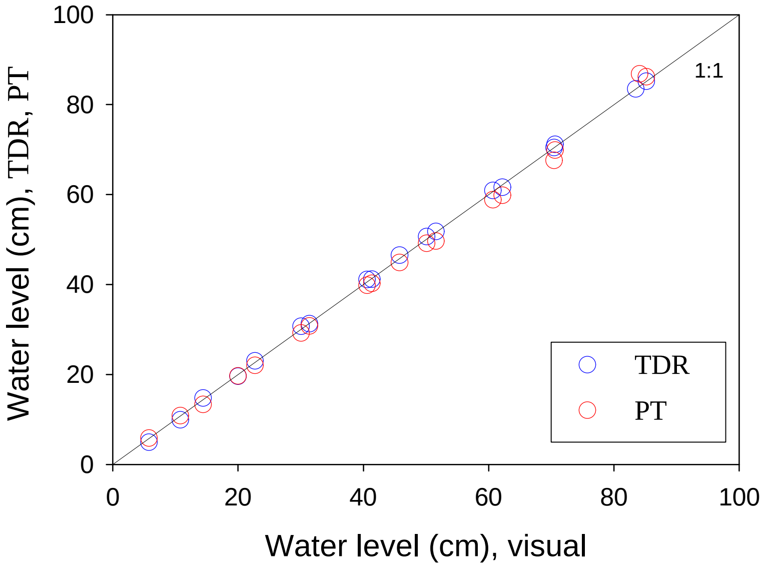

Figure 2.3. Relationship between the water level determined using a TDR probe and a single differential pressure transducer (PT) and the water level determined visually in a Mariotte column 90 cm high under laboratory conditions.

additional experiment in which TDR measurements were made in triplicate at 19 reference heights.

The field experiment demonstrated the performance of the proposed TDR-based technique during a typical infiltration test under field conditions (Fig. 2.4a). Again agreement between the visual and PT and TDR methods was excellent ($h_{PT} = 0.971\ h_{VIS} + 0.531$, $r^2 = 0.999$; $h_{TDR} = 0.996\ h_{VIS} + 0.593$, $r^2 = 0.999$).

If either the standard deviation of the regression (SD) or the root mean standard error (RMSE $= \sqrt{\sum_{i=1}^{n} (h_{TDR,PT} - h_{vis})^2 / n}$) is taken a measure of the dispersion between measured (TDR or PT readings) and reference (visual) water level values, the proposed TDR method appears to be slightly more accurate than the PT method. For the laboratory experiment (n=18), those parameters were lower for the TDR method (SD = 0.42 cm; RMSE = 0.41 cm) than for the PT method (SD = 0.46 cm; RMSE = 0.73 cm). This was also the case for the field experiment, where the SD and RMSE values (n=28) for the TDR technique were lower (SD = 0.25 cm; RMSE = 0.47 cm) than for the PT method (SD = 0.79 cm; RMSE = 0.73 cm). The standard error for the TDR measurements in the laboratory and field experiments was 1.0 and 0.5 mm, respectively. Thomsen et al. (2002) reported a standard error of 2.5 mm for a calibration experiment under laboratory conditions in which visual measurements of water depth were compared with measurements taken with their prototype of TDR water level probe.

The new automated TDR technique has certain advantages over other methods of measuring the water level change in the water-supply reservoir of tension disc infiltrometers. Firstly, the TDR water level reading is not subject to uncertainties arising from visual measurement errors due to parallax viewing and potential errors in recording the reading time. Secondly, since the proposed TDR method does not require any laboratory or field calibration before its use in the field, errors associated to pressure transducer calibration are also eliminated. Moreover, since

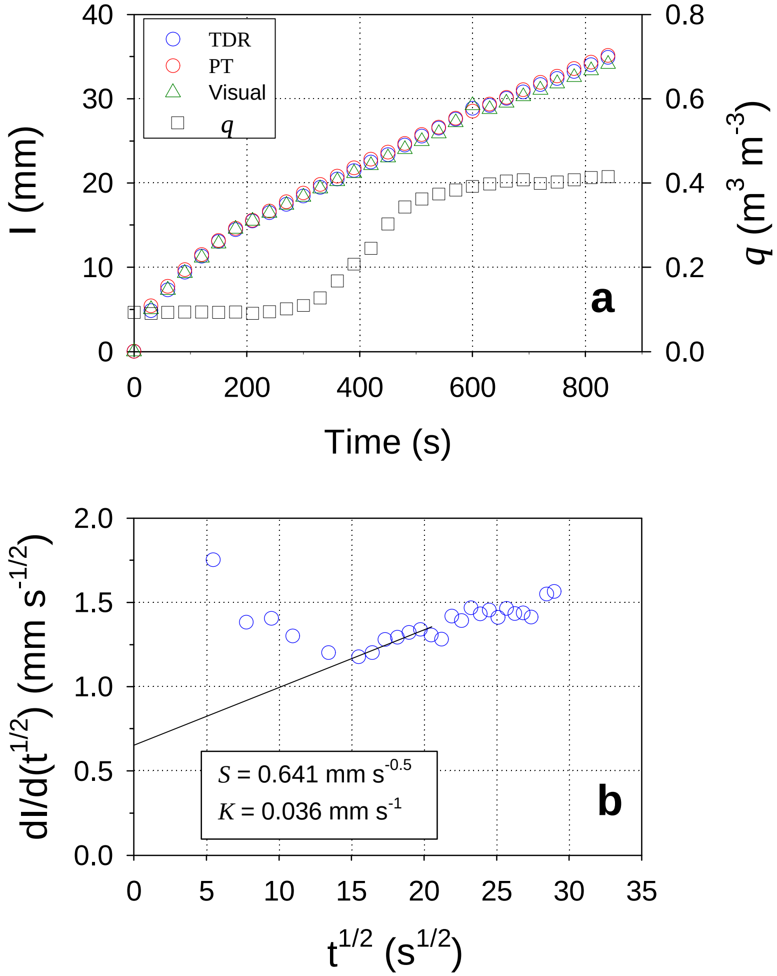

Figure 2.4. Infiltration test performed with a tension disc infiltrometer on a recently tilled loamy soil at a pressure head, *y*, of 0 cm: (a) cumulative infiltration (I) determined from TDR, pressure transducer (PT) and visual readings, and time curse of the volumetric water content of soil (*q*) measured with a TDR probe horizontally installed under the infiltrometer disc at a depth of 4 cm; (b) soil sorptivity (*S*) and hydraulic conductivity (*K*) estimates from TDR-measured infiltration according to Vandervaere et al. (1997).

the TDR method is based upon measurement of the changes in the apparent dielectric constant (e_{TDR}) of an air-water medium, its precision is not affected by pressure fluctuations due to bubbling.

A singular feature of the automated water level sensing method tested here is that TDR can be used for simultaneous recording of both water flow and transient volumetric water content of soil (q) underneath the infiltrometer disc. Figure 2.4a shows the cumulative infiltration obtained in our field infiltration experiment using TDR and other methods for water level measurements and the change of q measured during the infiltration run. This is particularly useful when inferring soil hydraulic properties using inverse parameter estimation techniques (Angulo-Jaramillo et al., 2000; Schwartz and Evett, 2002) that require not only accurate measurements of either transient or steady-state water flow but also the initial (q_i) and the final water content of soil (q_f) below the disc.

By using TDR to measure q_i and q_f, difficulties and errors associated to the conventional method of collecting soil cores to obtain the dry bulk density needed to convert gravimetric water contents into volumetric values are avoided. In our field experiment, the TDR-measured values of q_i and q_f were 0.093 and 0.415 $m^3 m^{-3}$, respectively (Fig. 2.4a). The q_f value was consistent with the average figures obtained in the infiltration tests performed on six locations under the same soil surface conditions, in which no significant differences were found between q_f determined by TDR ($\bar{q}_f$ = 0.403 $m^3 m^{-3}$) and gravimetrically on undisturbed soil cores ($\bar{q}_f$ = 0.423 $m^3 m^{-3}$).

Likewise, the proposed TDR method has proved to be satisfactory to estimate soil hydraulic properties from transient water flow data. Thus, soil sorptivity (S) for our field infiltration experiment (S = 0.641 mm $s^{-0.5}$) was estimated using the differentiated linearization method developed by Vandervaere et al. (1997) (Fig. 2.4b). According to this method, a saturated hydraulic conductivity (K) of 0.036

mm s^{-1} was calculated for our experimental soil from S and the TDR-measured values of q_i and q_f (Fig. 2.4b).

The new TDR application would be particularly suitable in spatial and temporal variability studies where both hydraulic and solute transport properties in unsaturated soils are to be measured with tension disc infiltrometers at a large number of sites in a short period of time. While one TDR-based disc infiltrometer is automatically recording water flow at a site a new measuring site can be prepared. Also, several TDR disc infiltrometers and TDR probes for measuring q (t) below the disc can be multiplexed and programmed to run simultaneously by using public domain software for TDR system control such as WinTDR (Or et al., 1998) or TACQ (Evett, 2000). Finally, the TDR disc infiltrometer can be run at different tensions sequentially by refilling the water-supply reservoir with water or a tracer solution without removal of the infiltrometer from the soil surface.

4. Conclusions

Three major conclusions can be drawn from the study. First, the TDR technique developed for automated measurement of water level drop in Mariotte-type reservoirs is simple to use, easy to implement and provides an accurate alternative to visual or pressure transducer methods. Second, this technique can be used successfully with tension disc infiltrometers to obtain reliable estimates of soil hydraulic properties. Third, the new application allows for simultaneous TDR recording of both water flow and the transient volumetric water content of soil below the infiltrometer disc and the future possibility of integrating cumulative infiltration and soil moisture measurements into a single TDR system.

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Capítulo 3

Limitations of Tension Disc Infiltrometers for Measuring Water Flow in Freshly Tilled Soil

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Submitted to: *Advances in Geoecology, CATENA-VERLAG Series*

Limitations of Tension Disc Infiltrometers for Measuring Water Flow in Freshly Tilled Soils

ABSTRACT

Knowledge of water transmission properties in fragile semiarid soils is crucial to evaluate their physical response to sustainable land management practices. Tension disc infiltrometers have become valuable tools for in situ estimates of soil surface hydraulic properties in soil management and tillage studies, but when measurements are made in loose soils near saturation supporting the weight of the infiltrometer with a tripod or similar device has been suggested. This paper examines the influence that the weight of the tension disk infiltrometer may have on the measurement of steady-state flow (*Q*) in a cultivated loam soil under three field conditions: structured soil, moldboard tilled soil, and rototilled soil. Infiltration tests were made using three disc infiltrometer configurations providing a decreasing weight on the infiltration surface. Results show that the weight of the infiltrometer affects *Q* only in freshly tilled soils. Neither a reduction in the weight of the infiltrometer nor the use of a supporting device alleviates the problem due to soil collapse under the infiltrometer at tensions close to saturation. Tension disc infiltrometers should be used with caution for in situ characterization of soil hydraulic properties in loose recently tilled soils.

1. Introduction

Physical degradation of dryland soils due to inadequate or intensive tillage in arid and semiarid regions is largely dependent on the hydrodynamic processes occurring at the soil surface (i.e. rainfall infiltration and runoff). Therefore, field measurement of soil water transmission properties is important not only for characterizing tillage-induced changes in soil structure, but also to evaluate alternative management practices for soil and water conservation in fragile agricultural lands.

Tension disc infiltrometers have become a standard tool for in situ estimates of soil hydraulic properties (Angulo-Jaramillo et al, 2000). However, in most soil tillage and management related studies tension infiltrometer measurements have been made after the soil structure has to some extent stabilized (Ankeny et al., 1990; Sauer et al., 1990; Coutadeur et al., 2002). Hence, the results cannot completely reflect the water flow properties of the freshly tilled soil (Klute, 1982). Actually, field measurement of soil surface hydraulic properties by disc infiltrometry during the transient, unstable post-tillage condition may have additional difficulties. For instance, when measurements in freshly cultivated soils are made at supply water pressure heads (y) close to zero, the strength of the soil may be not able to support the weight of the infiltrometer (White et al., 1992). When this occurs, subsequent soil macrostructure collapse under the infiltrometer can lead to negative values of hydraulic conductivity (K). In addition, inadequate or changing hydraulic contact between the infiltrometer disc and the infiltration surface may also result in unreliable low steady-state flow rates (Q). To alleviate this problem and that due to macrostructure collapse as well, supporting the weight of the infiltrometer with a large tripod or other methods has been recommended (Reynolds, 1993).

The objective of this work was to evaluate the influence that the weight of the tension disk infiltrometer may have on the measurement of Q in a cultivated loam soil under three different soil structural conditions. An alternative disk infiltrometer design for determining near-saturated $K(y)$ in recently tilled soils is proposed.

2. Materials and methods

2.1.Tension infiltration procedures

Basically, a tension infiltrometer consists of three elements: a disc, a water supply reservoir, and a bubbling tower with a moveable air-entry tube and a second tube to supply air to the water reservoir. The pressure head (h_o) is the difference of height h_2-h_1, where h_2 is the height from the base of the disc to the air-entry plane in the water supply reservoir and h_1 is the height between the bottom of the air-entry tube and the water level in the bubble tower (Angulo-Jaramillo et al., 2000). Normally, these three elements are integrated into a single configuration, but some commercial infiltrometers (based in the design of Ankeny et al., 1988), in which air flows directly from the bubbling tower to the water reservoir, can work with the disc separated from the water supply tower. This option substantially reduces the weight of the disc infiltrometer.

Three types of tension infiltrometers, home made following the design of Perroux and White (1988) and providing three different weights on the infiltration surface, were used in our experimentation. Their basic characteristics and the experimental procedure that we choose were the following.

i) *Mode 1*. A compact 0.25-m tension disc infiltrometer in which the drop of water level in the water supply reservoir is automatically registered using a three-rod time domain reflectometry (TDR) probe placed in the centre of the water reservoir and connected to a TDR pulser as described by Moret et al. (2002) (Capítulo 2, Fig. 2.1). This infiltrometer has a total weight of 2.56 kg when the supply reservoir is empty and 4.35 kg when the reservoir is full of water.

ii) *Mode 2*. To reduce the weight on the infiltration surface, the TDR-based disc infiltrometer used in *Mode 1* was modified to work with both the water supply reservoir and bubbling tower separated from the infiltrometer disc (Fig. 3.1). This new prototype consists of a triple mariotte system in which h_2 is kept constant and fully independent of the disc base position with respect to the water supply reservoir. In this case, the weight of the infiltration element (disc plus mariotte tube) is 0.93 kg when the mariotte tube is empty and 1.29 kg when this reservoir is full of water. Thus, the weight on the infiltration surface was reduced by about 70% as compared to

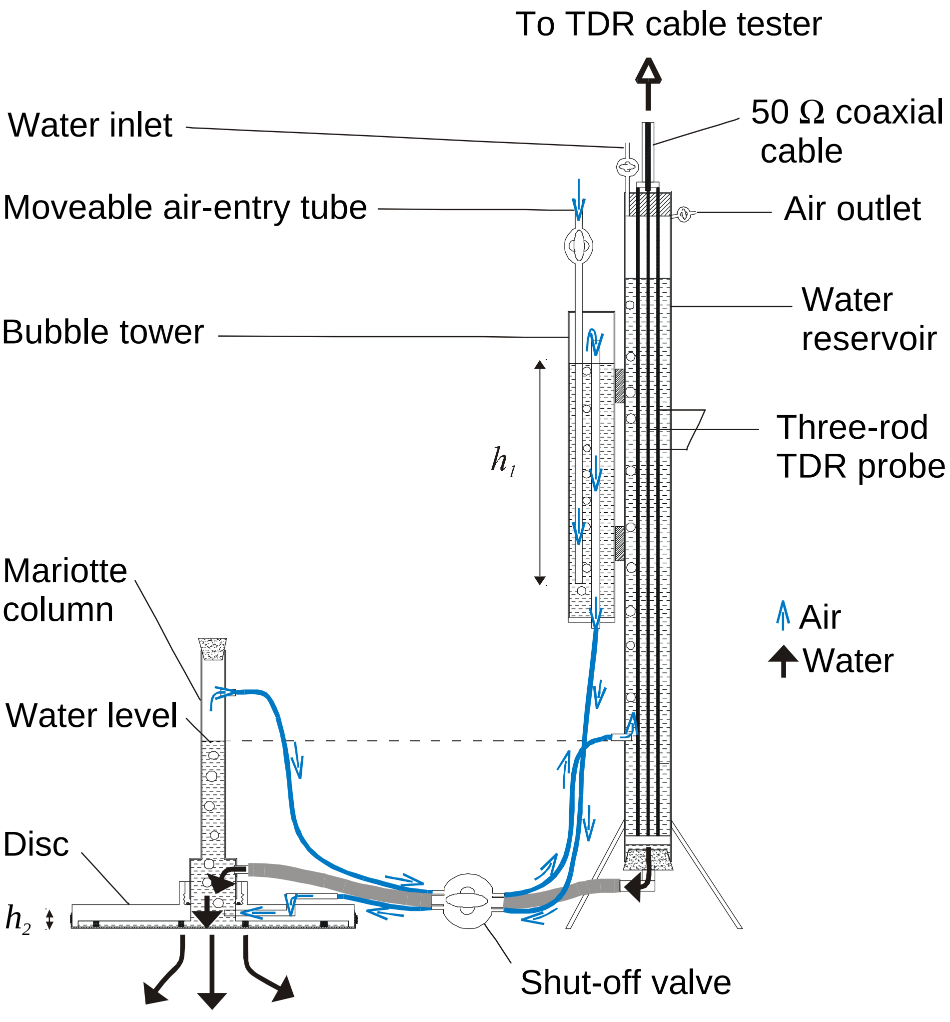

Figure 3.1. Schematic diagram of a tension disc infiltrometer with the water supply reservoir and the bubbling tower separated from the infiltrometer disc (*Mode 2*).

Mode 1.

iii) *Mode 3.* In order to eliminate entirely the weight on the infiltration surface, measurements were made with the infiltrometer shown in Fig. 3.1 (*Mode 2*) but placing beneath the infiltrometer disc a supporting element consisting of a 28 x 60 cm piece of a rigid thin wire mesh with rectangular openings of 2 x 4 cm. This template was actually placed between the base of the disc and the thin layer of sand (80-160 μm grain size) poured at the soil surface to ensure hydraulic contact between the disc and the soil.

2.2.Field measurements

The study was conducted at the Estación Experimental de Aula Dei (CSIC) dryland research farm located in Peñaflor, in semiarid Central Aragón (NE Spain) (41°44'N, 0°46'W). Infiltration tests were made on a 30 x 80 m experimental field on the surface of a loam soil (fine-loamy, mixed thermic Xerollic Calciorthid). More details on the experimental site and soil can be found in López et al. (1996). Q measurements were performed using the three infiltrometers above described under three different soil structural conditions:

i) Soil structured and consolidated eight months after the harvest of a barley crop grown under cereal-fallow rotation; mean dry bulk density (r_b) for the topsoil (0-5 cm depth) was 1.24 g cm^{-3}.

ii) Soil disturbed after a pass with a moldboard plough (r_b = 1.18 g cm^{-3}).

iii) Soil loose and highly pulverized after a pass with a rototiller (r_b = 0.87 g cm^{-3}).

For each soil condition and infiltration mode, Q measurements were made at six points randomly selected across the corresponding sampling area. At each sampling point, the infiltration tests were conducted on three spots successively 20 cm apart along the tillage direction. Each infiltrometer was run to steady state at four tensions (nominally -14, -4, -1 and 0 cm, applied in that order and at the same place) and K estimated according to Reynolds and Elrick (1991). The initial soil bulk density at the surface (0-5 cm depth) was measured nearby on 5 cm diameter (98.2 cm^3) undisturbed cores.

3. Results and dicussion

Figure 3.2 presents the variation of steady-state flow rate (Q) as a function of pressure water head (y) obtained with the different tension infiltrometers under the three soil strength conditions considered in our study.

When the soil is somewhat structured the three measurement techniques yield similar values of Q (Fig. 3.2a). Although slightly higher values are obtained at all tensions when *Mode 3* (zero weight) is used, it appears that tension infiltrometer measurements are not affected by the weight of the infiltration element in this particular soil condition. Whatever infiltration procedure is used, $Q(y)$ follows an exponential curve similar to the piecewise exponential relationship described by Reynolds and Elrick (1991) for estimating $K(y)$. As discussed by these authors, $K(y)$ depends on $\bar{a}_{x,y}$, which is the slope of the piecewise linear plot of the natural log of the steady-state flow rate (ln$Q$) versus the pressure water head (y) on the infiltration surface [$\bar{a}_{x,y} = \ln(Q_x/Q_y) / (y_x - y_y)$, where x = 1, 2, 3, ... and y = x +1]. On the other hand, $\bar{a}_{x,y}$ is the average value of a over the relevant ranges of y, and a is a soil texture/structure parameter measuring the relative importance of the gravity and capillarity forces during water flow in unsaturated soil (Reynolds and Elrick, 1991). Therefore, the performance of the different infiltration devices can be tested by analyzing the behaviour of $\bar{a}_{x,y}$ (Table 3.1). Thus, for all the infiltration runs conducted in the consolidated soil, $\bar{a}_{x,y}$ increases as the tension decreases as required by the theory.

On the contrary, in a freshly mouldboard plowed soil, with large clods and a more weak structure, the effect of the weight of the infiltrometer on Q

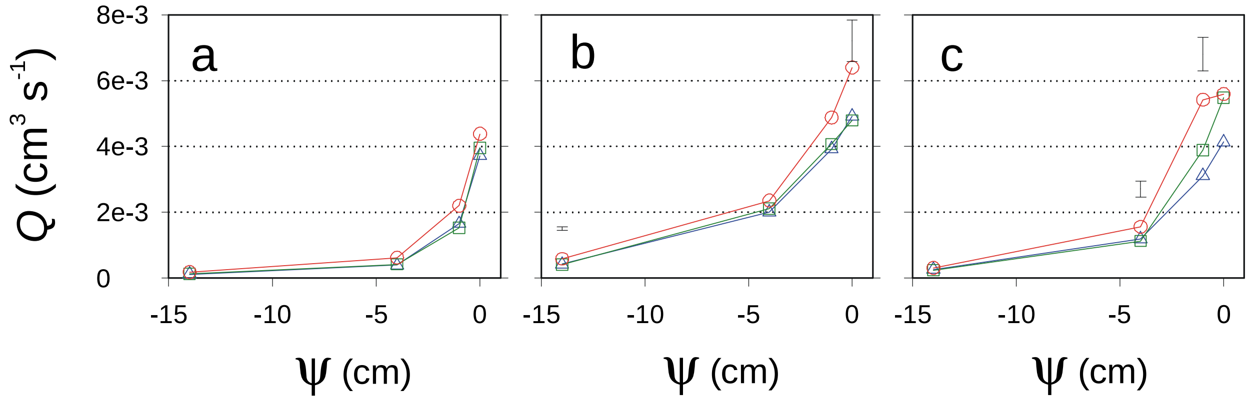

Figure 3.2. Relationship between steady-state flow rate (Q) and pressure potential (y) obtained on the surface of a loam soil with initial dry bulk density (r_b) values of 1.24 (a), 1.18 (b), and 0.87 g cm^{-3} (c), by using three tension disc infiltrometers (*Mode 1*, △; *Mode 2*, □ ; and *Mode 3*, O). Bars represent LSD ($P < 0.05$) for comparison among disc infiltrometers at the same tension and soil condition , where significant differences were found using the Duncan´s multiple range test.

Table 3.1. Average values of the piecewise linear slope ($\bar{\alpha}_{x,y}$) between adjacent (y,Q) data pairs (Fig. 3.2) and $K(y)$[†] calculated according to Reynolds and Elrick (1991) for the tension disc infiltrometers and soil conditions used in this study.

Soil	Tension disc infiltrometer[‡]	$\bar{\alpha}_{14,4}$	$\bar{\alpha}_{4,1}$	$\bar{\alpha}_{1,0}$	K_{14}	K_4	K_1	K_0
			m^{-1}			$mm\ h^{-1}$		
Structured soil	Mode 1	12.6	42.6	84.8	2.1b[§]	11.4b	52.2a	115.2a
($\rho_b = 1.24\ g\ cm^{-3}$)	Mode 2	12.2	41.5	93.8	2.3b	11.8b	50.4a	126.0a
	Mode 3	12.1	43.6	69.5	3.2a	18.0a	64.8a	133.2a
Disturbed soil	Mode 1	15.4	23.4	21.1	8.6b	43.2a	84.1b	108.0b
(mouldboard ploughed)	Mode 2	16.5	21.9	15.9	7.2b	46.8a	82.8b	97.2b
($\rho_b = 1.18\ g\ cm^{-3}$)	Mode 3	13.9	23.6	28.7	10.8a	54.0a	115.2a	151.2a
Structureless soil	Mode 1	15.6	31.8	28.8	3.6b	28.8b	75.6b	104.4a
(rototilled)	Mode 2	15.7	40.9	33.6	4.8b	32.4b	100.8b	147.6a
($\rho_b = 0.89\ g\ cm^{-3}$)	Mode 3	16.2	41.5	11.2	7.2a	43.2a	212.4a	115.2a

[†] Hydraulic conductivity measured at pressure head values of 0, -1, -4, and –14 cm (denoted K_0, K_1, K_4, and K_{14}).
[‡] The three disc infiltrometer configurations used provided a decreasing weight on the infiltration surface (Mode: 4.35 kg; Mode 2: 1.29 kg; Mode 3: 0 kg); see Material and Methods for details
[§] Values in the same column followed by the same letter are not significantly different at P<0.05 (Duncan's test).

measurements near saturation is clearly shown in Fig. 3.2b. The mean value of Q obtained with zero weight on the soil surface (*Mode 3*) at tensions of –1 and 0 cm was significantly higher as compared to *Mode 1* and *Mode 2* infiltrometers. The exponential form of the $Q(y)$ relationship is present only in *Mode 3*, in which $\bar{a}_{x,y}$ increases with a decreasing y. For *Modes 1* and *2*, in contrast, $\bar{a}_{x,y}$ decreases for the step between y = -1 cm and y = 0 cm. This anomalous behaviour can be explained by a soil macrostructure collapse under the infiltrometer disc caused by the weight of the infiltrometer, even though this weight is low as in the case the bubble tower and the water supply reservoir are separated from the infiltrometer disc (*Mode 2*). This fact is much more evident when measurements are made in a structureless soil like our experimental highly pulverised rototilled soil (Fig. 3.2c). In this loose soil condition Q values were in general lower than those for the mouldboard tilled soil. At tensions close to zero, Q decreases as the weight of the infiltrometer increases and again $\bar{a}_{x,y}$ decreases rather to increase. However, the variation of Q vs. y is markedly different for *Mode 3* (zero weight) infiltrations: Q barely increases between y = -1cm and y = 0 cm (Fig. 3.2c), which determines the abrupt decline of $\bar{a}_{x,y}$ as soil becomes saturated (Table 3.1). This conduct is due to the subsidence of soil under the supporting mesh during the infiltration as it was clearly observed in the field after removing the infiltrometer at the end of the infiltration run. This natural phenomenon is illustrated by the example of cumulative infiltration shown in Fig. 3.3. The inflection point after about three minutes of infiltration determines the moment at which the soil naturally collapses and the hydraulic contact between the soil surface and the disk is partially broken down, thus leading to unreliable low values of Q. Figure 3.4. shows an example of soil collapse during (Fig. 3.4a) and at the end (Fig. 3.4b) of infiltration at saturation with disc infiltrometer *Mode 3* on a structureless soil. Consequently, inconsistent estimates of $K(y)$ can be obtained. In our study, for instance, the values of hydraulic conductivity at saturation (K_0) in

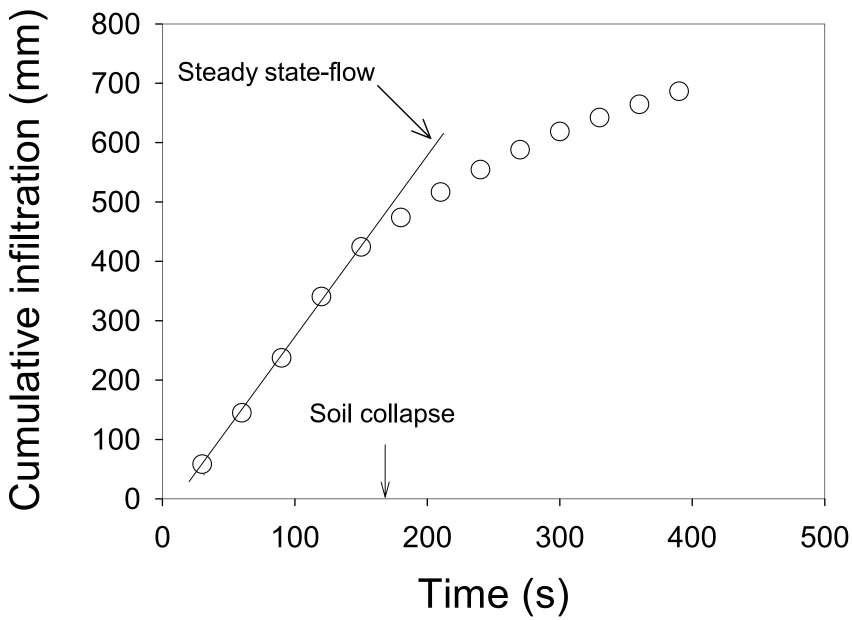

Figure 3.3. Cumulative infiltration at saturation ($\psi = 0$) on a structureless rototilled loam soil measured by using the tension disc infiltrometer shown in Fig. 3.1 with a supporting wire mesh beneath the disc (*Mode 3*).

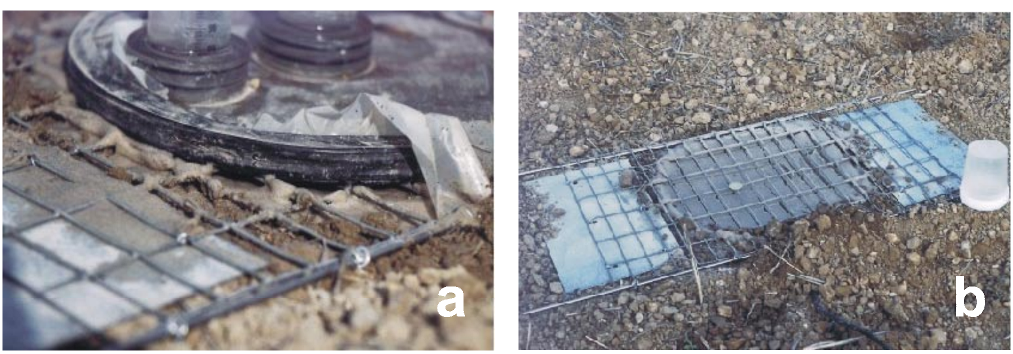

Figure 3.4. Soil collapse during (a) and at the end (b) of infiltration at saturation with disc infiltrometer *Mode 3* on a structureless soil.

freshly tilled soil are equal or even lower than those calculated for a consolidated soil (Table 3.1). Although the tension infiltrometers tested in our study did not provide a satisfactory performance in recently tilled soils, the use of an infiltrometer with the bubbling tower and the supply reservoir separated from the disc (*Mode 2*) can be more reliable under certain circumstances. In this new design, the experimental errors arising from an inadequate setting of the tension (h_o), particularly near saturation, are eliminated. The height h_1 is fixed at the bubbling tower without any manipulation on the infiltrometer disc and h_2 is constant regardless the position of the disc with respect to the water supply reservoir (Fig. 3.1).

In conclusion, the results of this study demonstrate that tension disc infiltrometers should be used with caution for in situ characterization of soil hydraulic properties in recently tilled soils. Neither a reduction in the weight of the infiltrometer nor the use of a supporting device, as previously suggested, overcomes the problem due to soil collapse under the infiltrometer when measurements are made at tensions close to saturation. Our results show how this factor leads to an of the steady-state water flow (Q) and, correspondingly, to inaccurate estimates of K and related hydraulic parameters. Further research aimed to the development of new simple and accurate methods for field characterization of hydraulic properties in freshly tilled soils is needed.

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Capítulo 4

Dynamics of Soil Hydrophysical Properties During Fallow as Affected by Conventional and Conservation Tillage Systems

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To be submitted to: *Soil Science Society of America Journal*

Dynamics of Soil Hydrophysical Properties During Fallow as Affected by Conventional and Conservation Tillage Systems

ABSTRACT

There is limited information on the effects of conservation tillage practices on soil hydraulic property changes during long-fallowing (16-18 months) in rainfed cereal-fallow cropping systems of semiarid central Aragon (NE Spain). Reduced tillage with chisel ploughing (RT) and no-tillage (NT), were compared with conventional mouldboard ploughing (CT) on a fallow loam soil (Xerollic Calciorthid) over three long fallow periods. After 8-10 years of trial in a long-term tillage experiment, measurements of hydrophysical properties were taken before and immediately after primary tillage, after post-tillage rains and at the end of fallow. Soil bulk density, r_b, soil water retention curve, $q(y)$, and soil hydraulic conductivity, $K(y)$, at –14, -4, -1 and 0 cm pressure head and related hydraulic parameters were measured at 2 and 40 cm depth. Compared with CT and RT, NT plots presented more compacted topsoil, which resulted in a lower water content at saturation and a lower available water-holding capacity. Regardless of tillage, soil water flow at 2 cm depth was mainly regulated by macropores, despite this pore fraction represents a small fraction of total porosity. Athough a larger macropore size was observed under NT, *K* under this treatment was significantly lower than under CT and RT due to a lower number of water transmitting pores per unit area. Overall, no significant differences in hydraulic properties were found between CT and RT. The lower *K* at 40 cm depth in these treatments agreed with corresponding higher r_b values at that depth. In the short term, soil loosening by tillage increased the aeration porosity (pores > 300 mm) and

decreased available water retention micropores (30-0.2 mm pores). Tillage also increased the number of water conducting mesopores, which increased *K*. Soil reconsolidation following post-tillage rains decreased total porosity, with a reduction of large pore-size fractions and *K*. These changes, which tended to restore pre-tillage soil structural conditions, increased with the intensity of rainfall events. Inconsistencies in estimating hydraulically active pore characteristics were analysed and an alternative pore index proposed. The use of this index to calculate the concentration of water transmitting pores and effective porosity showed an overestimation of these parameters when using the capillary rise approach.

1. Introduction

Soil water conservation is a critical issue for the sustainability of agricultural systems in semiarid dryland grain-growing areas in Central Aragon (NE Spain), where farmers traditionally rely on the cereal-fallow rotation to capture out-of-season rainfall during a 16-18 month period of fallow to supplement that of the growing season. However, in rainfed farming areas soil water balance and its components (i.e., evaporation, transpiration, water storage and drainage) during fallow depend not only on the soil type and rainfall pattern, but also on the water retention and transmission properties of soil (Lampurlanés et al., 2002). Tillage and rainfall events alter the structure of the topsoil layers and consequently their hydrophysical properties thus modifying the soil water regime. Thus, in order to define sustainable management practices for maintaining a favourable soil water budget for optimal crop growth and development, surface measurements of hydraulic properties under field conditions appear to be of paramount importance. It is precisely at the soil surface and in the few centimeters below where the soil hydrophysical conditions play an important role in partitioning incident water into either runoff or infiltration. For the latter, the absorption and transmission properties of the surface soil dictate the pattern of water entry and storage into the soil (Vauclin et al. 1994).

With regard to tillage effects on soil hydrophysical properties under well-structured soil conditions, a higher compaction in soil managed under no-tillage, compared with tilled soil, has been observed in a large number of tillage comparison studies (Pikul, et al., 1993; López et al., 1996; Moreno et al., 1997; Evett et al., 1999; Arvidsson, 1998). This compaction reduces the fractions of large pores and makes the water retention curves under no-tillage to present a more gradual reduction in water content as tension increases and lower water contents close to saturation (Azooz et al., 1996; Evett et al., 1999; Schwartz et al., 2003). In other studies conducted to evaluate the impact of different tillage systems on soil water transmission properties, results for the different tillage treatments are not always consistent across locations, soils and experiment designs (Green et al., 2003). Thus, whereas Chan and Heenan (1993) and McGarry et al. (2000), among others, reported higher infiltration rates under no-tillage relative to tilled treatments, due to a greater number of macropores (Logdson et al., 1990), increased fauna activity and accumulated organic matter forming a litter of residues (Logdson and Kaspar, 1995), other researchers found similar (Sauer et al., 1990) or lower (Miller et al., 1998; Evett et al., 1999) values of K under no-tillage. Similarly, in other studies where reduced tillage was compared with mouldboard ploughing (Logsdon et al., 1993; Moreno et al., 1997), minimum tillage provided the highest values of K, due to a different pore size distribution in the surface layer rather to total porosity (Moreno et al., 1997). However, the characterisation of water transmitting pore size fractions by examining the relative increase of K over a decreasing range of soil water tension (y) (Reynolds et al., 1995), indicates that, in general, macropores in structured soils have a large influence upon water flow despite the fact they occupy a very small fraction of total porosity (Sauer et al., 1990; Reynolds et al., 1995; Angulo-Jaramillo et al., 1997; Cameira et al., 2003). On the other hand, differences in K have been observed along the soil profile (Moreno et al., 1999; Cameira et al., 2003).

In spite of the large number of field studies conducted to evaluate tillage effects on hydraulic functioning of structured soils, these studies have been generally performed over the crop growing season. On the contrary, the information available in the literature about short-term tillage-induced effects on hydrophysical properties of agricultural soils and their dynamics over the fallow period is very scarce (Green et al., 2003). Results from studies on this subject have shown that loosening of surface soil by tillage operations increases the total soil porosity (Logsdon et al., 1999; Miller et al, 1998; Green et al., 2003) through both an increase in the pore volume at the wet end of the soil water retention curve (Mapa et al., 1986; Ahuja et al, 1998) and a decrease in the pore fractions corresponding to small pressure heads (Mapa et al., 1986). On the other hand, although a destruction of macropores and macropore continuity is probable after tillage (Malone et al., 2003), an increase of K has been commonly observed in recently tilled soils (Messing and Jarvis, 1993), probably as a consequence of an increase in the number of active mesopores. Tillage operations, however, have a transitory effect on soil physical characteristics because of rain impact on the freshly tilled soil, which promotes a steady breakdown of soil structure (Green et al., 2003). Thus, soil structural changes in recently tilled soil by precipitation and associated wetting and drying cycles lead to a destruction of the largest pores while keeping constant and sometimes even increasing the frequency of smallest ones (Rousseva et al., 2002). A decrease in K following rainfall after tillage has also been observed (Cameira et al., 2003; Schwartz et al., 2003). This can be attributed to a reduction in the fraction of conductive mesopores (Messing and Jarvis, 1993), in agreement with a concomitant increase in bulk density (Mellis et al., 1996). However, as recently reviewed by Green et al. (2003), further research is needed to improve current knowledge on tillage influence on soil hydrophysical properties of freshly tilled soils.

The present work is part of a long-term conservation tillage experiment initiated in 1989 to assess soil and crop responses under different tillage systems in a dryland semiarid cereal-growing area of Central Aragon. The study was aimed: i) to evaluate the effect of conventional and conservation tillage systems on soil bulk density, water retention and hydraulic conductivity after 8-10 years of trial; and ii) to quantify the dynamics of those soil hydrophysical properties over three long-fallow periods.

2. Materials and methods

2.1. Experimental site and procedures

The site is located at the dryland research farm of the Estación Experimental de Aula Dei (CSIC) in the 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 °C. Soil at the research site is a loam (fine-loamy, mixed thermic Xerollic Calciorthid) according to the USDA soil classification (Soil Survey Staff, 1975). Particle size distribution for the plough layer (0-40 cm) averages 25% clay, 47% silt and 28% sand. Selected soil physical and chemical properties for that layer were given in López et al. (1996).

The study was conducted on two adjacent large blocks of plots, which were set up on an area nearly level in 1991 (Field 1) and 1992 (Field 2) within a long-term conservation tillage experiment initiated in 1989. The two fields were in a winter barley (*Hordeum vulgare* L.)-fallow rotation, with each field cropped in alternate years. This study was conducted when both fields were in the long-fallow phase of this rotation, which extends from harvest (June-July) to sowing (November-December) on the following year. Field measurements were made during three fallow seasons: 1999-2000 and 2001-2002 fallows in Field 2, after 8 and 10 years of the trial, and 2000-2001 fallow in Field 1, after 10 years of the trial (Fig. 4.1a).

Three different fallow management treatments were examined: 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

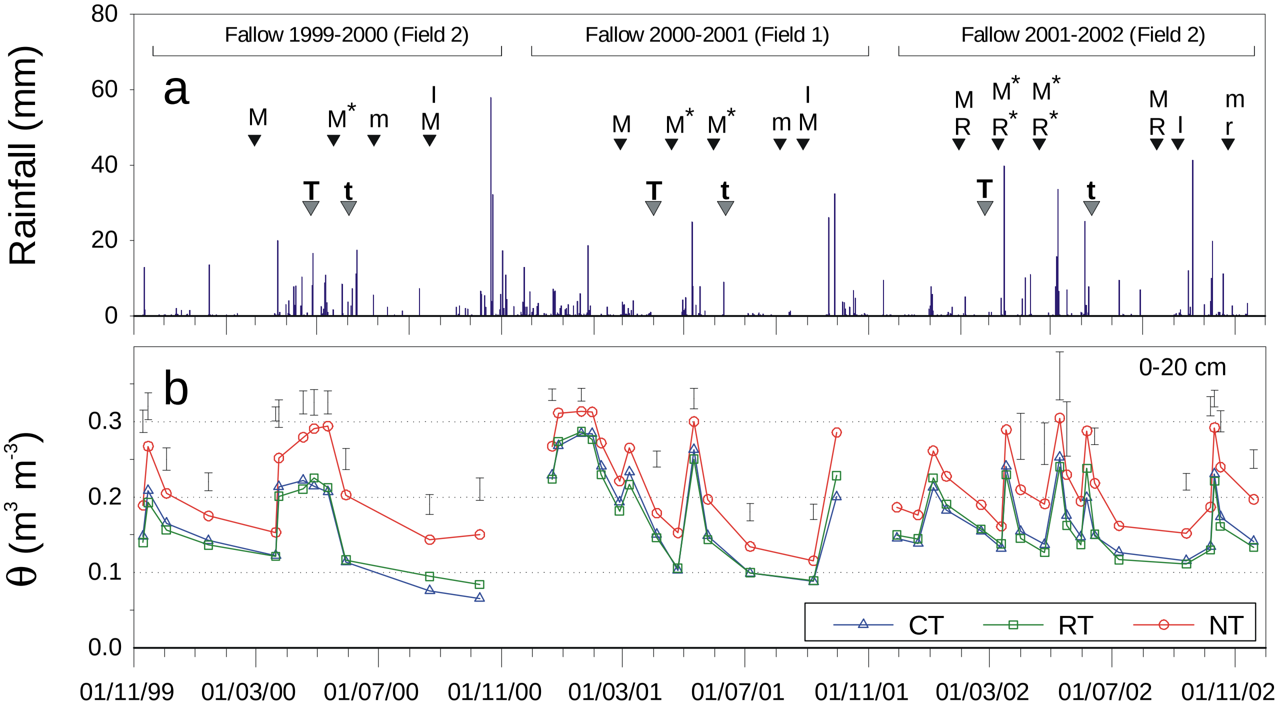

Figure 4.1. a) Timing of rainfall and tillage practices (**T**, primary tillage; **t**, secondary tillage) in relation to soil property measurement dates under conventional tillage (CT), reduced tillage (RT) and no-tillage (NT) treatments during three fallow seasons (M, infiltration and bulk density measurements at 2 cm depth; m, ibid. at 40 cm depth; I, infiltration measurements at saturation on surface-crusted soil; R, water retention curve determination at 5 cm depth; r, ibid. at 45cm; *, measurements taken only under CT and RT). b) Time course of volumetric water content in the surface soil (0-20 cm) under CT, RT and NT treatments. Bars represent LSD ($P < 0.05$) for comparison among tillage treatments where significant differences were found.

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 plowing 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, that were the same for the CT and RT treatments, corresponded with 25 April 2000, 10 April 2001 and 13 March 2002 for primary tillage and 29 May 2000, 6 June 2001 and 11 June 2002 for secondary tillage for the 1999-2000, 2000-2001and 2001-2002 fallow period, respectively (Fig. 4.1a). NT used exclusively herbicides (glyphosate) 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 to ensure a balanced design (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. Within each incomplete block a 7 m x 7 m region was delimited for either sampling or in situ measurement of the different soil properties considered in the study. Two observation points exist in each region, one per treatment. The distance between points was 5 m for all regions (López and Arrúe, 1995). With this sampling scheme, a total of 18 measurements (6 per treatment) were made on each fallow field per soil property, sampling depth and observation date. To compare the effects of tillage treatments, analysis of variance (ANOVA) for the incomplete block design was used (López and Arrúe, 1995). To compare the temporal effect of tillage practices along the fallow a simple analysis of variance (ANOVA) for each tillage treatment was used.

2.2. Experimental measurements

Field measurements of hydrophysical properties were made at four dates during the second year of the fallow period: (a) before primary tillage implemented in January-February (this set of measurements will be called *pre-tillage*); (b) after primary tillage but before any post-tillage rainfall events had occurred (this set of measurements made in freshly tilled soil in March-April will be called *post-tillage*); (c) after primary tillage but following a period of intermittent rainfall events in April-May (*post-tillage+rain*); and (d) during the last phase of the fallow period after secondary tillage practices, at the end of August (*late fallow*). The schedule of main soil property measurements in relation to tillage operations and rainfall events is shown in Fig. 4.1a. For the 1999-2000 fallow season, field measurements in freshly tilled soil were not possible due to a rain of 25 mm received on 26-27 April 2000, immediately after primary tillage (Fig. 4.1a). For each observation region and treatment, all the measurements were concentrated in a small area of ≈ 1 m^2.

Daily rainfall data were continuously registered with a datalogger (model CR10, Campbell Scientific Inc.) from an automatic weather station located at the experimental site.

2.2.1. Bulk density and moisture content

Soil dry bulk density (r_b) was determined by the core method (Grossman and Reinsch, 2002), with core dimensions of 50 mm in diameter by 50 mm height. Core samples were taken at 2 and 40 cm depth nearby the hydrophysical property (i.e. infiltration and water content-matric potential relationship) measurement locations. This sampling was made on the same day as infiltration measurements in order to determine the antecedent soil bulk density and moisture. The volumetric water content (q) was determined from gravimetric soil moisture (oven drying the soil at 105ºC) and bulk density values. Total soil porosity (x) was calculated from measured bulk density (r_b) and particle density (r_s) (r_s = 2.65 g cm^{-3}) as: x = 1-(r_b/rs). The bulk density of the surface crust (0 - 1 cm depth) was also measured at the end of the 2001-2002 fallow (November) by the clod method (Grossman and Reinsch, 2002) using paraffin wax as coating agent.

During the three experimental fallow periods, the volumetric water content in the 0-20 cm soil layer was continuously monitored by Time Domain Reflectometry (TDR). We used probes of two parallel stainless steel rods (diameter: 4 mm; length: 250 mm; spacing between rod centers: 50 mm), which were inserted vertically into the soil to a depth of 20 cm (Ferré and Topp, 2002). 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 (Dalton, 1992). Waveforms were transferred to a laptop with a SP232 serial communication module and analysed using the software WinTDR’98 (Or et al., 1998). The volumetric water content was obtained using the model proposed by Topp et al. (1980), which proved to be suitable for our soil in a previous laboratory calibration experiment.

2.2.2. Soil water retention

The water content-matric potential relationship, q (y), was determined during draining at 5 and 45 cm depth during the 2001-2002 fallow period on Field 2. For the 0 to –50 kPa range, simultaneous field measurements of q and y were taken at four dates (Fig. 4.1a). Three-rod probes (diameter: 4 mm; length: 100 mm; spacing for the outermost rods: 30 mm) were used to measure q by TDR as described above. The matric potential y was measured using microtensiometers (model SMS 2030S3, SDEC) 30 cm long, having a porous ceramic cup 30 mm long with an external diameter of 12 mm. The tensiometers, with a bubbling pressure of -150 kPa, were previously calibrated in the laboratory and read in the field using pressure transducers (model 26PCDFA6D, Microswitch, Honeywell) with an upper range limit of 207 kPa.

After appropriate trenching to prepare the measurement area at each location (Bruce and Luxmoore, 1986), both sensors were inserted horizontally at the measurement depth, with a separation of 5 cm to avoid measurement interference.

A plastic 12 x 16 cm plastic frame was driven into the soil to a depth of about 1 cm to serve as a dike and to allow ponding of water over the surface and wetting a soil volume enough to include the sphere of influence of both sensors. Water was then added until a thorough saturation of soil to the desired depth was achieved, which was indicated by constancy in tensiometer readings. After a first simultaneous measurement of q and y under this initial saturation condition, water application was ceased and free drainage allowed. Readings of q and y were frequently taken during early drainage (i.e. first 20 minutes) and then after 6, 24, 32 and 48 hours of drainage.

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 (model 1000, Soilmoisture Equipment Corp.). The gravimetric water content values were converted to volume basis using the bulk density values obtained for the same depth at the different measurement dates. Finally, soil water retention curves were obtained by fitting the observed data to the van Genuchten (1980) model. Pore-size distributions were inferred from the soil water retention data using the capillary theory and pore size categories defined by De Leenheer (cited by Cresswell et al., 1993).

2.2.3. Soil hydraulic properties

Field soil hydraulic property characterization was achieved at each observation point using a modified Perroux and White (1988) tension disc infiltrometer with a base radius of 125 mm as described by Moret et al. (200x) for structured soils (Capítulo 2) and Moret and Arrúe (200x) for freshly tilled soils (Capítulo 3). Infiltration measurements on the soil surface were done on areas cleared of large clods, crop residue and surface crust when formed, and brushed smooth enough to ensure a good hydraulic contact between the disc and the soil. To this end, a thin layer of commercial sand (80-160 μm grain size) was also poured at the soil surface. On average, surface measurements were taken at 2 cm depth. Infiltration measurements below the plough layer were taken at 40 cm depth (Fig. 4.1a). The base of the disc was covered with a nylon cloth of 20-μm mesh. Infiltration runs were performed at four y values (namely, -14, -4, -1, and 0 cm, applied in that order and at the same place). Flow monitoring continued until attainment of steady-state flow from the disc. Flow readings were automatically recorded every 30 seconds from the water level drop on the water supply reservoir of the infiltrometer using the TDR application and procedure developed by Moret et al. (200x) (Capítulo 2). For each sampling date, infiltration runs at the 18 sampling points were accomplished in 2 days by working simultaneously with two tension disc infiltrometers connected to a multiplexer (model SDMX50, Campbell Scientific Inc.).

The soil hydraulic conductivity, *K*, at the different water pressure heads (K_{14}, K_4, K_1, and K_0) was obtained from cumulative infiltration using the multiple-head method (Ankeny, 1992) based on Wooding's (1968) equation for steady-state asymptotic flux. Sorptivity at saturation, S_o, was determined following the approach of White and Sully (1987). The hydraulic conductivity of the surface crust (K_c) was determined at saturation according to the Vandervaere et al. (1997) procedure for crusted soils.

The representative mean pore radius, l_y, which represents an effective "equivalent mean" pore radius that conducts water when infiltration occurs at a given value of y (White and Sully, 1987), was calculated according to Ankeny (1992)

$$l_y = (sK)/(rgf) \tag{4.1}$$

where s (g s^{-2}) is the surface tension of water, r (g cm^{-3}) is the density of water, g (cm s^{-2}) is the acceleration due to gravity and f is the matric flux potential. The number of l_y pores per unit area of infiltration surface, N_y, required to produce the measured K was estimated using the Poiseuille's law for flow in a capillary tube

$$N_y = (8mK)/\left(rgp\, l_y^4\right) \tag{4.2}$$

where m (g cm^{-1} s^{-1}) is the dynamic viscosity of water (Reynolds et al., 1995).

In order to determine the contribution of each pore class to flow, we have defined the "representative mean pore radius for two consecutive soil water tensions", l_{Dy}, as

$$l_{\Delta y} = \frac{s\,(K_i - K_{i-1})}{rg(f_i - f_{i-1})} \qquad i = 1, 2, \ldots n \tag{4.3}$$

where n is the number of measurements performed in a sequence. Therefore, the number of effective l_{Dy} pores per unit area, N_{Dy}, was calculated according to Watson and Luxmoore (1986)

$$N_{\Delta y} = [8m(K_i - K_{i-1})]/\left[rgp\left(l_{\Delta y}\right)^4\right] \qquad i = 1, 2, \ldots n \tag{4.4}$$

The effective porosity for two consecutive soil water tensions, q_x, is then given by the expression

$$q_x = N_{\Delta y}\, p\,(l_{\Delta y})^2 \tag{4.5}$$

According to classical capillary rise theory, the maximum pore radius, C_0, that will remain full of water under a given applied pore water pressure y is calculated (Reynolds et al., 1995) as

$$C_0 = -(2s)/(rgy) \qquad y < 0 \tag{4.6}$$

In our study we have defined macropores as those pores that drain at y >- 4 cm (C_0 > 0.375 mm; Clothier and White, 1981) and mesopores as those pores draining for y between - 4 and –14 cm (0.375 > C_0 > 0.107 mm). The contribution of both macropores and mesopores to the total saturated water flux, j, was calculated from

K_{14}, K_4, and K_0 (Watson and Luxmoore, 1986; Cameira et al., 2003) according to the expression

$$j_i(\%) = \frac{K_i - K_{i-1}}{K_0} x100 \qquad i = 1, 2, \ldots, n \qquad (4.7)$$

where n is the number of measurements performed in a sequence, K_i and K_{i-1} the hydraulic conductivity for two consecutive tensions and K_0 the saturated hydraulic conductivity.

The volumetric water content of soil beneath the infiltrating surface was determined just at the end of the infiltration measurement (steady-state flow at y = 0 cm) by TDR using the same TDR set-up described above. For this purpose, and prior to the infiltration run, a three-rod TDR probe (diameter: 2 mm; length: 100 mm; spacing for the outermost rods: 25 mm) was installed horizontally into the soil at 3-4 cm below the infiltrometer disc.

3. Results and discussion

3.1. Weather conditions and dynamics of soil water content

Precipitation records over the 3-yr experimental period show a high variability in the rainfall pattern for the different fallow periods and, particularly, around the tillage application dates (Fig. 4.1a). Thus, total precipitation between primary and secondary tillage practices was in general high and effective (effective rainfall is here defined as rainfall > 10 mm day-1). Effective rainfall between primary tillage and the post-tillage + rainfall sampling was 49, 33, and 61 mm for the 1999-2000, 2000-2001 and 2001-2002 fallow periods, respectively. It is worth to note the intense rainfall event after primary tillage in the 2001-2002 fallow period (40 mm in 24 h on 16 March 2002). Rainfall from secondary tillage to late fallow sampling was low and less effective.

Figure 4.1b shows the time course of volumetric soil water content (θ) in the upper 20 cm measured over the three experimental fallow periods under the CT, RT and NT treatments. Overall, while there were no differences in soil moisture between CT and RT before primary tillage, when the soil was consolidated, θ under NT was on average 0.03-0.04 m^3 m^{-3} higher than in tilled systems. These differences, however, were even larger after primary tillage (0.06-0.08 m3 m-3) as it can be observed for the rainy period after the 1999-2000 primary tillage practices as compared with the water recharge period at the beginning of the 2000-2001 fallow before tillage.

3.2. Soil bulk density

Table 4.1 presents the field bulk density (r_b) and corresponding q values measured in the 2-7 cm soil layer at the time of the infiltration measurements under the different fallow management treatments during the three experimental fallow seasons. Overall, *pre-tillage* values of topsoil r_b after 8-10 years under continuous NT were greater than under CT and RT treatments. A greater soil compaction under NT has been observed in other long-term experiments (Logsdon et al., 1990; Evett et al., 1999; Hernanz et al., 2002; Schwartz et al., 2003; Lampurlanés and Cantero-Martínez, 2003). This fact is commonly associated with the gradual consolidation of the soil matrix over time owing to rainfall and absence of annual tillage-induced loosening. On the other hand, the lower r_b values found 7-8 months after harvest of a barley crop under RT compared with CT can be related to a greater persistence of the soil loosening after chisel ploughing compared with mouldboard ploughing (Lopez et al., 1996).

As observed by several authors (Sauer et al., 1990; Logsdon et al., 1999; Miller et al, 1998; Mellis et al., 1996; Green et al., 2003), soil loosening of the plough layer after primary tillage decreased r_b in the 2-7 cm layer (Table 4.1; *post-tillage*). Soil reconsolidation due to post-tillage rainfall events and associated wetting and drying cycles (Mellis et al., 1996; Green et al., 2003) increased r_b in tilled plots

Table 4.1. Average dry bulk density (r_b) and volumetric water content (q) of the surface soil (2-7 cm) determined on four dates over the three experimental fallow seasons under conventional tillage (CT), reduced tillage (RT) and no-tillage (NT).

		Pre-tillage		*Post-tillage*		*Post-tillage + rain*		*Late fallow*	
Fallow season	Tillage treatment	ρ_b (g cm^{-3})	θ (m^3 m^{-3})	ρ_b (g cm^3)	θ (m^3 m^{-3})	ρ_b (g cm^{-3})	θ (m^3 m^{-3})	ρ_b (g cm^{-3})	θ (m^3 m^{-3})
1999-2000	CT	1.22	0.06	-	-	1.17	0.12	1.22	0.03
	RT	1.14	0.07	-	-	1.10	0.14	1.21	0.04
	NT	1.30	0.09	-	-	-	-	1.29	0.05
	LSD†	0.08	NS	-	-	NS	NS	NS	NS
2000-2001	CT	1.29	0.17	1.18	0.09	1.23	0.09	1.31	0.04
	RT	1.24	0.15	1.20	0.09	1.21	0.09	1.30	0.05
	NT	1.37	0.19	-	-	-	-	1.35	0.08
	LSD	0.07	NS	NS	NS	NS	NS	NS	NS
2001-2002	CT	1.25	0.16	1.17	0.12	1.20	0.13	1.17	0.07
	RT	1.17	0.18	1.09	0.10	1.11	0.14	1.07	0.10
	NT	1.38	0.20	-	-	-	-	1.45	0.16
	LSD	0.19	NS	NS	NS	NS	NS	0.14	0.04

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

(Table 4.1; *post-tillage + rain*). At this stage, the higher values of r_b observed under CT can be related as above mentioned with a more unstable topsoil structure induced by mouldboard ploughing. At the end of fallow, and following secondary tillage and additional rainfall events, the soil tends to recover the pre-tillage values of r_b (Table 4.1).

In the 40-45 cm soil layer, no significant differences in r_b were observed between tillage treatments at the end of the three fallow periods (data not shown). Regardless of tillage treatment, average values of r_b in this layer were higher (1.32, 1.54, and 1.38 g cm^{-3} in 2000, 2001 and 2002, respectively) than in the 2-7 cm layer (1.24, 1.32, and 1.23 g cm^{-3}). However, while r_b under NT presented comparable values in both layers, r_b under CT and RT was higher at 40 cm depth as expected in tilled soils (Moreno et al., 1999; Hernanz et al., 2002).

The bulk density of the surface crust, r_c, measured at the end of the 2001-2002 fallow period showed an average value of 1.28 g cm^{-3}, within the range of r_c values obtained by Roth (1997). No significant differences in r_c were found between tillage treatments. Crust thickness was similar in all plots (8 mm on average).

3.3. Soil water retention and pore-size distribution

The water retention curves, $q\ (y)$, estimated at 5 cm depth during the 2001-2002 fallow period are presented in Fig. 4.2. The fit of the van Genuchten's (1980) retention function to retention data showed marked differences between tillage treatments under consolidated soil conditions after 10 years of trial (Fig. 4.2a). Compared with CT and RT, NT water retention curves were characterised by a more gradual reduction in q as y increases and by greater values of q at y > -7 kPa. In addition, whereas fitted values of water content at saturation,q_{sat}, were 8% lower under NT than under CT and RT, water retention at field capacity, q_{FC} (y = -10 kPa) and permanent wilting point, q_{PWP} (y = -1500 kPa) was 2% and 3%

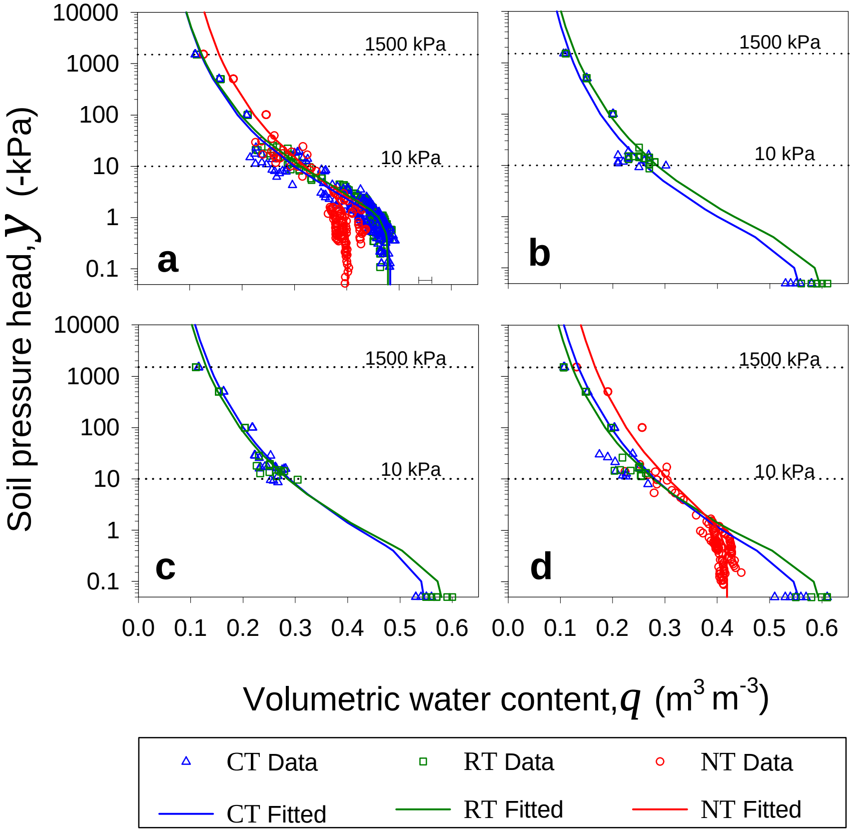

Figure 4.2. Soil water retention curves for conventional tillage (CT), reduced tillage (RT) and no-tillage (NT) at 5 cm depth on four dates over the 2001-2002 fallow period (Field 2): (a) before primary tillage (*pre-tillage*); (b) after primary tillage but before any rainfall event (*post-tillage*); (c) after primary tillage but following a period of intermittent rainfall events (*post-tillage+rain*); and (d) during the last phase of the fallow period (*late fallow*). Fitted curves for CT and RT in (b), (c) and (d) plots were obtained using total porosity, *x*, data as soil water content at saturation.

greater, respectively, under NT than under CT and RT. Similar results were found by Evett et al. (1999) on a clay loam soil after 12 years of trial. In contrast, Azooz et al.. (1996) found at the end of 13 years in a silt loam and four years in a sandy loam that soil under NT retained more water than under CT (i.e. chiselling) in the 0-7.5 cm depth of both soils along a soil matric pressure gradient (from -2 to - 400 kPa). After 8 years of trial, Hill et al. (1985) reported that the water retention of a loam soil at the surface (5-12.5 cm depth) was greater under NT than under CT (mouldboard ploughing) at any matric potential with the exception of 0 kPa. Other studies have reported greater water retention under NT than under mouldboard ploughing in the Ap horizon of silt loam soils for soil water potentials values from 0 to –40 kPa (Datiri and Lowery, 1991) and less than -10 kPa (Wu et al., 1992), but not in a clay loam soil (Wu et al., 1992) as found by Evett et al. (1999). The differences in $q\ (y)$ between tillage treatments near the soil surface have been associated to significant rearrangements of pore fractions (Azooz et al., 1996). In our study, an analysis of selected pore-size fractions showed that the structured topsoil (*pre-tillage* sampling) in the more dense NT plots presented the lowest values of aeration porosity (pores > 300 μm equivalent pore diameter, EDP), transmission porosity (pores between 30 and 300 μm EDP) and available water-holding capacity (AWHC) porosity (pores between 0.2 and 30 μm EDP) (Table 4.2).

Given that field measurements of q near saturation were inconsistent not only in loose, freshly tilled soils (*post-tillage* sampling) but also following a period of rainfalls (*post-tillage + rain*) and at the end of fallow (*late fallow*), soil water retention curves for CT and RT plots at those sampling dates were estimated from total porosity x (calculated from soil particle and bulk densities) and q measurements at y < -10 kPa (Fig. 4.2b, c and d). *Post-tillage* results showed that the increase in porosity observed after soil loosening by tillage is mostly associated

Table 4.2. Total pore volume and selected pore-size fractions[†] in the surface soil (2-10 cm depth) estimated from soil water retention curves (Fig. 4.2) at four times during the 2001-2002 fallow period under conventional tillage (CT), reduced tillage (RT) and no-tillage (NT).

Fallow samplings date	Tillage treatment	Total pore volume	Aeration porosity	Transmission porosity	AWHC
			%		
Pre-tillage	CT	48.3	3.0	15.2	18.0
	RT	47.9	1.9	14.9	18.9
	NT	40.2	0.5	8.2	16.0
	LSD[‡]	4.6	1.3	2.1	1.2
Post-tillage	CT	55.8	17.8	13.9	13.7
	RT	58.9	17.3	14.5	14.1
	NT	-	-	-	-
	LSD	NS	NS	NS	NS
Post-tillage + rain	CT	54.7	13.6	13.0	14.6
	RT	58.1	16.3	14.2	15.0
	NT	-	-	-	-
	LSD	NS	NS	NS	NS
Late fallow	CT	55.8	11.8	14.0	15.7
	RT	59.6	17.2	14.6	15.0
	NT	41.8	1.7	9.4	13.8
	LSD	9.4	2.7	2.1	NS

[†] Aeration porosity refers to pores > 300 μm equivalent pore diameter (EDP); transmission porosity refers to pores between 30 and 300 μm EDP; and AWHC is the available water-holding capacity or pores between 0.2 and 30 μm EDP.
[‡] Least significant difference, $P<0.05$. NS, not significant.

with an increase in the soil water retention at the wet end of the $q\ (y)$ curve. This result is in agreement with findings reported by Hamblin and Tennant (1981) and Lindstrom and Onstad (1984), cited by Ahuja et al. (1998), which showed that, in general, most of the increase in porosity is associated with the increase in number or volume fraction of the larger pores (i.e. pores corresponding with y > - 6 kPa). Thus, compared with *pre-tillage* pore-size distribution, aeration porosity increased by about 15%, transmission porosity did not change, and AWHC porosity decreased about 4% (Table 4.2).

In general, the post-tillage rainfall events modify $q\ (y)$ and pore-size distribution of freshly tilled soils through slaking and dispersion of soil aggregates during associated cycles of wetting and drying (Ahuja et al., 1998). In our study, this natural soil reconsolidation process slightly reduced the *post-tillage* total pore volume and changed pore-size distribution by destroying the largest pores, as indicated by a lower aeration porosity, and increasing the AWHC porosity (Fig. 4.2c; Table 4.2). These results agree with those found by Rousseva et al. (2002), who observed by image analysis of thin sections that after a series of simulated rainfalls, the macroporosity of a loam soil at the surface layers showed a strong decrease in the frequency of the larger pores, while the frequency of the smaller either increased or remained almost constant. In *late fallow*, soil water retention curves measured under CT and RT were similar to those estimated after primary tillage (Fig. 4.2b and d) because the scarce rainfall events recorded to the last fallow sampling were not enough to reconsolidate a loose tilled soil after secondary tillage implementation.

At 45 cm depth, the soil water retention curves were similar for the three tillage management systems, with average values of q_{sat}, q_{FC} , and q_{PWP} of 0.42, 0.23 and 0.13 $m^3\ m^{-3}$, respectively. However, whereas $q\ (y)$ curves under NT did not differ from those measured at 5 cm depth, $q(y)$ curves under CT and RT showed lower q_{sat} and greater q_{FC} and q_{PWP} values than at 5 cm depth.

3.4. Soil hydraulic properties

3.4.1. Soil hydraulic conductivity (K) and sorptivity (S).

K measurements at 2 cm depth for the different fallow periods and sampling dates, y values, and tillage treatments are summarised in Fig. 4.3. For structured, consolidated soil conditions (Fig. 4.3a), NT soil presented, after 8-10 years of

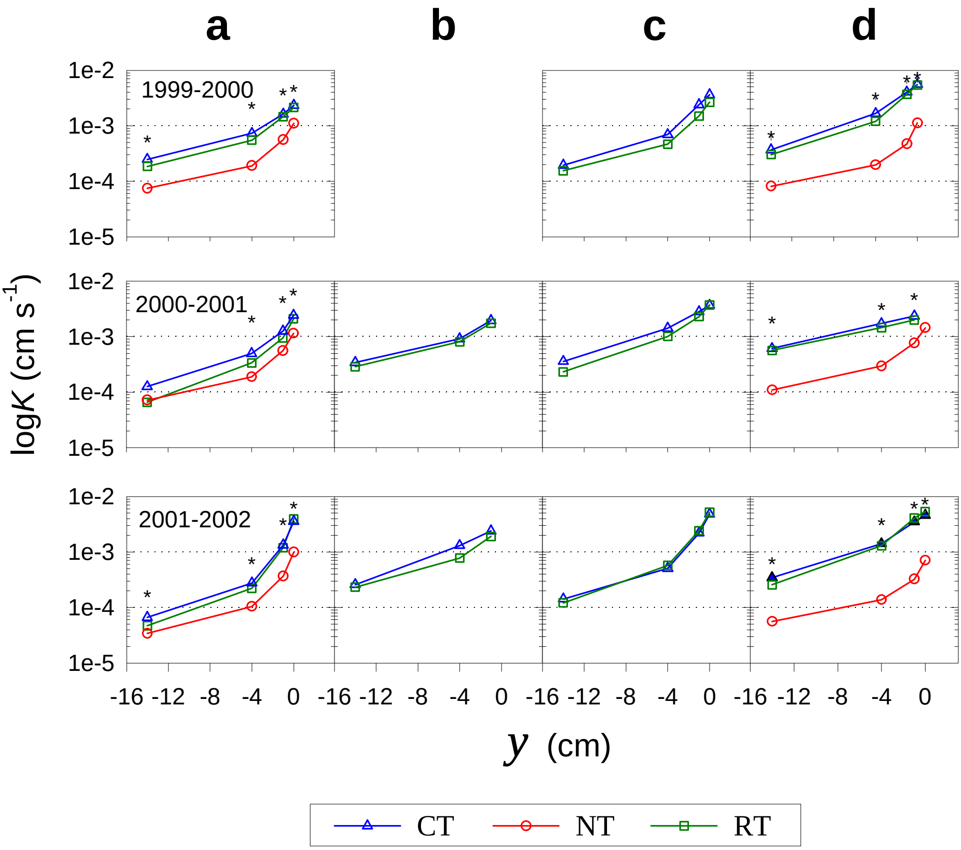

Figure 4.3. Soil hydraulic conductivity (K) versus pressure head (y) relationships for conventional tillage (CT), reduced tillage (RT) and no-tillage (NT) at 2 cm depth on four dates over the 1999-2000 (Field 2), 2000-2001 (Field 1) and 2001-2002 (Field 2) fallow periods: (a) before primary tillage (*pre-tillage*); (b) after primary tillage but before any rainfall event (*post-tillage*); (c) after primary tillage but following a period of intermittent rainfall events (*post-tillage+rain*); and (d) during the last phase of the fallow period (*late fallow*). * Significant difference among tillage treatments at $P < 0.05$.

continuous no-tillage management, and for the entire range of applied soil water pressure heads, K values significantly lower than those observed in CT and RT soils. However, no differences in K were found between CT and RT treatments. These results are similar to those found in other studies (Sauer et al., 1990; Moreno et al., 1997; Miller et al., 1998; Evett et al., 1999), but deviate from the general tendency in the long-term for NT soil to increase its near-saturated K as compared with CT practices (Green et al., 2003). Regardless of the fallow periods, as y decreased from –14 to 0 cm, overall K was found to increase by 1.3, 1.5, and 1.3 orders of magnitude for CT, RT and NT, respectively. Mean K_o and K_1 values under CT and RT were significantly greater in 2002 than in 2000 and 2001, which might reflect an important inter-annual variability in the process of soil consolidation during fallow and crop growing season. However, K under NT kept constant values throughout the three experimental fallow periods, which indicates a greater stability in soil water transmission properties in this treatment.

Primary tillage operations in CT and RT plots increased K_{14}, K_4 and K_1 (Fig. 4.3b) compared with *pre-tillage* values. This result is in agreement agrees with findings in other studies (Sauer et al., 1990; Messing and Jarvis, 1993; Cameira et al., 2003), in which greater infiltration rates were measured after tillage due to an increase in soil porosity. Unreliable *post-tillage* infiltration measurements at $y = 0$ cm, probably due to soil macrostructure collapsing below the infiltrometer (Moret and Arrúe, 200x; Capítulo 3), were discarded from the analysis. No differences in K were observed between CT and RT treatments.

Rainfalls following primary tillage affected K under CT and RT, as a consequence of soil structural changes caused by subsequent wetting and drying cycles (Angulo-Jaramillo et al., 1997). In general, a decrease of K_{14} and K_4 was observed, which is in agreement with the concomitant slight increase in bulk density (Table 4.1). On the other hand, the change in K was directly proportional to rainfall intensity, which controlled soil aggregate breakdown and, consequently, the rate of soil reconsolidation. This was the case of the 2001-2002 fallow period, where high effective rainfall events received after primary tillage (61 mm) resulted in a higher decrease in K_{14} and K_4, compared with the 2000-2001 fallow, with only 33 mm of effective precipitation (Fig. 4.1a). Overall, the high values of K in *late fallow* (Fig. 4.3d), 2-3 months after secondary tillage (Fig. 4.1a) can be explained by the scarce rainfall events recorded in that period, which did not allow a complete soil reconsolidation. K_o for CT and RT in the 2000-2001 fallow are not shown in Fig. 4.3d due to inconsistent soil water flow values as explained above.

At 40 cm depth, no significant differences in K were observed between tillage systems over the three experimental fallow years. K_{14}, K_4, K_1, and K_0 showed an average value of 1.4 x 10^{-3}, 0.7 x 10^{-3}, 0.3 x 10^{-3} and 0.1 x 10^{-3} cm s^{-1}, respectively. This result indicates that neither mouldboard nor chisel management disturbed the soil below the depth of ploughing (Logsdon et al., 1999). Compared with K values at 2 cm depth, whereas no differences in K were observed under NT, tilled treatments showed lower K values at 40 cm depth. A similar result was obtained in a clayey soil by Moreno et al. (1999), who suggested that differences in K between the soil surface and a depth of 30 cm in tilled soils may be associated with a larger number of macropores and fissures near the surface.

The average values of K at saturation for the surface crust (K_c) under CT, RT, and NT were 1.7 x 10^{-3}, 1.3 x 10^{-3}, and 1.1 x 10^{-3} cm s^{-1}, respectively, with no significant differences between tillage treatments and years. These figures are within the range of K_c values reported by Chartres (1992) for rain-impact crusts developed following cultivation in Australian Alfisols also with loamy textured A horizons. On the other hand, K_c under CT and RT was from 1/3 to 1/6 the underlying soil K_0, as observed in previous crust studies by Tackett and Pearson (1965) and Vandervaere et al. (1997). No differences between K_c and K_0 at 2 cm depth were observed under NT.

Table 4.3. Sorptivity of the soil surface (2 cm) at 0 cm tension measured on three occasions within three experimental fallow seasons under three management treatments (CT, conventional tillage; RT, reduced tillage; NT, no-tillage).

Fallow period	Tillage treatment	*Pre-tillage*	*Post-tillage + rain*	*Late fallow*
		mm $s^{-0.5}$		
1999-2000	CT	0.732	0.724	1.255
	RT	0.633	0.553	1.147
	NT	0.345	-	0.371
	LSD†	0.161	0.121	0.121
2000-2001	CT	0.449	1.100	1.433
	RT	0.421	0.826	1.196
	NT	0.304	-	0.488
	LSD	0.106	NS	0.301
2001-2002	CT	0.460	0.596	0.986
	RT	0.471	0.466	1.064
	NT	0.261	-	0.278
	LSD	NS	NS	0.212

† Least significant difference, P<0.05. NS, not significant.

Soil sorptivity at saturation, S_o, measured at 2 cm depth is presented in Table 4.3. After 8-10 years of trial, S_o under NT was significantly lower than under CT and RT treatments, for which no differences in S_o were observed. These results, which were comparable to those obtained by Sauer et al. (1990), agree with the lower porosity measured under NT (Table 4.2). Average *pre-tillage* S_o at 2 cm depth (0.45 mm $s^{-0.5}$) was within the same order of magnitude of the S_o measured by López and Arrúe (1997) at 20 cm depth in the same soil after harvest (0.62 mm $s^{-0.5}$) using a Guelph permeameter. The increase in S_o under CT and RT at the *post-tillage + rain* and *late fallow* sampling dates should be related with an increment in total soil porosity and number of conductive mesopores induced by the tillage (Cresswell et al., 1993; Logsdon et al., 1993). There were no differences in S_o among tillage treatments at 40 cm depth, where the average value of S_o was 0.36 mm $s^{-0.5}$.

3.4.2. K, l_y and N_y relationships

Regardless of tillage treatment, the l_y and N_y vs. K relationships at 2 cm depth for structured soil conditions (Fig. 4.4a) were similar to those reported by Reynolds et al. (1995). On one hand, l_y was relatively constant at its minimum value of about 0.1 mm for small K, but then increased with increasing K when K became large. This behaviour could be the result of constrictions (e.g. pore necks, entrapped air bubbles) and discontinuous pores within the y range where l_y is constant (Reynolds et al., 1995). On the other hand, N_y, which is inversely related to l_y (Fig. 4.4a), increases when K decreases. Thus, for a given K, small values of l_y were compensated by larger N_y values and vice versa. For instance, whereas K_1 and K_o for the 2000-2001 fallow period were defined by large N_y and small l_y values, in the 2001-2002 fallow period lower N_y values were compensated by an increase in l_y (Fig. 4.4a). The N_y vs l_y relationship in the 2000-2001 fallow season under CT and RT presented, as found by Reynolds et al. (1995), a maximum N_y in the vicinity of l_y = 0.1-0.2 mm. In the other cases, the maximum N_y occurred for l_y < 0.1 mm. For the three tillage treatments, and throughout the entire range of y, l_y varied between 0.1 and 0.9 mm, as reported by other researchers (Sauer et al., 1990; Reynolds et al., 1995; Angulo-Jaramillo et al., 1997). Likewise, N_y values for the three tillage systems varied between 20 and 17000 pores per m^2 for y = 0 cm and y = –14 cm, respectively.

For sampling before primary tillage implementation (Fig. 4.4a), both l_y and N_y were also affected by the different tillage treatments. Thus, for K_{14}, l_y and N_y were smaller and greater, respectively, under NT than under CT and RT. These results are consistent with the lower porosity found under NT (Table 4.2), as a

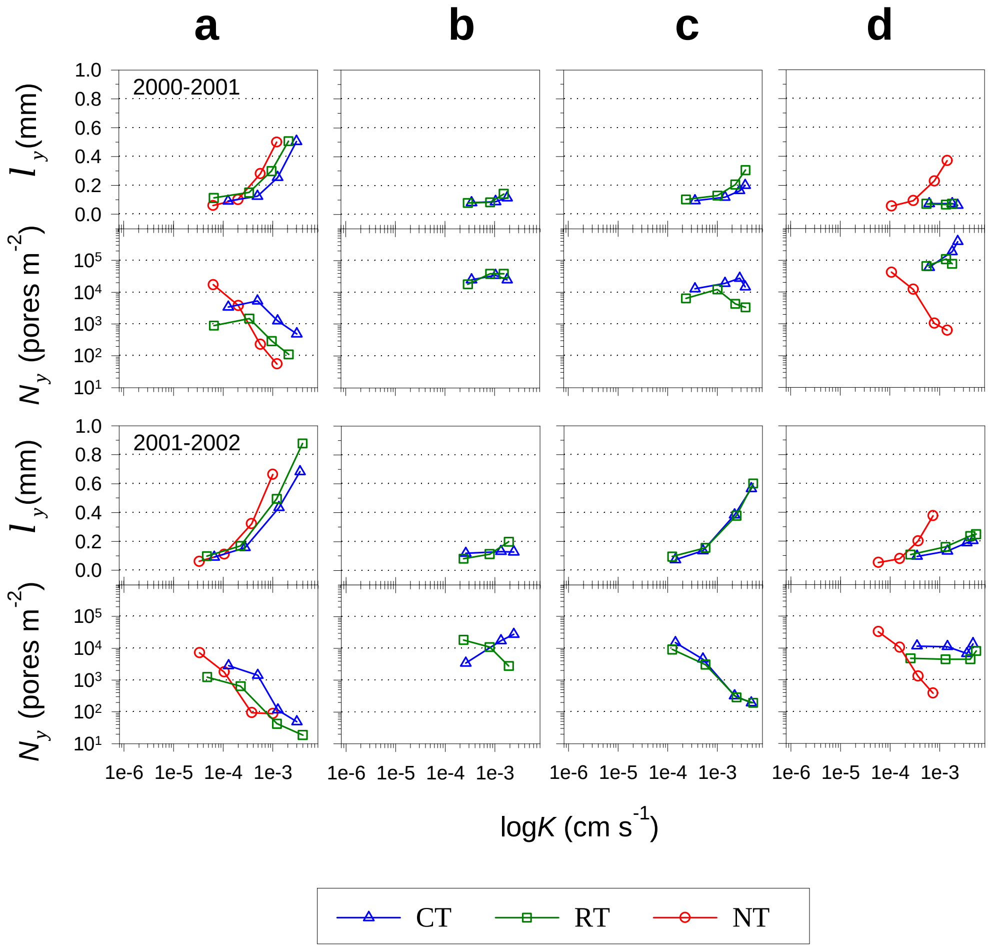

Figure 4.4. Number of effective water transmitting macropores per unit area (N_y) and representative mean pore radius (l_y) versus soil hydraulic conductivity (K) at 2 cm depth under conventional tillage (CT), reduced tillage (RT) and no-tillage (NT) at four dates over the 2000-2001 (Field 1) and 2001-2002 (Field 2) fallow periods: (a) before primary tillage (*pre-tillage*); (b) after primary tillage but before any rainfall event (*post-tillage*); (c) after primary tillage but following a period of intermittent rainfall events (*post-tillage+rain*); and (d) during the last phase of the fallow period (*late fallow*). Bars represent LSD (P < 0.05) for comparison among tillage treatments where significant differences were found.

consequence of the gradual consolidation of the soil matrix over time due to rainfall and absence of annual tillage-induced loosening (Reynolds et al., 1995).

Primary tillage strongly modified the configuration of the water transmitting pores within the soil matrix in the CT and RT plots. Although, in general, an increase in N_y and a reduction of l_y were observed in these treatments over the K_1 to K_{14} range, these changes were more important at K_1 (average increase of 65% for N_y and average decrease of 70% for l_y) (Fig. 4.4b). This behaviour may be the result of soil pulverisation at the soil surface due to ploughing (Sauer et al., 1990), which destroys active macropores thus increasing the number of smaller pores (Malone et al., 2003). For the K measurement range, average values of l_y and N_y varied between 0.1 and 0.2 mm in the first case and between 3500 and 24000 pores per m^2 in the second. There were no significant differences in l_y and N_y between CT and RT treatments (Fig. 4.4b).

Post-tillage rainfalls during the 2000-2001 and 2001-2002 fallow periods increased l_y and reduced N_y at K_1, but slightly modified these parameters at K_{14} and K_4. These changes, which depend on the amount and intensity of rainfall events recorded after primary tillage, were more dramatic in the 2001-2002 fallow period characterised by a high effective precipitation (Fig. 4.4c). In *late fallow*, the l_y and N_y vs K_y relationships under CT and RT (Fig. 4.4d) were similar to those obtained after primary tillage (Fig. 4.4b). This was due to both the effect of secondary tillage that loosened the upper 15 cm of soil and the low rainfall received from secondary tillage date to late fallow sampling (Fig. 4.1a).

No significant differences in l_y and N_y were observed among tillage systems at 40 cm depth. The average values of l_y for K_o, K_1, K_4 and K_{14} were 0.36, 0.18, 0.09 and 0.07 mm, respectively. Similarly, average N_y for K_o, K_1, K_4 and K_{14} was 2300, 3600, 16000 and 22000 pores per m^2, respectively.

3.4.3. Contribution of macropores and mesopores to water flow

The large increase in K over the small increase in y at 2 cm depth (Fig. 4.3a) indicates, as suggested by Sauer et al. (1990) and Reynolds et al. (1995), that extensive macropores networks exist in the three tillage treatments near saturation under consolidated soil conditions. For convenience we have defined macropores and mesopores as those pores delimited by values of y between - 4 and 0 cm and between - 4 and -14 cm, respectively. For these pore classes, the representative mean pore radius, l_{Dy}, and the concentration of l_{Dy} pores, N_{Dy}, are presented in Table 4.4. On average, and regardless of tillage system, macropores have a greater l_{Dy} (1.3 mm) than mesopores (0.2 mm) and a lower N_{Dy} (65 pores x m^{-2}) than mesopores (1400 pores x m^{-2}). This results in a lower effective porosity, q_x, of macropores (Eq. 4.5) than that calculated for mesopores (Table 4.5). However, the higher q_x observed for mesopores did not denote a higher contribution of these pores to the flux, j (Table 4.5). Results indicate that macropores have a larger influence upon water flow than mesopores despite the fact that they occupy a much smaller fraction of total soil porosity, as observed by Messing and Jarvis (1993) and Cameira et al. (2003).

Pre-tillage values of l_{Dy} and N_{Dy} (Table 4.4) and q_x (Table 4.5) measured at 2 cm depth were affected by the tillage treatments. Thus, NT macropores have a lower N_{Dy} (3.9 pores x m^{-2}) and a lower q_x (0.0003%) but a greater l_{Dy} (2.09 mm) than CT and RT macropores (on average, N_{Dy} = 96 pores x m^{-2}, q_x = 0.0039%, and l_{Dy} = 0.97 mm). On the contrary, whereas no differences in l_{Dy} for mesopores were detected between tillage treatments, CT and RT showed a significantly greater N_{Dy} and q_x than NT. These results suggest, as proposed by Sauer et al. (1990), that different soil structural conditions existed for the three tillage treatments. On the other hand, despite the differences found in soil water transmitting pore characteristics among tillage systems, the water flux was mainly dominated by

Table 4.4. Representative pore size, l_{Dy} (mm) and number of l_{Dy} pores per unit of area (pores per m^2), N_{Dy}, for soil macropores ($0<y<4$ cm)† and mesopores ($4<y<14$ cm)‡ measured at 2 cm depth on four dates during the experimental fallow seasons under different management treatments (CT, conventional tillage; RT, reduced tillage; NT, no-tillage).

Fallow season	Tillage treatment	*Pre-tillage*				*Post-tillage*				*Post-tillage+rain*				*Late fallow*			
		Macropores		*Mesopores*		*Macropores*		*Mesopores*		*Macropores*		*Mesopores*		*Macropores*		*Mesopores*	
		$\lambda_{\Delta\psi}$	$N_{\Delta\psi}$	$\lambda_{\Delta\psi}$	$N_{\Delta\psi}$	$\lambda_{\Delta\psi}$	$N_{\Delta\psi}$	$\lambda_{\Delta\psi}$	$N_{\Delta\psi}$	$\lambda_{\Delta\psi}$	$N_{\Delta\psi}$	$\lambda_{\Delta\psi}$	$N_{\Delta\psi}$	$\lambda_{\Delta\psi}$	$N_{\Delta\psi}$	$\lambda_{\Delta\psi}$	$N_{\Delta\psi}$
1999-2000	CT	0.88	166	0.13	5200	-	-	-	-	0.42	274	0.18	1150	0.32	1666	0.16	6392
	RT	0.66	337	0.27	2400	-	-	-	-	0.94	132	0.21	533	0.41	2459	0.18	2162
	NT	2.44	3.7	0.29	118	-	-	-	-	-	-	-	-	2.34	1.0	0.23	7257
	LSD§	NS	NS	NS	2090	-	-	-	-	NS	NS	NS	NS	0.93	789	NS	NS
2000-2001	CT	1.02	45	0.14	2781	-	-	0.09	76804	0.45	12236	0.13	10470	-	-	0.07	63872
	RT	0.96	11	0.16	871	-	-	0.09	15282	0.41	860	0.14	6917	-	-	0.06	58068
	NT	1.96	0.4	0.25	536	-	-	-	-	-	-	-	-	1.59	0.4	0.16	906
	LSD	0.62	NS	NS	NS	-	-	NS	NS	NS	NS	NS	NS			0.04	268
2001-2002	CT	1.08	12	0.20	367	-	-	0.15	14619	0.97	58	0.22	476	0.46	9137	0.15	4536
	RT	1.25	7.0	0.21	199	-	-	0.14	26634	1.01	91	0.21	548	0.28	14284	0.19	2175
	NT	1.89	7.1	0.19	165	-	-	-	-	-	-	-	-	1.98	0.2	0.15	1864
	LSD	NS	NS	NS	NS	-	-	NS	NS	NS	NS	NS	NS	0.44	1304	NS	NS

† Pressure head range defining macropores (pore radius > 0.375 mm) according to the capillary rise theory.
‡ Pressure head range defining large mesopores (pore radius between 0.375 and 0.107 mm) according to the capillary rise theory.
§ Least significant difference (P<0.05). NS, not significant.

Table 4.5. Effective porosity ($q_{å}$) and contribution to flow (j) of soil macropores ($0<y<4$ cm)† and mesopores ($4<y<14$ cm)‡ measured at 2 cm depth on four dates during the experimental fallow seasons under different management treatments (CT, conventional tillage; RT, reduced tillage; NT, no-tillage).

Fallow season	Tillage treatment	*Pre-tillage*				*Post-tillage*				*Post-tillage+rain*				*Late fallow*			
		Macropores		*Mesopores*		*Macropores*		*Mesopores*		*Macropores*		*Mesopores*		*Macropores*		*Mesopores*	
		θ_ε	φ	θ_ε	φ	θ_ε	φ	θ_ε	φ	θ_ε	φ	θ_ε	φ	θ_ε	φ	θ_ε	φ
									%								
1999-2000	CT	0.0066	69	0.0228	21	-	-	-	-	0.0121	80	0.0113	15	0.0395	71	0.0401	23
	RT	0.0079	77	0.0128	15	-	-	-	-	0.0052	86	0.0056	9	0.0501	76	0.0205	18
	NT	0.0006	79	0.0012	13	-	-	-	-	-	-	-	-	0.0001	77	0.0095	14
	LSD§	NS	11	0.0085	7	-	-	-	-	NS	NS	NS	NS	0.0101	NS	0.0265	7
2000-2001	CT	0.0027	78	0.0139	16	-	-	0.0731	-	0.0485	57	0.0477	32	-	39	0.0126	-
	RT	0.0013	83	0.0071	14	-	-	0.0042	-	0.0186	72	0.0314	22	-	54	0.0104	-
	NT	0.0003	83	0.0039	16	-	-	-	-	-	-	-	-	0.0018	78	0.0056	14
	LSD	NS	NS	0.0072	NS	-	-	NS	-	NS	NS	NS	NS	-	37	0.0030	-
2001-2002	CT	0.0029	91	0.0041	7	-	-	0.0488	-	0.0062	89	0.0062	8	0.0583	69	0.0321	24
	RT	0.0022	94	0.0027	4	-	-	0.0351	-	0.0079	89	0.0072	9	0.0766	75	0.0215	20
	NT	0.0001	88	0.0016	8	-	-	-	-	-	-	-	-	0.0001	76	0.0052	12
	LSD	0.0032	NS	0.0016	NS	-	-	NS	-	NS	NS	NS	NS	0.0662	5	0.0093	4

† Pressure head range defining macropores (pore radius > 0.375 mm) according to the capillary rise theory.
‡ Pressure head range defining large mesopores (pore radius between 0.375 and 0.107 mm) according to the capillary rise theory.
§ Least significant difference (P<0.05). NS, not significant.

macropores (Table 4.5). In agreement with Miller et al. (1998), it can be concluded that the lower K values under NT are related to a lower number of large pores, which is consistent with the significantly greater values of r_b under NT (Table 4.1).

Data available for mesopores after primary tillage showed a significant reduction in l_{Dy} and increase in N_{Dy} (Table 4.4) and q_x (Table 4.5), which indicates, as suggested by Sauer et al. (1990) and Malone et al. (2003), that tillage destroys macropores and changes their characteristics (tortuosity, continuity, etc.). Later,wetting and drying cycles associated with intermittent rainfall events after primary tillage contributed to rearrange the soil pore configuration towards the initial *pre-tillage* conditions, as indicated by an increase in l_{Dy} and a decrease in N_{Dy} and q_x for mesopores (Tables 4.4 and 4.5). These results agree with Messing and Jarvis (1993), who observed a decrease in the mesopores fraction (for y between –6 and –11 cm) after post-tillage rainfalls. In our case, these changes varied for the different long-fallow periods as a function of the amount and intensity of effective rains after tillage. Thus, in the 2000-2001 fallow, a low effective rainfall after primary tillage helped to maintain the large number of small pores created by tillage (Table 4.4) and increase j for mesopores compared with the *pre-tillage* situation (Table 4.5). In contrast, in the 1999-2000 and 2001-2002 fallow periods, where a strong soil reconsolidation following intensive rains after tillage, macro- and mesopores characteristics and contribution to flow were closer to those measured under *pre-tillage* soil conditions.

Mesopore characteristics in *late fallow* under CT and RT in the 2000-2001 and 2001-2002 fallow periods were rather similar to those obtained after primary tillage cultivation (Tables 4.4 and 4.5). Soil loosening by secondary tillage, along with a low precipitation after this cultivation (Fig. 4.1a), increased N_{Dy} and q_x and decreased l_{Dy} for both macro- and mesopores. Likewise, an increase of j for mesopores was observed in relation to a *pre-tillage* situation.

No significant differences in l_{Dy} and N_{Dy} were observed for both macro- and mesopores between tillage systems and fallow periods at 40 cm depth. For this layer, average values of l_{Dy} for macropores and mesopores were 0.98 and 0.10 mm, respectively. The average N_{Dy} for macro- and mesopores was 7 and 13290 pores per m^2, respectively. Although NT presented a similar number of effective macropores at both 2 and 40 cm depth, these macropores decrease with depth in tilled plots as observed by Trojan and Linden (1998).

3.4.4. Validity of l_{Dy} as a pore index

Malone et al. (2003) have recently reviewed the literature on the use of tension infiltrometer measurements to quantify soil surface and subsurface macropores as affected by tillage. Normally, total “hydraulically active” macroporosity is determined from tension infiltrometer data according to the procedure proposed by Watson and Luxmoore (1986). The minimum equivalent pore radius, C_0, calculated from the capillary equation (Eq. 4.6) for a give tension range is used to compute the maximum number of effective pores per unit area, N_{WL}, using the Poiseuille’s law

$$N_{WL} = [8m(K_i - K_{i-1})] / \left[rgp\,(C_0)^4\right] \qquad i = 1, 2, \ldots n \qquad (4.8)$$

The effective porosity, q_{WL}, is computed from C_0 and N_{WL} (Watson and Luxmoore, 1986)

$$q_{WL} = N_{WL}\,p\,(C_0)^2 \qquad (4.9)$$

However, as pointed out by Reynolds et al. (1995), this approach introduces an inconsistency because K in (Eq. 4.8) is related to the range of pore size participating in water transmission and C_0 relates the maximum pore size of water storage for a given tension under static conditions. For this reason, we propose to compute both the number of conductive pores and effective porosity for each pore-size class using an alternative pore index, l_{Dy} (Eq. 4.3), that defines the representative mean pore radius for two consecutive soil water tensions relevant to dynamic conditions (Reynolds et al., 1995). In theory, l_{Dy} for a given tension range cannot be higher than the maximum corresponding C_0 radius. The fact that l_{Dy} for y between – 4 and – 14 cm (Table 4.4) was in all cases less than the maximum C_0 for that y range (0.375 mm), demonstrates the consistency of l_{Dy} as a pore index.

If the number of water transmitting pores, N_{WL} (Eq. 4.8), under consolidated soil conditions is compared with N_{Dy} (Eq. 4.3), results show that the procedure of Watson and Luxmoore (1986) overestimates the number of both macropores (N_{Dy} = 0.20 N_{WL} + 0.013; R^2 = 0.04) and mesopores (N_{Dy} = 0.02 N_{WL} - 0.004; R^2 = 0.34). This finding is explained by the fact that the minimum C_0 for macropores (0.375 mm) and mesopores (0.107 mm) considered in (Eq. 4.8) is in most cases smaller than l_{Dy} (Table 4.4). Consequently, q_{WL} (Eq. 4.9) is greater than q_x (Eq. 4.4) for macropores (q_x = 0.15q_{WL} + 0.0001; R^2 = 0.42) and mesopores (q_x = 0.62q_{WL} – 0.0001; R^2 = 0.58).

4. Conclusions

Results show that the type of fallow tillage management in the cereal-fallow rotation significantly affects soil hydrophysical properties in both the long- and the short-term. Thus, after 8-10 years of trial in a long-term tillage experiment in Central Aragon, soil under no-tillage (NT) presented more compacted topsoil than under conventional (CT) and reduced tillage (RT). Likewise, soil water retention characteristics showed significant differences between NT and tilled treatments. Compared with CT and RT, the more dense NT soil resulted in retention curves exhibiting a more gradual reduction in water content as tension increased, with lower water content near saturation and a lower available water-holding capacity. Regardless of tillage system, soil water flow at the soil surface was mainly regulated by macropores, despite the fact this pore fraction occupies a very small fraction of total soil porosity. However, although a bigger macropore size was observed under NT, soil hydraulic conductivity (*K*) near saturation under this treatment was significantly lower than under CT and RT due to a lower number of water transmitting macro- and mesopores per m^2. Overall, no significant differences in hydraulic properties were found between CT and RT. On the other hand, and compared with values found at the soil surface, lower *K* values were observed at 40 cm depth under CT and RT in agreement with greater soil bulk density values at that layer.

In the short-term, soil hydrophysical properties under CT and RT changed over the fallow period as a function of soil structure modification by tillage operations and subsequent rainfall events. Surface soil loosening by tillage increased the aeration porosity (pores > 300 μm) and decreased the available water retention micropores (pores between 30 and 0.2 μm). Likewise, tillage significantly increased the number of water conducting mesopores, which determined a significant increase of *K*. However, a decrease of total soil porosity occurred as a consequence of soil reconsolidation by post-tillage rains and associated wetting and drying cycles. This implied a reduction of the larger pore-size fractions and, consequently, a decline of *K*. The magnitude of these soil structural changes, which tended to restore pre-tillage conditions, increased with the intensity of post-tillage rainfall events.

Inconsistencies arising from the application of classical capillary rise theory to calculate the effective radius of hydraulically active pores and related parameters (Reynolds et al., 1995) were analysed and an alternative pore index proposed. The soundness of this new index, which is relevant to dynamic conditions and represents the mean equivalent pore radius for two consecutive soil water tensions, was verified. The use of this index to calculate the number of water transmitting pores per unit area of infiltration surface and corresponding effective porosity has shown how the use of capillary rise approach may overestimate these parameters.

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Capítulo 5

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

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To be submitted to: *Agricultural Water Management*

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

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 used to increase soil water storage and water available for the next crop. However, the ability of long fallow to store water has been questioned in several semiarid regions. 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 three 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 each fallow phase or the entire fallow period , increased when most of seasonal

effective rainfalls (≥ 10 mm day^{-1}) were received in the last two months of each period regardless of total rainfall. 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 with long fallow compared with short fallow was 22 mm. Correspondingly, the average precipitation storage efficiency of long fallow relative to short fallow was only 5.2%. As a conclusion, long fallowing as an agronomic practice to enhance soil water storage for the subsequent crop is not enough justified on the study area.

1. Introduction

Water is the main limiting factor for grain production in rainfed farming systems of many semiarid dryland regions. Cereal crops are frequently grown under a crop-fallow system (one crop every two years), which generally involves a long-fallow period used 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 judgements of fallow use to increase soil water storage are found in the literature. Thus, whereas Bonfil et al. (1999) observed, working in a semiarid region 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 USA since only about 20% of fallow precipitation was stored as soil water.

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) and soil protection against wind and water erosion (Pannkuk et al., 1997). Thus, adoption of conservation tillage systems has been proposed as an alternative to the traditional fallow tillage management (Schillinger, 2001). However, the agronomic advantages of conservation tillage have been also questioned when soil water storage efficiency during and at the end of the fallow period is analysed. Whereas some authors (Incerti et al., 1993; Dalrymple et al., 1993; Unger, 1994; Pannkuk et al., 1997; and Tanaka and Anderson, 1997) did not observe differences in soil water storage between conventional and conservation tillage, other researchers (Schillinger and Bolton, 1993; O'Leary and Connor; 1997; Jones and Popham, 1997) reported that no-tillage increases the fallow precipitation storage efficiency. Although this efficiency has substantially increased under the modern no-till and residue management techniques, it is evident that even under these conservation practices, the original criticism of fallow still remains, and fallow precipitationstorage efficiency remains low (Farahani et al., 1998a).

In the cereal growing areas of Central Aragon, a semiarid region in the Ebro River valley of Spain with an average annual precipitation less than 400 mm, rainfall is sporadic and highly variable from year to year during both the fallow period and the growing season. The fallow period extends from harvest (June-July) and continues for 16 to 18 months until 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 fallowing in the cereal-fallow rotation, with either traditional or conservation tillage management, appears to be an inefficient practice for improving soil water storage when compared with continuous cropping. 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.

The objectives of this study, which is included in a long-term field experiment aimed to evaluate the feasibility of conservation tillage systems in a dryland cereal-growing area of Central Aragon, were to quantify and compare the efficiency of conventional tillage vs. conservation tillage (reduced tillage and no-tillage) to conserve water over three 16-18 month fallow periods. In addition, soil water losses by evaporation immediately after primary and secondary tillage implementation were evaluated. Finally, the precipitation storage efficiency of long-fallow under the three fallow tillage management systems was compared with the efficiency of the short-fallow (5-6 month long) 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 °C. 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 (hereafter called 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, 2000-2001season in field CF2 and 2001-2002 season again in field CF3) and three short fallow periods in field CC1 (Table 5.1). 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 early summer* (FS) and the third one from *early summer 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 5.1). NT used exclusively herbicides (glyphosate) 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). The three large blocks of ten plots were arranged 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

Table 5.1. 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 (17-18 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.

range test was used to compare between 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 (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, 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 (q) content in the 0-10, 0-20, 0-40 and 0-70 cm soil layers was continuously monitored, on a weekly basis or as a function of rainfall events, by Time Domain Reflectometry (TDR). 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 q for each soil depth. The multiple length probe method described by Miyamoto et al. (2001) was used afterwards to calculate q 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 before implied a total of 18 measurements of q (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:

$$P = E + SWS \tag{5.1}$$

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 minus the profile soil water at the beginning of the fallow period.

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

$$PSE = (SWS / P) \times 100 \quad (5.2)$$

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

$$RPSE = (\Delta SWS / P_{TS}) \times 100 \quad (5.3)$$

where ΔSWS is the additional soil water (0-70 cm) at sowing with 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 cropping systems on the following year (López et al., 1996).

3. Results and discussion

3.1. Weather conditions

The experimental (26 June 1999-19 November 2002) period 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%, respectively, below the long-term average. Rainfall patterns were also contrasted among the three fallow periods and, particularly, among fallow sub-periods (Table 5.2). 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 and 28% above normal in the 2000-2001 fallow. In the second sub-period, FS (December-May), rainfall below long-term average in the 2001-2002 fallow. On the other hand, while the contribution of 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 5.2, the effective rainfall (here defined as the fraction of monthly precipitation received in days with a rainfall $\geq$ 10 mm) can be very low or even nil in almost every month. These

Table 5.2. 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 (ET_0) for the 1999-2002 period at Peñaflor experimental site.

	Precipitation										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).

features are consistent with those reported by McAneney and Arrúe (1993) analysing a 35-yr time series of monthly rainfall data from a 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 5.3 summarises the soil water loss (*E*), soil water storage (*SWS*) and precipitation storage efficiency (*PSE*) for the three experimental fallow periods. As discusses below, tillage management and rainfall pattern during the three periods in which the fallow was partitioned differently affect these fallow characteristics.

3.2.1. Soil water losses

Overall, during the first phase of fallow, HF, from harvest to late fall, soil water loss (*E*) was small compared with the second an third fallow phases in the three fallow periods (Table 5.3). Even though in the first part of HF (July-September) potential evaporation is high (6.5 mm day^{-1}) (Table 5.2), the reasons for a low *E* in the entire HF phase can be related with: i) a higher crop residue on soil surface (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 surface 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 actes as a surface resistance to soil evaporation (van de Griend and Owe, 1994); and iii) a low q and rainfall after harvest (July-August), when ET_0 is high, and a low

Table 5.3. 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	4	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 stored water 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

evaporative demand at the end of the sub-period (Table 5.2). Over the three fallow periods, *E* was positively correlated with the precipitation, *P*, received in the HF period ($E = 0.54\ P + 26.82$; $R^2 = 0.92$). 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. 5.1). 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. 5.2a). This important soil water losses immediately after tillage, also reported by Reicosky et al. (1999), may be related with an increment in soil surface roughness (Fig. 5.3), 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 c*ierzo* 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 in the CT plots induced a higher *E* than vertical chisel ploughing in RT (Fig. 5.2a). 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, 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

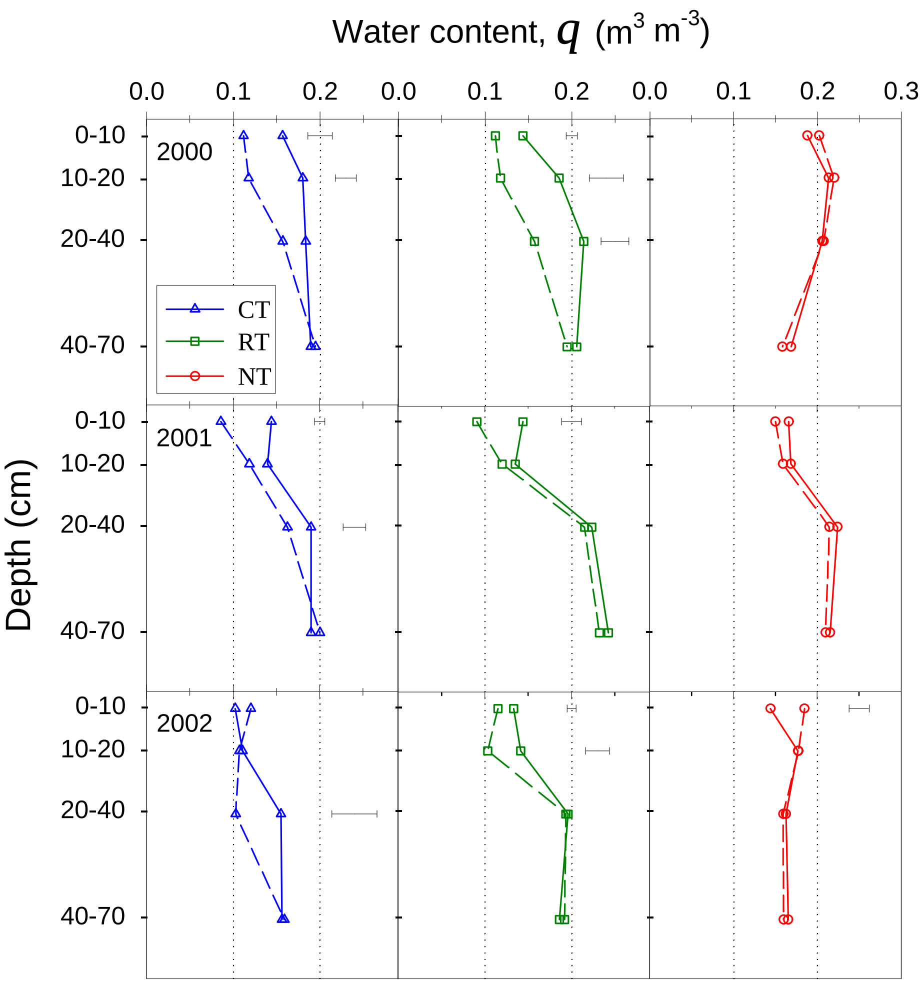

Figure 5.1. Soil water content profile measured under conventional tillage (CT), reduced tillage (RT) and no-tillage (NT) treatments before (continuous line) and after (broken line) primary tillage implementation on CT and RT plots in the 1999-2000, 2000-2001 and 2001-2002 fallow periods. Horizontal bars represent LSD (P<0.05) for comparison among tillage treatments, where significant differences were found.

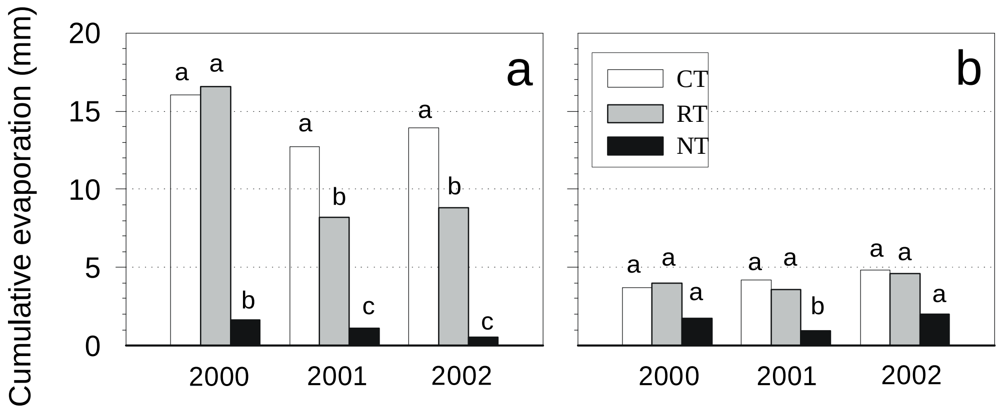

Figure 5.2. Cumulative water loss by evaporation under conventional tillage (CT), reduced tillage (RT) and no-tillage (NT) for the first 24 hours after tillage implementation on CT and RT plots in the 1999-2000, 2000-2001 and 2001-2002 fallow periods: (a) from the 0-40 cm soil layer after primary tillage; and (b) from the 0-20 cm soil layer after secondary tillage. Different letters above bars indicate significant differences at $P<0.05$.

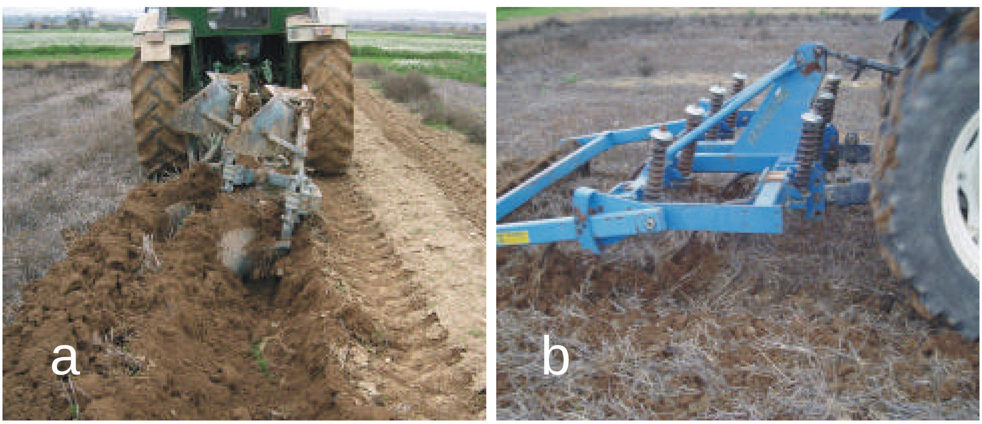

Figure 5.3. Soil surface roughness following mouldboard ploughing (a) and chiselling (b) at the experimental site.

period (Fig. 5.2a) could be explained by a higher ***q*** 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 5.4a) that favoured soil water loss immediately after tillage. The constancy of the differences in ***q*** between tillage systems for a certain period after primary tillage (Fig. 5.4) proves the reliability of the measured water losses by TDR 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 los from the 0-10, 10-20 and 20-40 cm represented, respectively, 18, 31 and 51% of the total *E*, soil water lost from the 0-40 cm depth 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. 5.1). 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. 5.5a). These water losses mainly occurred, as explained above, on the first day after tillage. Afterwards, and compared with NT, a higher decrease in the daily evaporation rate, E_r, is 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 amore 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 5.3).

During the late fallow phase, SS (late spring to barley sowing), secondary tillage induced additional soil water loss under CT and RT, which mainly occurred from the upper 20 cm of soil. Overall, the average *E* for the first 24 hours after

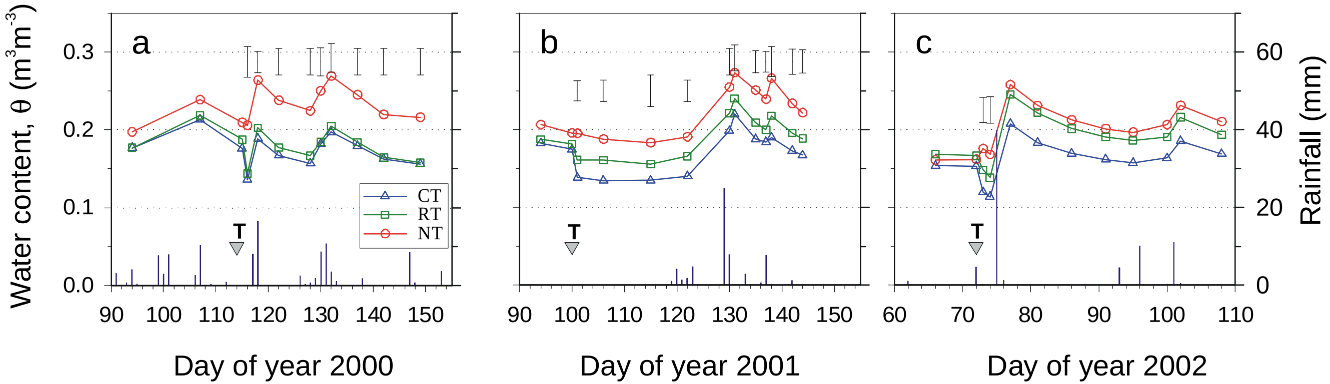

Figure 5.4. Time course of rainfall and volumetric soil water content (*q*) in the plough layer (0-40 cm depth) under conventional tillage (CT), reduced tillage (RT) and no-tillage (NT) following the implementation of primary tillage (**T**) on CT and RT plots in the second year of the 1999-2000 (a), 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.

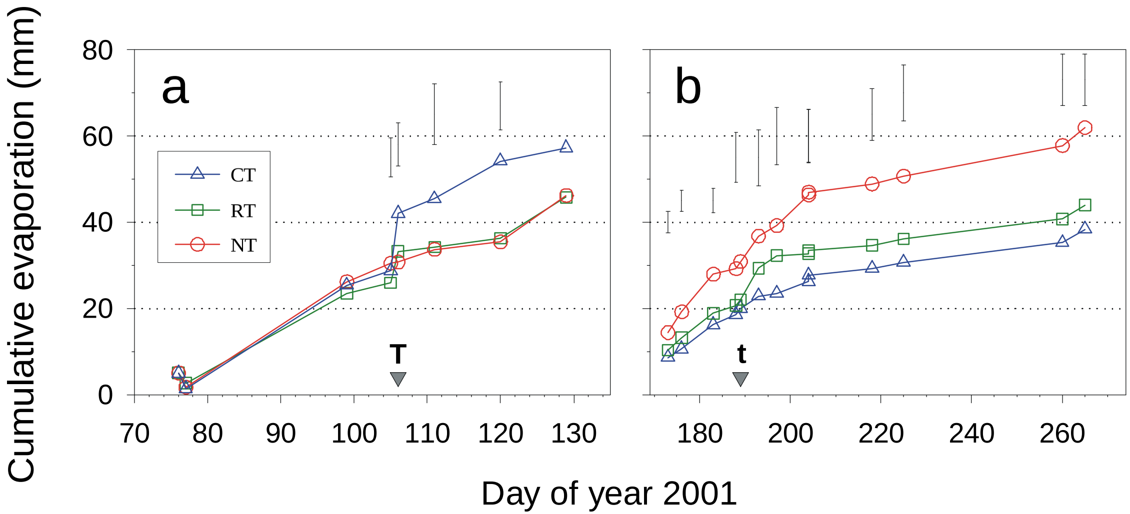

Figure 5.5. Cumulative water evaporation from the upper 40 cm of soil under conventional tillage (CT), reduced tillage (RT) and no-tillage (NT): (a) for a 23-day period after primary tillage and (b) for a 96-day period after secondary tillage in the 2000-2001 fallow season. **T** and **t** indicate primary and secondary tillage dates and; bars represent LSD (P<0.05) for comparison among tillage treatments, where significant differences were found.

secondary tillage application was again greater under CT (4.2 mm) and RT (4.1 mm) than under NT (1.6 mm) (Fig. 5.2b). Hatfield et al. (2001) reported soil water evaporation fluxes from 10 to 12 mm for a 3-d period following a pass with a cultivator in spring and < 2 mm under NT over the same period. Although lower than the water losses occurred immediately after primary tillage, *E* after secondary tillage can be also 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, E_r 96 days after secondary tillage application was the lowest for CT and RT (0.40, 0.46 and 0.64 mm day^{-1} for CT, RT and NT, respectively) (Fig. 5.5b). These results are in agreement with Jalota and Prihar (1998), who reported that while a short time after tillage 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, E_r from tilled soil lags behind E_r from untilled soil. This change in 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 5.1), a loose structure and dryness of fine tilled soil could also have contributed to reduce 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 E_r, this field operation did not induced significant differences among tillage systems in *E* at the end of the SS period (Table 5.3).

Overall, the early HF period had the lowest 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 log-fallow period, *E* was not significantly affected by the fallow tillage system (Table 5.3). Although it has been showed that tillage implementation increases *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 long-term a reduction of E_r in the tilled plots relative to untilled system, which leads to similar total E in the three tillage treatments.

3.2.2. Soil water storage and efficiency

Effects of seasonal fallow precipitation

Figure 5.6 shows the dynamics of the water stored in the 0-70 cm soil profile (*SWS*) over the three experimental long-fallow periods computed in reference to the start of each fallow period. In general, the variation of *SWS* and *PSE* for a given fallow phase can be, in principle, related to the potential evaporation, but sometimes such variation can be more closely related to the rainfall received either at the beginning or at the end of the preceding phase (French, 1978; Jones and Popham, 1997). For instance, negative values of *SWS* and *PSE* for the FS phase of the 2000-2001 fallow period and the SS phase of the 2000-2001 and 2001-2002 fallows (Table 5.3) occurred when initial *SWS* was high and/or most of the sub-period precipitation was concentrated at the beginning of the phase (Fig. 5.6). 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. 5.6). Only the HF phase presented positive *SWS* values in the three experimental fallow seasons. The positive relationship between *SWS* and *P* for this phase ($SWS = 0.45\ P + 26.82$; $R^2 = 0.89$) 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 5.2). 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

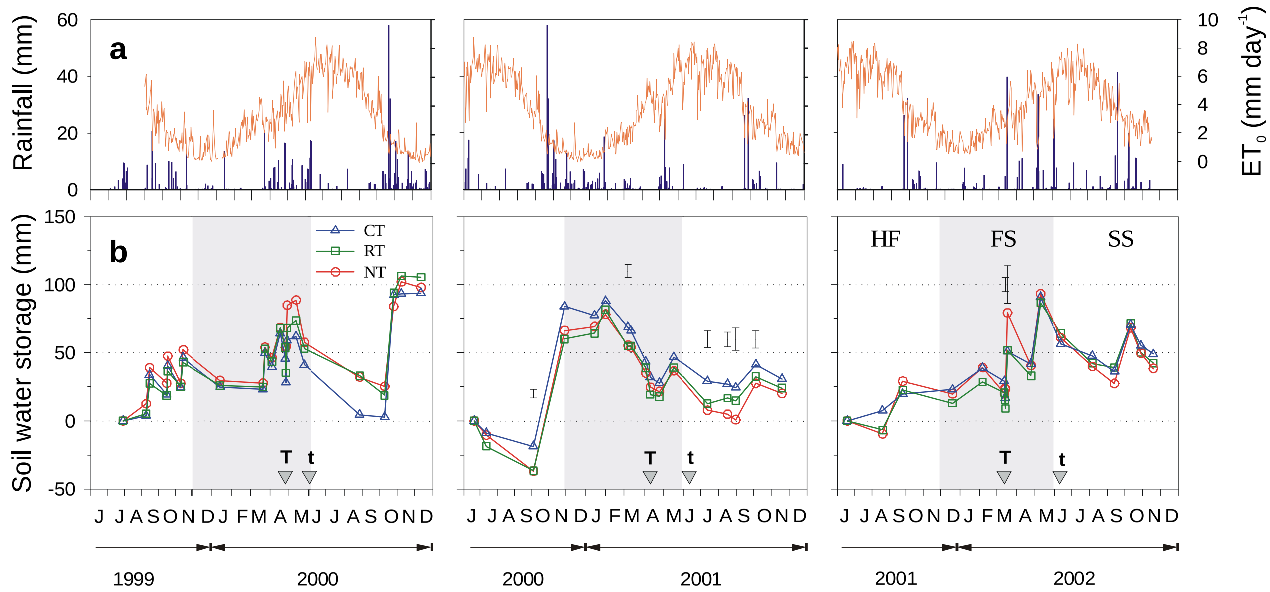

Figure 5.6. (a) Daily precipitation (columns) and reference evapotranspiration (ET_0) (continuous line) during the 1999-2000, 2000-2001 and 2001-2002 fallow periods. (b) Time course of water stored in the soil profile (0-70 cm) (*SWS*) for the same fallow periods under conventional tillage (CT), reduced 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. *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.

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 5.3). This difference is due to a greater effective precipitation (≥ 10 mm day^{-1}) in April-May in the 2001-2002period (67%) compared to the 1999-2000 period (32%) (Table 5.2).

With regard to the entire fallow period, the greatest *SWS* and *PSE* values were observed in the 1999-2000 fallow season (Table 5.3) with the greatest effective seasonal-fallow precipitation in the last two months of fallow (Table 5.2). This result indicates that the rainfall received at the beginning and during mid-fallow has no effect on soil water storage at sowing, in agreement with Austin et al (1998a), who found that rainfall during the last months of the fallow is the principal determinant of the amount of water stored in the profile in Central Aragon. However, French (1978) found in semiarid south Australia, that fine-textured soils stored much additional water when rain occurs at the beginning of a 8-10 months 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 summary, 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 5.3). As observed in semiarid fallow regions of Northern Great Plains (Farahani et al., 1998b) and Pacific Northwestern (Schillinger, 2001) of the USA, soil water storage efficiency, computed in reference to the start of fallow, decreased over the long fallow period (Fig. 5.7). At the end of fallow (sowing time), average *PSE* values were small (11%) (Table 5.3) but similar to those reported in previous studies conducted in semiarid fallow regions (French, 1978; López et al., 1996; Tanaka and Anderson, 1997; Pannkuk et al., 1997; Lampurlanés et al., 2002; Latta and O'Leary, 2003). The 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.

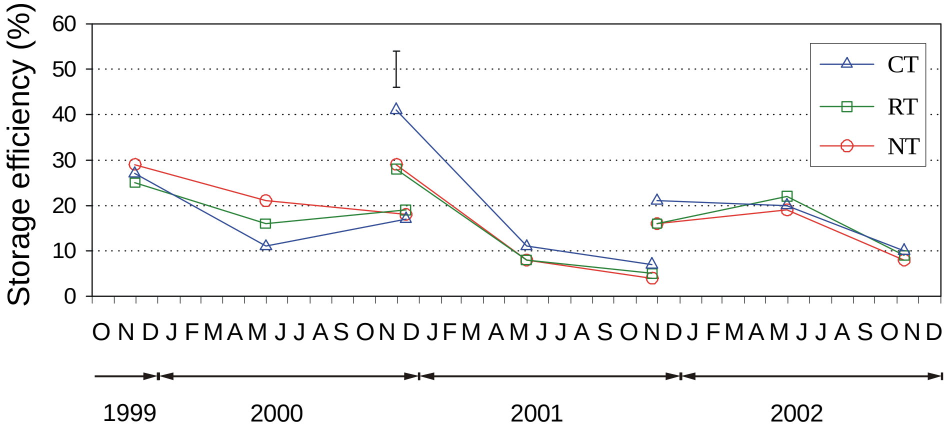

Figure 5.7. Soil water storage efficiency during the 1999-2000, 2000-2001 and 2001-2002 fallow periods under conventional tillage (CT), reduced tillage (RT) and no-tillage (NT) treatments. Bars represent LSD ($P<0.05$) for comparison among tillage treatments, where significant differences were found. (The efficiency values are computed in reference to the start of each fallow period).

Effects of fallow tillage management

The distribution of water stored in the soil profile during fallow varied with the tillage treatments. Figure 5.4 shows that in general, water content in the plough layer (0-40 cm depth) was greater under NT than under CT and RT. This fact may be due to a higher soil water retention capacity measured at the topsoil under NT (Moret and Arrúe, 2004; Capítulo 4). On average, while water stored under NT in the 0-20, 20-40 and 40-70 cm soil layers represented the 29, 30 and 41%, respectively, of total soil water storage, 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, but differ from findings by Lampurlanés et al. (2002) in a semiarid area of Ebro River valley. These authors found that the amount of water stored by a loamy soil in the deeper soil layers was greater under NT than under subsoil tillage and minimum tillage.

Despite this different soil water content distribution with depth between tilled and untilled soils, in general, no significant differences in *SWS* (Fig 5.6) and *PSE* (Fig 5.7) among tillage systems were observed for the entire fallow, in agreement with findings by other researchers (Tanaka and Anderson, 1997; Schillinger, 2001; Lampurlanés et al., 2002; Latta and O'Leary, 2003). O'Leary and Connor (1997) indicated that a proper crop residue cover would favour soil water storage at the end of fallow. In our study area, however, crop residue cover, which is very low even under NT over the whole fallow period (López et al., 2003) would not be an influential factor in water conservation.

The additional soil water at sowing with a long fallow (16-18 months) compared with a short fallow (5-6 months) averaged for four years (1999-2002) and the three tillage systems 22 mm (Table 5.4). This figure is within the range of values (11-33 mm) given 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) in Central Aragón. Accordingly, the average precipitation storage efficiency of long fallow relative to short fallow (*RPSE*) was 5.2%, close to the mean value of 2.5%found by López et al. (1996) in Central Aragon and within the range of values obtained by Latta and O'Leary (2003) in south-eastern Australia (1-26%) using a comparable index of relative water storage efficiency. Although the influence of tillage treatment on the additional water storage at the end of fallow is nor clear, RT appears to be the most efficient system to increase the water storage (Table 5.4).

Table 5.4. Precipitation storage efficiency of long fallow relative to short fallow (RPSE) for the 1998-1999, 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§ *(%)*
1998-1999	CT	351	22	6.2
	RT		31	8.8
	NT		7	2.0
1999-2000	CT	494	28	5.7
	RT		29	5.9
	NT		18	3.6
2000-2001	CT	301	6	2.0
	RT		37	12.3
	NT		25	8.3
2001-2002	CT	413	18	4.4
	RT		23	5.6
	NT		12	2.9

† 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).

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

4. Conclusions

Results show that 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 (16-18 months) fallow period. 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. This shallower cultivation would break the continuity of capillary channels from the subsoil to the soil surface thus reducing soil water evaporation. Despite tillage operations imply in the short-time a substantial and rapid water loss from the plough layers, total water lost measured for the entire fallow period was similar for CR, RT and NT. This results 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 of the preceding barley crop 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 grater daily evaporation rates (0.93 and 1.09 mm day^{-1}, respectively) and variable soil water storage as a function of the rainfall regime in those periods. Precipitation storage efficiency (*PSE*) for each fallow phase, and also for the entire fallow period, increases when most of seasonal effective rainfalls ($\geq$ 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, small *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 the tillage system. 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 (16-18 months) period compared with short-fallow (5-6 months) was 22 mm. Correspondingly, the average precipitation storage efficiency of long fallow relative to short fallow was only 5.2%. In conlusion, 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).

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Capítulo 6

Water Balance Simulation of a Dryland Soil during Fallow under Conventional and Conservation Tillage in Semiarid Aragón (NE Spain)

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To be submitted to: *Soil and Tillage Research*

Water Balance Simulation of a Dryland Soil during Fallow under Conventional and Conservation Tillage in Semiarid Aragón (NE Spain)

ABSTRACT

In Central Aragon, winter cereal is sown in the autumn (November-December), commonly after a 16-18 month fallow period to conserve soil water. In order to predict the effect of long fallowing under three tillage management systems (conventional tillage, CT; reduced tillage, RT; and no-tillage NT) on available soil water at sowing, the Simple-Soil-Plant-Atmosphere Transfer (SiSPAT) model was used. The model was calibrated and satisfactorily validated using data from three long-fallow seasons over the period 1999-2002 of a long-term tillage experiment. The capability of the model to simulate the soil water balance and its components over long fallowing was demonstrated. Both fallow rainfall pattern and tillage management system affected the soil water budget and components estimated by the model. On the assumption that soil properties measured under the three tillage treatments do not change over the whole fallow period, the model estimated that about 80% of fallow seasonal precipitation 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. On the contrary, 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 estimated water lost by evaporation was higher under NT (70%) than under RT (48%) and CT (49%). The comparison between observed and estimated soil water storage at the end of a wet-autumn fallow showed that fallow water storage efficiency measured under CT and RT was about half of the efficiency predicted by the model. Postponing mouldboard and chisel ploughing to the last phase of the fallow period could substantially improve fallow water storage efficiency

1. Introduction

In 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 precipitation 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 issues, to increase total stored water at the time of sowing for efficient use by the succeeding crop. However, the low rainfall regime, with a 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). Though mouldboard ploughing, followed by repeated shallow tillage operations, remains the commonest form of fallow management to control weeds during the fallow period, this traditional tillage practice is being slowly replaced by conservation tillage systems due to the lower labour, fuel, and machinery costs of these systems. However, and regardless of tillage practices, field measurements by López et al. (1996) and calculations by Austin et al. (1998), suggest that benefits from water storage during fallow are quite small.

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

As reviewed by Conolly (1998), many simulation models have been used to simulate the water balance in soil-crop systems, but few of them have been applied to study specifically soil water changes during the fallow period. To this respect, Fischer et al. (1990) used a simulation model to predict the effect of fallow and of new tillage systems on 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 evaluate the applicability of the SiSPAT model to simulate the soil water balance during the long fallow phase of the traditional cereal-fallow cropping system in Central Aragon and understand the effects of different tillage management systems on fallow water storage efficiency. The performance of the model was tested on the long-term basis using data sets from three contrasting fallow seasons of a long-term tillage experiment in which conventional tillage, with mouldboard ploughing as primary tillage, is compared with alternative conservation tillage practices, namely, reduced tillage, with chisel ploughing as main cultivation, and no-tillage.

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) and only a brief summary is presented here. 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 used here the bare soil version of the model. Coupled heat and water transfer equations are solved in the soil 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 and allows the derivation of the surface fluxes of heat and water using a two equations system (surface energy balance and continuity of the mass flux at the soil surface).

At the experimental site and regardless of the type of fallow management system, soil cover by cereal crop residues was very low (< 30-40%) during the specific fallow periods considered in the study (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. On this assumption, the original version of SiSPAT was used instead of the SiSPAT-mulch version (González-Sosa et al., 1999), which takes explicitly into account 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 Zaragoza province (latitude 41º 44’N; longitude 0º 46’W; altitude 270 m). The climate is semiarid with an annual precipitation of 390 mm and an average annual air temperature of 14.5 °C. Soil at the research site is a loam (fine-loamy, mixed thermic Xerollic Calciorthid). A more detailed description of soil and crop management is given by López et al. (1996). 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. Both fields have a loam texture in the top 70 cm of soil, with the exception of Field 2 where a textural heterogeneity is present below 40 cm, with some plots showing a sandy loam texture in the 40-70 cm layer.

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) on the following year. Field measurements were made during the 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, 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 early summer. Primary tillage operations in CT and RT plots were implemented on 25 April 2000, 10 April 2001 and 13 March 2002, and 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.

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 periods using an automatic weather station. Air temperature and humidity measured at 1.8 m and wind speed at 2 m were used for the forcing of the model. A tipping bucket rain gauge was used to measure rainfall. Incoming short-wave solar radiation was measured using a pyranometer sensor at 2 m height. During the third fallow period, net short-wave radiation (*Rn*) was recorded at 1 m above the soil surface on a NT plot using a net radiometer. All sensors were connected to a data-logger, which continuously recorded 60-min averages of data acquired at intervals of 10s. The long-wave incoming radiation was calculated by 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. Total precipitation 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. Rainfall patterns were contrasted among the three fallow periods, with monthly totals irregularly distributed over each fallow period (Table 6.1). The 2000-2001 fallow was characterised by a high precipitation (62% above normal) in the autumn (September-November) of the first year of fallow, which represented almost half of the total fallow season precipitation, and a dry spring (30% below normal) concentrating in the March-May period only 17% of fallow rainfall. In contrast, the 1999-2000 and 2001-2002 fallows had a low precipitation (about 22% below normal in both cases) in autumn (19% of total fallow precipitation) and a precipitation 11 and 33% above normal, respectively, in spring (24 and 30% of total fallow precipitation) (Table 6.1).

2.2.3. Soil parameters

For the initialisation and validation of the model, soil temperature (T_{soil}) was measured using thermistors horizontally inserted at 2, 6 and 10 cm depth on one per tillage treatment during the three fallow periods. Soil temperature was additionally measured at 20 cm during the 2000-2001 fallow period and at 20, 50 and 70 cm

Table 6.1. Monthly precipitation (mm) during the 1999-2000, 2000-2001 and 2001-2002 long-fallow seasons compared with long-term monthly totals (1954-2002 average) at Peñaflor 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

during the 2001-2002 fallow period. Soil thermistors were connected to a datalogger and data signals 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 (q) 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 of two parallel stainless steel rods were vertically inserted into the soil to a depth of 10, 20, 40 and 70 cm, and connected to a TDR cable tester (model 1502C, Tektronix) to calculate q using the model proposed by Topp et al. (1980). Two measurements of q

were made per experimental plot, which according to 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.

Fallow tillage management affected soil water dynamics during the three fallow periods. Figure 6.1 provides an example of the variation of q 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 25 April 2000 (first long-fallow period). As compared to CT and RT, 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 it occurred at the beginning and the end of the period (Fig. 6.1) reflecting the rainfall events in September-November 1999 and March-April 2000, respectively (Table 6.1).

Soil dry bulk density (r_b), hydraulic conductivity (K), and water retention curve were measured in situ on the 1-10 cm and 40-50 cm soil layers for the different tillage systems. r_b was determined by the core method and K using a tension disc infiltrometer (Perroux and White, 1988). Infiltration runs were made at four pressure head (h) values (namely, -14, -4, -1, and 0 cm, applied in that order and at the same place). K was calculated according to the multiple-head method (Ankeny et al., 1991). The volumetric water content of soil beneath the infiltrometer disc was determined just at the end of each infiltration measurement by TDR. For this purpose, and prior to the infiltration measurements, a three-rod TDR probe was installed horizontally into the soil at 3-4 cm depth. The drying water content-matric potential relationship, $q(h)$, was determined during the 2001-2002 fallow period on Field 2. For the 0 to –30 kPa range, simultaneous field measurements of q, 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 Likewise, the hydraulic conductivity of the surface crust (K_c) (0-1 cm depth) was.

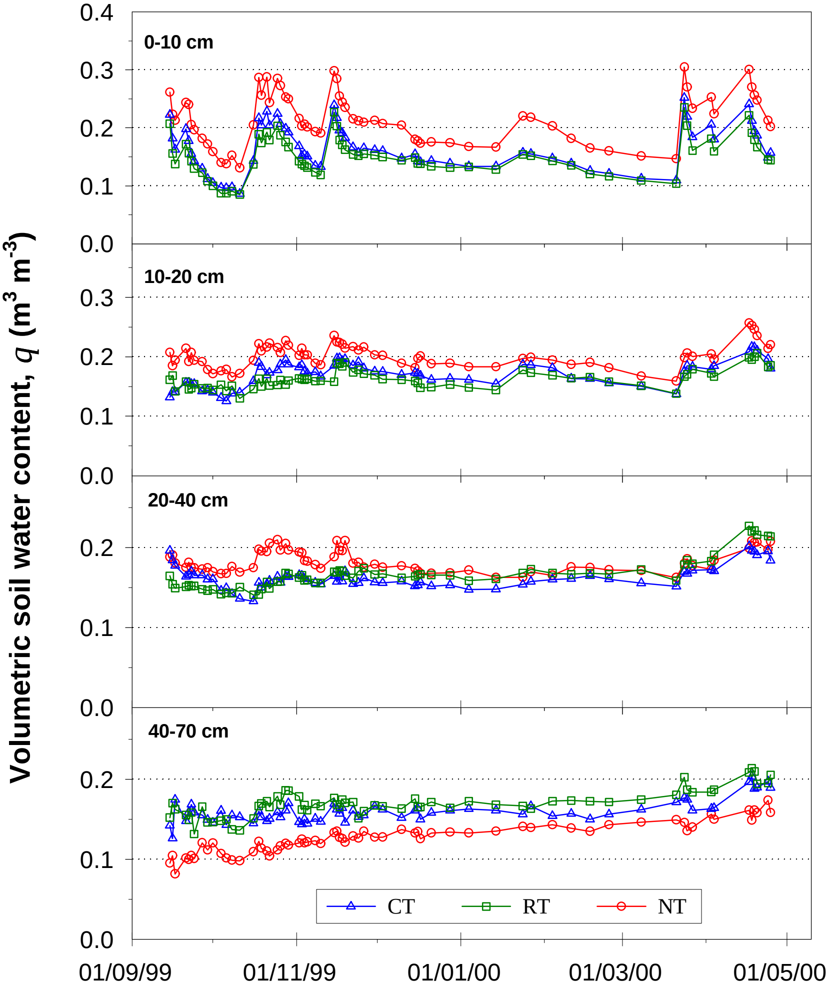

Figure 6.1. Time course of the volumetric soil water content (*q*) in the the 0-10 cm, 10-20 cm, 20-40 cm and 40-70 cm layers measured in Field 2 under conventional tillage (CT), reduced tillage (RT) and no-tillage (NT) during the 1999-2000 fallow season from 21 September 1999 to 25 April 2000.

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 coating agent. All the soil hydrophysical property measurements were made between January and March, before the implementation of primary tillage operations in the CT and RT treatments.

2.2.4. Field water balance

Assuming a negligible runoff from the nearly level experimental plots at both Field 1 and Field 2, soil water budget for a given fallow period simplifies to:

$$P - E = \Delta S \tag{6.1}$$

where P (mm) is the rainfall recorded over the time period in question, E (mm) is the sum of all water losses by evaporation from the soil surface and deep percolation and DS is the change in soil water storage (0-70 cm depth) calculated using the volumetric moisture content profiles.

2.2.5. Modelling strategy

Soil and climate measured 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, x, was calculated from the soil dry bulk density r_b and soil particle density r_s (r_s = 2.65 g cm-1), through $x = 1 - \left(r_b / r_s\right)$. The soil water retention curve was obtained by fitting the measured (h, q) values to the van Genuchten (1980) model

$$\frac{q - q_r}{q_{sat} - q_r} = \left[1 + \left(\frac{h}{h_g}\right)^n\right]^{-m} \tag{6.2}$$

where n is the shape factor and m = 1-(2/n) (Braud, 2000). In this equation, q_{sat} and q_r are the saturated and residual volumetric water contents, respectively, and h_g is the scale factor. In our case, q_r was fixed as the water content measured in the field on a very dry soil (van Genuchten, 1980) (Table 6.2).

The hydraulic conductivity curve $K(q\,)$ was fitted using the Brooks and Corey (1964) model:

$$K(q\,) = K_{sat}\left(q\,/\,q_{sat}\right)^{b} \tag{6.3}$$

where K_{sat} is the saturated hydraulic conductivity, b a shape factor deduced from the field measured $K(h)$ relationship, q is the soil water content below the infiltrometer disc at the end of each tension infiltration measurement, and q_{sat} is the water content below the infiltrometer disc at the end of the infiltration measurements at saturation.

The values for all above soil parameters are given in Table 6.2. Soil depth was fixed at 0.7 m and, according to tillage management (e.g. ploughing depth) and soil crusting characteristics, divided in five horizons (0-1 cm; 1-10 cm; 10-20 cm; 20-40 cm; and 40-70 cm). Values of soil parameters measured at 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 l, this parameter was derived using the Van de Griend and O'Neil model (Braud, 2000), as the most appropriate option to our experimental set up where only soil texture is known and no soil thermal properties measurements are available. Other non-measured surface parameters that must be prescribed are the bare soil albedo, a, and the roughness length for the momentum, z_{om}. The relationship of Passerat de Silans (Braud, 2000), calibrated for a loam soil was used to calculate a and z_{om} was set to 0.004 m (M.V. López, personal communication). November 2001 to 19 November 2002 during the 2001-2002 fallow period were used to calibrate the model. Similarly, the measurements of q, T_{soil} and G from 21

Table 6.2. Average values of soil parameters[†] measured in the surface crust (0-1 cm), and the 1-10 and 40-50 cm soil horizons in Field 2 under conventional tillage (CT), reduced tillage (RT) and no tillage (NT) treatments.

Soil layer	Tillage treatment	ρ_b (kg m^{-3})	ξ	θ_{sat} (m^3 m^{-3})	θ_r (m^3 m^{-3})	h_g (m)	n	K_{sat} (m s^{-1})	β
Horizon 1 (0-1 cm)	CT/RT/NT	1.28	0.52	-	-	-	-	1.0×10^{-5}	-
Horizon 2 (1-10 cm)	CT	1.24 (1.29)[‡]	0.53 (0.51)	0.49 (0.49)	0.04	-0.08	2.25	2.8×10^{-5} (2.4×10^{-5})	13 (16)
	RT	(1.15) 1.24	0.56 0.53	0.49 (0.49)	0.04	-0.10	2.25	2.8×10^{-5} (2.2×10^{-5})	13 (16)
	NT	1.34 (1.37)	0.49 (0.48)	0.42 (0.42)	0.06	-0.27	2.22	1.1×10^{-5}	19 (19)
Horizon 3 (40-50 cm)	CT	1.38 (1.37)	0.48 (0.48)	0.40 (0.41)	0.04	-0.15	2.26	1.9×10^{-5} (1.7×10^{-5})	14 (14)
	RT	1.36 (1.37)	0.48 (0.48)	0.40 (0.42)	0.04	-0.13	2.28	1.8×10^{-5} (1.4×10^{-5})	14 (14)
	NT	1.37 (1.37)	0.48 (0.48)	0.40 (0.39)	0.04	-0.14	2.28	2.3×10^{-5} (1.6×10^{-5})	13 (16)

[†] r_b, soil dry bulk density; x, total soil porosity; q_{sat}, saturated soil volumetric water content; q_r, residual 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; b; shape factor in the Brooks and Corey (1964) model for the hydraulic conductivity curve.

[‡] Figures in parenthesis are values for Field 1

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 calibration and validation of SiSPAT under NT conditions, only data subsets until the primary tillage dates (e.g. 25 April 2000, 10 April 2001 and 13 March 2002) were considered for CT and RT treatments. Finally, modelling of soil water balance under the three fallow management systems was made for the measurement periods with available soil and climate and data sets on the assumption that soil parameters measured under CT and RT before primary tillage remained unchanged until the end of the fallow season.

For the comparison between observed, Var(obs), and model calculated variables, Var(mod), regressions of the form Var(mod) = Slope x Var(obs) + Intercept were performed. The root mean square error (RMSE) was also calculated by

$$RMSE = \left[\frac{1}{N} \sum_{i=1}^{N} \left(Var_i(\mathrm{mod}) - Var_i(obs) \right)^2 \right]^{1/2} \qquad (6.4)$$

where N is the number of pairs available.

3. Results and discussion

3.1. Model performance

The results gathered during the calibration phase are summarised in Table 6.3. Overall, there is a satisfactory agreement between measured and modelled soil and surface fluxes variables. The statistics (R^2, slope, intercept and root mean square error) for the regressions between observed and modelled values of soil temperature (T_{soil}), volumetric soil water content (q), net radiation (Rn) and soil heat flux (G) are within the order of magnitude found for these variables in previous SiSPAT assessment studies (Braud et al., 1997; Boulet et al., 1997; Gonzalez-Sosa et al., 1999; Gonzalez-Sosa et al., 2001). As a whole, the determination coefficient (R^2) and slope of the regressions for the different fallow tillage management systems are

Table 6.3. 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.

Model	CT					RT					NT				
variable	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 °C for soil temperature (T_{soil}), in m^3m^{-3} for volumetric soil water content (*q*) and in Wm^{-2} for soil heat flux (*G*) and net radiation (*Rn*).

in most cases close to one with intercept values relatively small. Soil temperature at different depths is well predicted by the model, with an average RMSE value of 2.7 °C. This relatively high value could be due to an overestimation of the thermal amplitude by the model. The small RMSE found for *q* at all soil depths indicates that the model predicts reasonably well the soil water dynamics. For the soil heat flux *G*, the deviation between observed and predicted values can be related in this case to an overestimation of observed values of *G* during night-time. However, given the limitations and uncertainties associated to the calorimetric method used to calculate *G* (Sauer, 2002), the RMSE values obtained for this variable (average of 44.5 W m-2) could be considered as acceptable.

Table 6.4 summarises, for the different tillage systems, the comparison between predicted and measured values of T_{soil}, *q* and *G* used to validate the model during the 1999-2000 and 2000-2001 fallow periods. Globally, the model tends to underestimate the soil temperature as shown by the negative values of the regression intercept. However, the difference of about 1 °C observed can be considered as very small. As an example, Fig. 6.2 shows the time course of soil temperature at 6 cm depth measured in CT, RT and NT plots on Field 2 on the 7-9 November 1999 and that calculated by SiSPAT. For the soil moisture, and except for $q_{\text{0-70 cm}}$ under CT and RT in the 1999-2000 fallow period, the model was able to simulate satisfactorily the dynamics of the soil water content in the soil profile (0-70 cm depth). As an example of the agreement between model and observation, Fig. 6.3 compares the time evolution of measured and modelled *q* for the plough layer (0-40 cm depth) under the CT, RT and NT treatments from 21 September 1999 to 23 November 2000, during the first fallow season. As it can be observed, the excellent agreement between measured and simulated *q* under NT for the entire period worsens under the CT and RT treatments, particularly under CT, from the date of primary tillage implementation (shaded area). *G* values predicted by the model agree fairly well with observed values, as high determination coefficients,

Table 6.4. 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

Model	CT					RT					NT				
variable	N†	R^2	Slope	Intercept‡	RMSE‡	N	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	0.88	1.21	-2.9	2.6	4350	0.92	1.13	-3.6	2.9	8157	0.98	1.05	-2.2	2.0
$T_{soil\ 6\ cm}$	4350	0.68	0.90	-0.6	2.9	4350	0.70	0.86	-0.5	3.3	8157	0.89	0.91	0.2	3.0
$T_{soil\ 10\ cm}$	4350	0.86	1.17	-2.1	2.1	4350	0.80	1.05	-2.2	2.9	8157	0.94	1.03	-1.8	2.6
$T_{soil\ 20\ cm}$	4350	0.79	1.00	0.3	1.9	4350	0.86	1.05	-1.8	2.4	8157	0.97	0.97	-0.7	1.9
$\theta_{0\text{-}10\ cm}$	42	0.90	0.90	0.019	0.035	42	0.90	0.92	0.026	0.048	86	0.95	0.81	0.041	0.018
$\theta_{0\text{-}20\ cm}$	42	0.88	0.83	0.035	0.037	42	0.88	0.84	0.042	0.040	86	0.96	0.86	0.031	0.013
$\theta_{0\text{-}40\ cm}$	42	0.89	0.84	0.033	0.038	42	0.92	0.91	0.026	0.038	86	0.94	0.88	0.016	0.017
$\theta_{0\text{-}70\ cm}$	42	0.95	1.00	0.024	0.033	42	0.94	0.97	0.008	0.036	86	0.90	0.94	0.012	0.011
G	900	0.83	1.03	6.96	44.6	800	0.88	0.86	4.2	48.5	4350	0.86	0.75	7.5	55.5

† Number of pairs available.

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

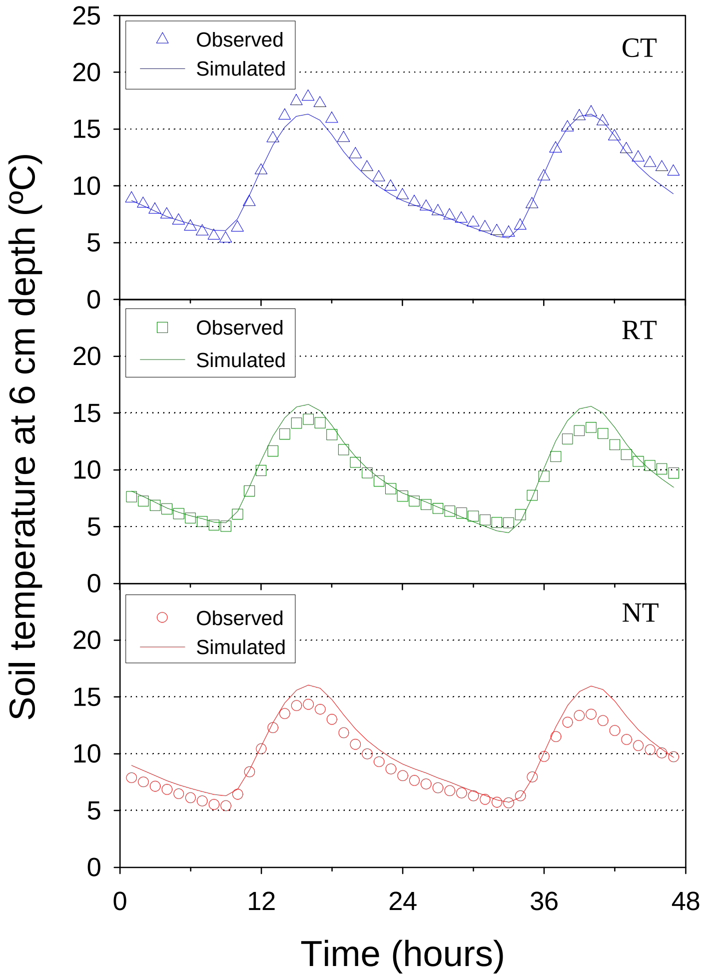

Figure 6.2. Simulated (continuous line) and measured (symbols) soil temperature at 6 cm depth in Field 2 under conventional tillage (CT), reduced tillage (RT) and no-tillage (NT) for 7-9 November 1999.

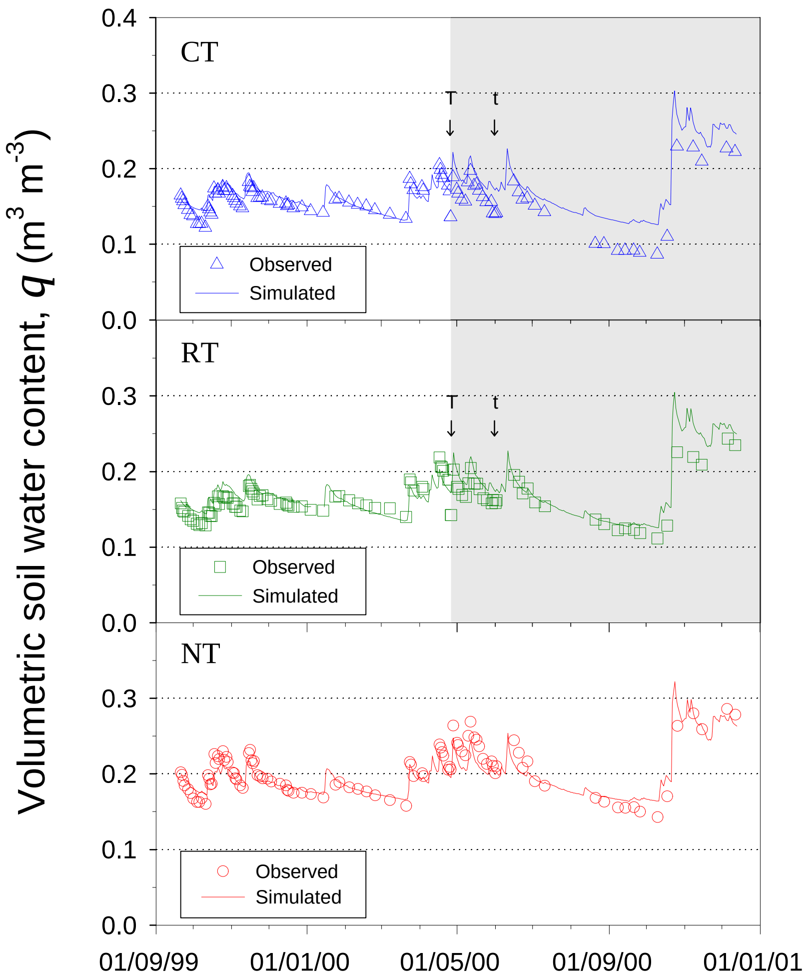

Figure 6.3. Comparison of simulated (continuous line) soil volumetric water content (*q*) for the 0-40 cm horizon with observations (symbols) from TDR measurements in Field 2 under conventional tillage (CT), reduced tillage (RT) and no-tillage (NT) during the 1999-2000 fallow season from 21 September 1999 to 13 December 2000 (**T**, primary tillage; **t**, secondary tillage).

slopes close to one and small intercepts indicate (Table 6.4). An example of this satisfactory agreement for *G* is given in Fig.6.4.

3.2. Simulation of soil water balance and components during fallow

Figure 6.5 presents in a summarised way the water balance predicted by SiSPAT for the three experimental fallow periods and distinct tillage management systems on the assumption that the soil parameters used to run the model for the CT and RT treatments remain constant along the whole fallow period. The results show that the soil water budget components for each fallow season were influenced by the fallow rainfall pattern. On average, soil water evaporation and deep drainage estimated by the model for the 1999-2000, 2000-2001 and 2001-2002 fallow periods represented 70, 56 and 91% of the total precipitation, respectively, in the first case and 18, 35

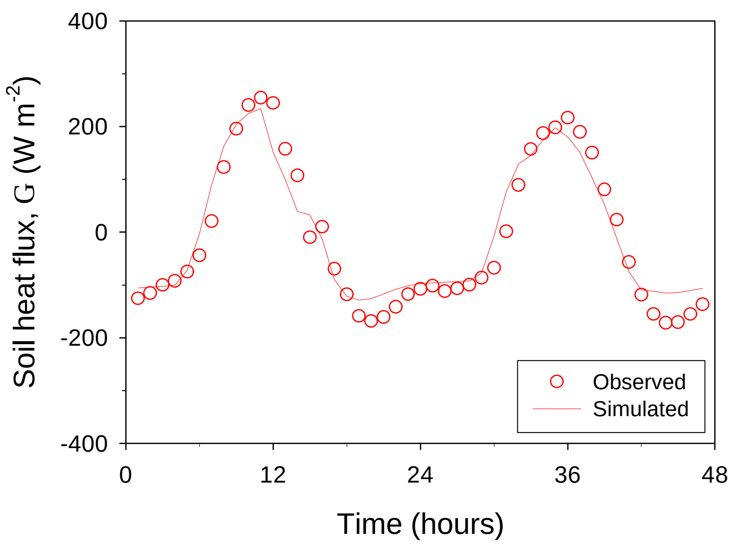

Figure 6.4. Comparison of simulated (continuous line) and observed (dotted line) soil heat flux under no-tillage (NT) in Field 2 on 25-27 June 1999.

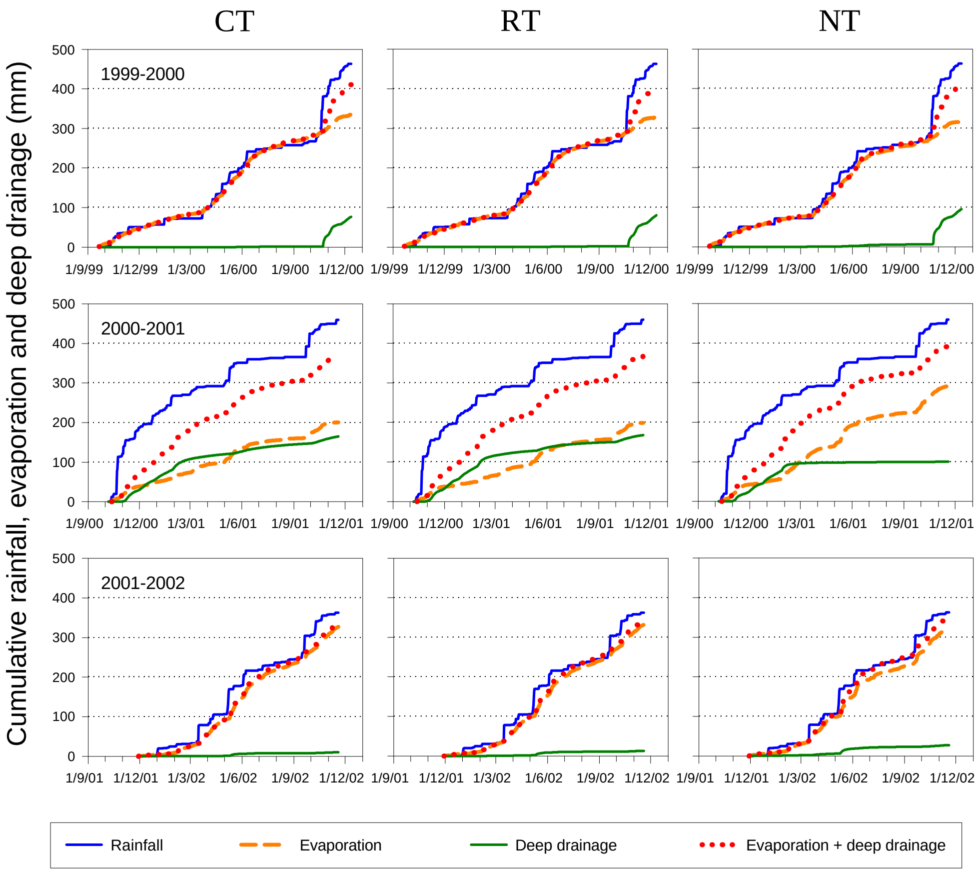

Figure 6.5. Cumulative precipitation received during the 1999-2000, 2000-2001 and 2001-2002 long-fallow periods and corresponding cumulative water losses from the soil profile (0-70 cm depth) by evaporation and deep drainage predicted by SiSPAT under conventional tillage (CT), reduced tillage (RT) and no-tillage (NT).

and 5%, respectively, in the second case. These results, along with the time course of the cumulative precipitation (Fig. 6.5), indicate that rains received during the autumn-winter period of the first year of fallow play a crucial role to offset soil water losses due to evaporation. If most of the fallow season precipitation is received during that fallow phase, when the evaporative demand is low, water storage in the soil profile is possible even below its maximum useful depth (70 cm in our case). As a result, water stored deep in the soil is kept protected against evaporation during late spring and summer when the atmospheric evaporative demand is higher. From the agronomic point of view, these differences in fallow soil water balance could partially explain the crop response during the growing season that follows the fallow period. Thus, whereas the amount of water lost by evaporation is no longer available for the subsequent winter cereal crop, soil water accumulated in deep layers might be still partially used by the crop. As shown by Lampurlanés et et al. (2002), in a study conducted in a semiarid area of the Ebro River valley, in northeastern Spain, the root system of winter cereal crops can extract water up to 1 m depth.

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 precipitation events 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 water to flow to deep soil layers.

The soil water balance components estimated by SiSPAT varied also with the fallow tillage treatment. This effect was more 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 (70%) were higher than those estimated under CT and RT (49 and 48%, respectively). On the contrary, model estimates of the drainage component showed that 25, 40 and 41%

of the total precipitation received during the 2000-2001 fallow period drained below 70 cm depth under NT, CT and RT, respectively. These differences in water balance components among tillage systems could be related to both differences in soil hydrophysical properties and a low atmospheric evaporative demand during the fall-winter phase of the first year of fallow, which, as mentioned before, favours water flow to deep soil layers in the CT and RT plots. Thus, a high topsoil water content under NT (Fig. 6.1), could have enhanced soil water evaporation during the following spring and summer fallow periods in that treatment. In contrast, a lower water content under CT and RT at the surface horizons just after a rainfall event (Fig. 6.1) would be indicative of a higher amount of water flowing to deeper soil layers, thus promoting drainage and reducing soil water evaporation.

In fallow seasons with a dry autumns in the first year of fallow and a wet springs (e.g. the 1999-2000 and 2001-2002 fallows), no significant differences in the soil water balance components were observed among tillage systems. In those fallow seasons, the evaporative demand during a rainy spring period appears to be the main factor regulating the soil water fluxes. On the other hand, the slightly higher drainage under NT compared to CT and RT predicted by the model for the 1999-2000 and 2001-2002 fallows (Fig. 6.5) could be related to the coarser texture observed on the NT plots in Field 2, and, correspondingly, to the higher hydraulic conductivity measured in the 40-50 cm layer under NT (Table 6.2).

The comparison between measured and simulated soil water storage at the time of sowing allowed us to quantify the influence of tillage on fallow precipitation storage efficiency (*WSE*). This index is here defined as the percentage of the fallow season precipitation stored in the soil profile (0-70 cm depth) at the end of fallow. Table 6.5 shows the efficiencies measured (WSE_M) and estimated by SiSPAT (WSE_S) for the three experimental fallow seasons. The absence of significant differences between both efficiencies (WSE_S / $WSE_M \approx 1$) under NT, without any soil disturbance due to tillage, demonstrates the robustness and suitability of the

Table 6.5. Fallow precipitation storage efficiency† measured (WSE_M) and simulated by SiPSAT (WSE_S) under conventional tillage (CT), reduced tillage (RT) and no tillage (NT) treatments during the 1999-2000, 2000-2001 and 2001-2002 fallow periods.

Fallow period	Tillage treatment	Rainfall (mm)	WSE_S	WSE_M	WSE_S / WSE_M
			%	%	
1999-2000	CT	545	16.2	17.2	0.94
	RT		16.3	19.4	0.84
	NT		17.3	18.0	0.96
2000-2001	CT	486	12.1	6.3	1.91
	RT		8.6	4.9	1.77
	NT		4.5	4.2	1.07
2001-2002	CT	463	10.0	10.6	0.94
	RT		7.1	9.2	0.77
	NT		8.9	8.3	1.07

† Precipitation storage efficiency = (*SWS* / *P*) x 100, where *SWS* is the soil water storage defined as the profile soil water measured or simulated at the end of fallow minus the profile soil water measured at the beginning of fallow, and *P* is the total fallow seasonal precipitation.

SiSPAT model to simulate soil water balance during fallow in our semiarid rainfed farming conditions. In tilled treatments, however, some differences between WSE_M and WSE_S were observed among fallow periods. While for the 1999-2000 and 2001-2002 fallows both efficiencies were very similar, WSE_S under both CT and RT for the 2000-2001 fallow period was almost twice as big as WSE_M (Table 6.5). This fact would indicate a negative influence of both mouldboard and chisel ploughing on soil water conservation in fallow periods with a very wet autumn during the first year of fallow. Thus, during the 2000-2001 fallow season, a substantial portion of the water stored in October-November 2000 in deep soil layers due to the abundant and effective precipitation registered in that period (approximately 68% of total precipitation was received in rainfall events > 10 mm) could have been evaporated as a consequence of an increase in soil hydraulic conductivity after primary tillage operations (Chapter 4) as observed by Sillon et al. (2003) in a similar experiment. However, this would not have occurred in the absence of tillage operations as predicted by SiSPAT for the CT and RT treatments. From these considerations it can be concluded that eliminating or postponing primary tillage operations towards the end of the fallow period, when the evaporative demand is low, could be beneficial for soil water conservation, particularly in long-fallows characterised by a high soil water recharge during the autumn of the first year of fallow. On the contrary, in long-fallow periods with a low soil water recharge in autumn (e.g. 1999-2000 and 2001-2002 experimental fallows), soil water is basically stored in the surface horizons from which is more easily and continuously evaporated throughout the second year of fallow whether the soil is tilled or not. This would explain the similarity between WSE_M and WSE_S found for these fallow seasons (Table 6.5).

In order to investigate the short-term effects of tillage on soil water evaporation, the SiSPAT model was applied to simulate the evaporation losses following primary and secondary tillage implemented during the three experimental fallow seasons. The evaporation losses calculated by the model for specific post-tillage time periods assuming constant soil water transfer properties over the entire simulation period, were compared with experimental values obtained from the soil water balance. This comparison is better illustrated by the results of the 2000-2001 fallow season since a relatively long dry period followed both primary tillage on DAY 100 (Fig. 6.6a) and secondary tillage on DAY 157 (Fig. 6.6b). As it can be seen, SiSPAT correctly simulated the cumulative evaporation losses under NT for both post-tillage periods. On the contrary, there were clear differences in the tilled treatments between observed and calculated evaporation losses just immediately after tillage, especially after primary tillage under CT (Fig. 6.6a). This discrepancy is due to the fact that the model does not take into account the soil loosening caused by tillage and its effects on the water transmission properties at the soil surface. This modification determines the time course of evaporation from tilled soil differs from that of untilled soil (Jalota and Prihar, 1990). As reviewed by these authors, soil loosening increases surface roughness, which increases potential evaporation by concentrating heat in the surface layers. Similarly, roughness increases the surface area of soil exposed to the atmosphere and allows greater wind penetration. In our experimental conditions, soil loosening up to 40 and 30 cm by mouldboard and chisel ploughing, respectively, with soil inversion in the first case, and, concurrently, strong WNW cierzo wind at the time of tillage (average daily wind speed values of 5.3 and 7.8 m s^{-1} were recorded on DOY 100 and DOY 101, respectively) could have been major responsible factors for the high evaporation rates measured just one day after primary tillage (12.7 and 8.3 mm day^{-1} under CT and RT, respectively) (Fig. 6.6a).

The time course of cumulative evaporation from the top 10 cm of soil following secondary tillage in the 2000-2001 fallow season (Fig. 6.6b) shows how for a short time after tillage water is rapidly lost in the CT and RT plots (DOY 157-165). This fact, which is due to soil loosening and surface crust breaking by tillage, makes on a short-term the evaporation rate in the tilled plots to exceed that from untilled plots. However, as soon as a dry layer is formed by the accelerating drying of the tilled surface (e.g. 15 days after tillage in our case), evaporation from tilled soil decreases, thus the differences between cumulative evaporation measured and simulated by SiSPAT. This reduction in the rate of evaporation loss in tilled plots is due not only to a depletion of water in the surface tilled layer but also to the breaking of capillaries by tillage at the interface of tilled and untilled layers, which decreases the hydraulic conductivity of the loosened layer and, consequently, retards upward water flow from untilled layers (Jalota and Prihar, 1990). Regardless of tillage treatment, the model is also able to simulate the evaporation increase observed shortly after either a single rainfall, for instance the 9 mm rain received on DOY

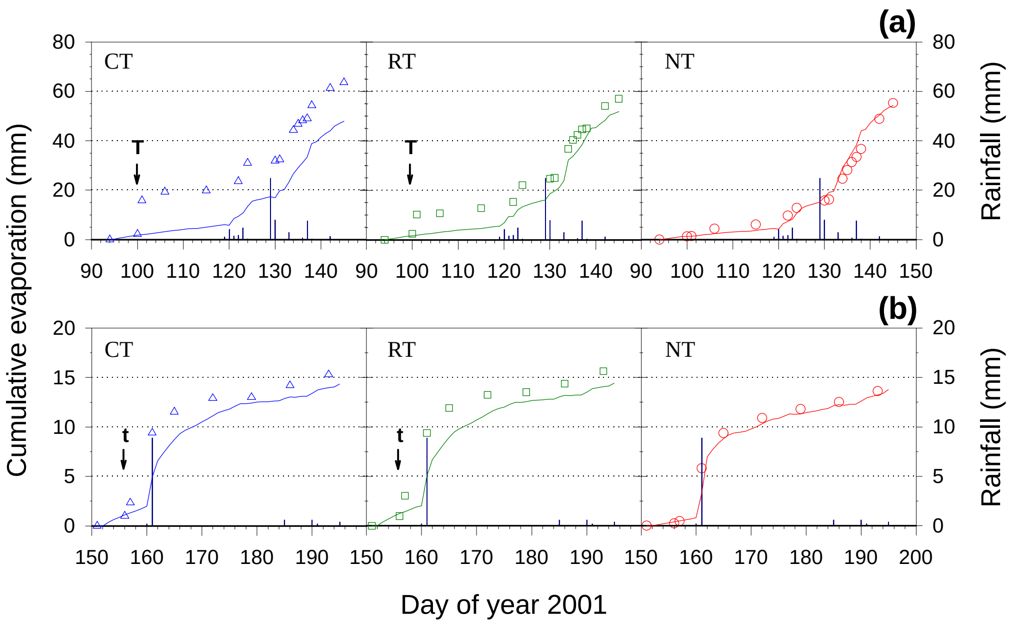

Figure 6.6. Cumulative evaporation measured (symbols) and predicted by SiSPAT (continuous line) under conventional tillage (CT), reduced tillage (RT) and no-tillage (NT) during the 2000-2001 fallow period: (a) from the upper 40 cm of soil following primary tillage (**T**) and (b) from the upper 10 cm of soil following secondary tillage (**t**). Bars indicate rainfall events.

161, five days after secondary tillage (Fig. 6.6b), or a rainy period as that occurred between DOY 120 and DOY 123 following a 20-day drying period after primary tillage (Fig. 6.6a).

4. Conclusions

The SiSPAT (Simple-Soil-Plant-Atmosphere Transfer) model was satisfactorily applied 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). Model performance was evaluated by comparing numerical results and field data covering specific sub-periods of three 17-18 month fallow seasons. Most of the soil hydrodynamic and thermal parameters were measured in situ and directly introduced into the model without the need of any adjustment or calibration. The model calibration was performed on a 356-day period within the 2002-2002 fallow season and the validation on two periods of 450 and 413 days within the 1999-2000 and 2000-2001 fallow seasons, respectively. For the different fallow management practices, the model has shown a good agreement between measured and predicted soil parameters (soil temperature and volumetric water content at different depths) and surface fluxes (soil heat flux and net radiation). Both fallow rainfall pattern and tillage management system affect the soil water budget and components estimated by the model. On the assumption that measured soil hydraulic properties affecting the soil water balance do not change over the whole fallow period under the three tillage systems, the model estimated that about 80% of fallow seasonal precipitation is lost by evaporation from the soil surface 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 is characterised by a wet autumn during the first year of fallow the model predicted an increase in the water storage and deep drainage components and a decrease in soil water evaporation. In this case, soil water evaporation under NT was about 20% higher than that estimated under CT and RT. The comparison between measured and estimated soil water storage at the end of fallow allowed to evaluate the potential total soil water losses due to tillage practices in dryland semiarid zones of Central Aragon (NE Spain). Our results show that mouldboard and chisel ploughing may have a negative effect on soil water conservation in long-fallow seasons with a wet autumn during the first year of fallow. In this case, the simulation appears to indicate that postponing primary tillage operations to the last phase of the fallow period, when the evaporative demand is low, could double the fallow water storage efficiency by eliminating evaporation losses after primary tillage normally implemented in late winter or early spring.

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Capítulo 7

Winter Barley Performance under different Cropping and Tillage Systems in Semiarid Aragón (NE Spain)

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To be submitted to: *European Journal of Agronomy*

Winter Barley Performance under different Cropping and Tillage Systems in Semiarid Aragón (NE Spain)

ABSTRACT

Barley is the winter cereal grown in most of semiarid dryland of central Aragón (NE Spain), where it is traditionally cultivated under a crop-fallow rotation. In this study we compared, under both a continuous cropping (CC) (5-6 months fallow) and a crop-fallow rotation (CF) (16-18 months fallow), the effects of three fallow management treatments (conventional tillage, CT; reduced tillage, RT; and no-tillage, NT) on winter barley growth and yield and water use efficiency (*WUE*) during three consecutive growing seasons (1999-2000, 2000-2001 and 2001-2002). Daily precipitation and monthly measurements of soil water storage to a depth of 0.7 m were used to calculate crop water use (*ET*) and its components. The average growing season precipitation was 195 mm. Above-ground dry matter (*DM*) and corresponding *WUE* were high in years with high effective rainfalls (>10 mm day^{-1}) either in autumn or spring. However, the highest values of *WUE* for grain yield were mainly determined by effective rainfalls from stem elongation to harvest. Despite the similarity in *ET* for the three tillage treatments, NT provided the lowest *DM* production, in agreement with a higher soil water loss by evaporation and a lower crop transpiration (*T*), as showed by the lowest *T*/*ET* ratio values found under NT. No clear differences in crop yield were observed among tillage treatments in the study period. These findings suggest that conventional tillage can be substituted by conservation tillage for fallow management in semiarid dryland cereal production areas in central Aragon. On average, and regardless of tillage, CF provided the highest values of *DM* and *WUE* and yielded 49% more grain than CC. These differences between crop systems increased when water-limiting conditions occurred in the early crop growth stages, probably due to the additional soil water storage under CF at sowing time. Although no significant

differences in precipitation use efficiency (*PUE*) were observed between CC and CF, *PUE* was higher under the CC system, which yielded 34% more grain than the CF rotation when yields were adjusted to an annual basis including the length of fallow. Crop yield under CF was not dependent on the increase in soil water storage at the end of long fallow.

1. Introduction

In semiarid rainfed cereal-growing areas, bare long fallowing enables two seasons' rainfall to be conserved for growing a single crop. With this practice, soil nitrogen and water storage at sowing time and water use efficiency are increased and weed and disease control improved in comparison with continuous cropping (Unger, 1994; Aase and Pikul, 2000). However, long fallowing has been controversial because of inefficiency on soil water storage and water- and wind-erosion (Amir et al., 1991; Farahani et al., 1998). When adjusting the grain production to an annual basis including fallow time the continuous cropping system shows to be more efficient at using seasonal precipitation (Jones and Popham, 1997).

In the same way, in semiarid dryland cereal agriculture, conventional mouldboard ploughing as primary tillage to control weeds during fallow results in many cases an inefficient practice for soil water conservation (Singh et al., 1998). That is the reason why conservation tillage systems (i,.e., reduced tillage and no-tillage) have been proposed as an alternative to the traditional soil management. However, although conservation tillage practices have shown to improve soil properties, save time and energy, and help to control water and wind erosion, different and contradictory results have been obtained in semiarid dryland areas when both crop growth and grain yields are compared under conventional and conservation tillage treatments. Thus, whereas some authors (Unger, 1994: Schillinger, 2001) obtained no differences in cereal production among tillage systems, other researchers (Lawrence et al., 1994; Johnston et al., 1995; Singh et al., 1998; Bonfil et al., 1999) have observed a greater soil water storage under no-tillage and thus better crop yields and water use efficiencies.

In Aragon, agricultural land accounts for 38% of the total surface of this region (47,700 km^2), where about 760,000 ha within the rainfed arable land (1.38 million ha) are cultivated with herbaceous crops (80% grown to wheat and barley) and about 460,000 ha are fallowed every year (López et al., 2001). In central Aragon, rainfed cropland is located in areas with an average annual rainfall of < 400 mm. In these areas, the most common cropping system is the traditional cereal-fallow rotation, which extends over about 430,000 ha and involves a long-fallow period of 16-18 months, running from harvest (June-July) to sowing (November-December) in the following year. Although the main purpose of long fallowing is to increase soil water storage and the water available for the next crop, the cereal-fallow rotation does not always result in improving water economy of cereals (López and Arrúe, 1997; Lampurlanés et al., 2002). Based on barley yield / rainfall regressions for data from a dry area in the Ebro valley, Austin et al. (1998a) estimated that the annual yields from a crop-fallow system would be 15% greater than those obtained with continuous cropping and stated that for fallowing to be economic, grain yields in the traditional cereal-fallow would need to be at least twice those obtained with annual cropping. These findings and calculations suggest that the benefits from water storage during the long-fallow period are quite small and that, consequently, the sustainability of long fallowing, a characteristic feature of dryland cereal agriculture in central Aragon and other semiarid areas in the Ebro River valley can still be seriously questioned.

On the other hand, mouldboard ploughing, which is the traditional fallow tillage management in the cereal cropping systems in the region, is being slowly replaced by conservation tillage practices. However, knowledge available on cereal crop response to conservation tillage as alternative fallow tillage management in semiarid Ebro River valley is still limited. López and Arrúe (1997) found in central

Aragon a 53% reduction in grain yield with no-tillage compared to conventional tillage. On the contrary, Angás (2001) and Lampurlanés et al. (2002) found in the eastern Ebro River valley that no-tillage fallow appears to be the best management system for barley production.

The aim of this paper was to compare the effects of three fallow management treatments (conventional tillage, CT; reduced tillage, RT; and no-tillage, NT) on winter barley growth and yield and water use efficiency during three consecutive growing seasons under both continuous cropping (CC) and a crop-fallow rotation (CF) in a dryland cereal-growing area of central Aragon.

2. Material and methods

2.1. Site, tillage, crop management and experimental design

The site is located at the dryland research farm of the Estación Experimental de Aula Dei (CSIC) in the 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 °C. Soil at the research site is a loam (fine-loamy, mixed thermic Xerollic Calciorthid) according to the USDA soil classification (Soil Survey Staff, 1975). Other selected soil physical and chemical properties for that layer have been previously presented by 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 in Field 1 as continuous cropping (CC) (hereafter called CC1) after a 5-6 month fallow period, and under the traditional cereal–fallow rotation (CF) in Fields 2 (CF2) and 3 (CF3), after a long-fallow period 17-18 months long. Field soil and crop measurements were taken from November 1999 to June 2002 and comprised three consecutive growing seasons, which extended from 4 November 1999 to 20 June 2000 (in CC1 and CF3 fields), from 13 December 2000 to 29 June 2001 (in

CC1 and CF2 fields) and from 23 November 2001 to 27 June 2002 (in CC1 and CF3 fields). A schematic of the CC and CF cropping systems, including their different phases and length and the main cultural practices is given in Fig. 7.1.

Three soil tillage systems, implemented during the fallow period as indicated in Fig.7.1, were compared: conventional tillage (CT), consisting of mouldboard ploughing to a depth of 30-40 cm in late winter or early spring, followed by secondary tillage with a sweep cultivator to a depth of 10-15 cm in late spring. (10-15 cm); reduced tillage (RT), similar to CT but using chisel ploughing to a depth of 25-30 cm as primary tillage practice; and no-tillage (NT), where weeds during fallow were controlled with herbicides (glyphosate).

Whereas a conventional seeder was used to sow the CT and RT treatments, a tine zero-till seeder was used to sow the NT plots. The average sowing rate for the three growing seasons was 175 kg ha^{-1}. Except for the NT treatment, which needed one or two more herbicide applications, herbicides and fertilisers rates were the same for all treatments.

Tillage treatments were arranged in an incomplete block design based on geostatistical concepts, with three replications for the RT and NT treatments and four for the CT treatment (López and Arrúe, 1995). The three large blocks of ten plots were arranged according to a split block design with 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 field measurements at two observation points (one per treatment) separated by a distance of 5 m. To compare the effects of the fallow tillage treatments within each cropping system, analysis of variance (ANOVA) for incomplete block design was used. To evaluate the cropping systems irrespective of tillage treatment and tillage x cropping system interaction, ANOVA according to the split block design with three replications was performed (López and Arrúe, 1995). Duncan’s multiple range test was used to compare between treatment means.

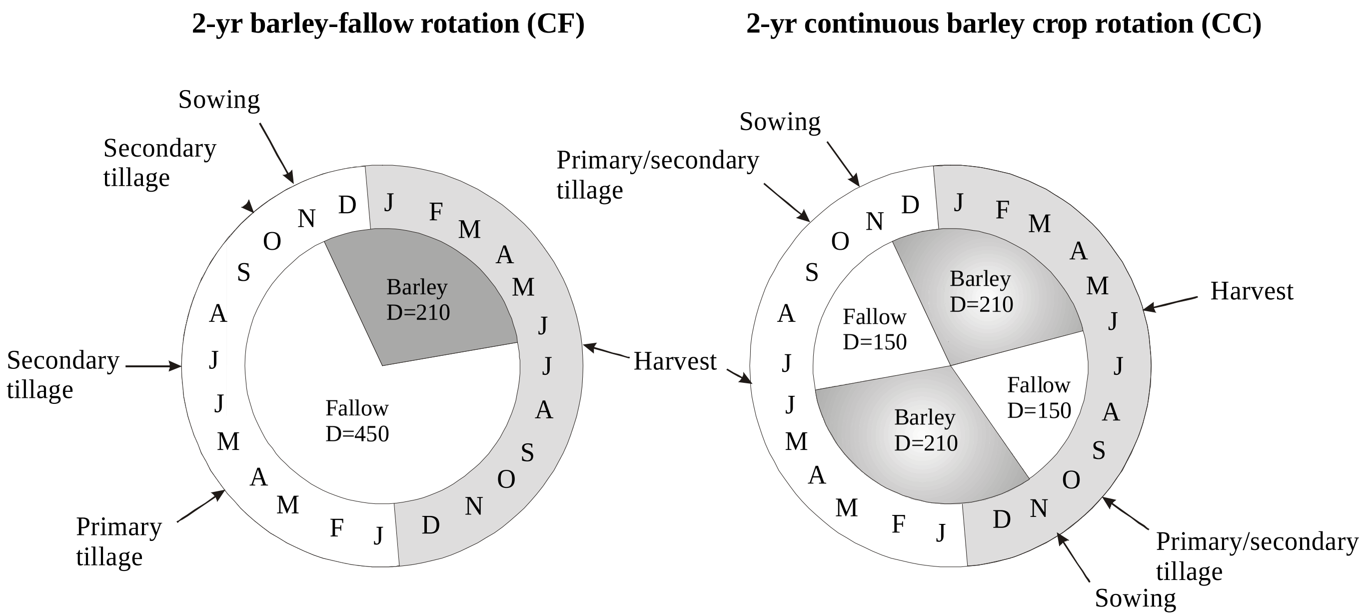

Figure 7.1. Schematic of dryland cropping systems showing phases, phase length in days (D) and agronomic practices.

Soil and crop parameters measured in CC1 in the three growing seasons were compared with those obtained in CF2 in 1999-2000 and 2001-2002 and CF3 in 2000-2001.

2.2. Sampling and measurements

2.2.1. Weather

Daily meteorological observations were made at the experimental site over the whole experimental period using an automated weather station. Precipitation was measured at 1.5 m using 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). The sensors were connected to a data-logger (model CR10, Campbell Scientific Inc.), which continuously recorded 60-min averages of data acquired at intervals of 10 s.

2.2.2. Soil water content

The volumetric soil water content (q) in the soil profile (0-70 cm depth) at each observation point was monitored by Time Domain Reflectometry (TDR) using probes of two parallel stainless steel rods (diameter: 4 mm; length: 150, 250, 450 and 750 mm; spacing between rod centers: 50 mm). TDR probes were inserted vertically into the soil to a depth of 10, 20, 40 and 70 cm. 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 (Dalton, 1992). Waveforms were transferred to a laptop with a SP232 serial communication module and analysed using the software WinTDR’98 (Or et al., 1998). q was estimated at 0-10, 10-20, 20-40 and 40-70 cm depth layers using the model proposed by Topp et al. (1980), which proved to be suitable for our soil in a previous calibration experiment, and the multiple length probe method described by Miyamoto et al. (2001). Soil water profile was monitored on a monthly basis in both CC and CF at two observation points per plot according to the incomplete block design. With this sampling scheme, a total of 18 measurements (6 per treatment) were made on each field and observation date. The plant available soil water (*PASW*) was calculated as the difference between q in the soil profile (0-70 cm) and q at the permanent wilting point (y = –1500 kPa) previously determined for the three tillage systems (Chapter 4).

2.2.3. Crop growth and yield

Crop establishment was determined as the percentage of seeds sown for which seeding emerged. Seed depth was estimated by measuring the length of white stem above the seed of 5 plants randomly sampled from each row (López and Arrúe, 1997). Crop growth was monitored from biomass samplings at selected growth stages according to the Zadoks scale (Zadoks et al., 1974). During the 1999-2000 growing season, plant samplings were made at early seeding growth (ZGS 11-12), flag leaf extending (ZGS 41), dough development (ZGS 80) and maturity (ZGS 99). During the 2000-2001 and 2001-2002 seasons, samplings were made at early seeding growth (ZGS 11-12), tillering (ZGS 22-28), anthesis (ZGS 60) and maturity (ZGS 99). An additional sampling was made at stem elongation (ZGS 32-38) in the 2001-2002 season. The last sampling date corresponded to the harvest day. Four 0.5 m long rows per plot according to the incomplete blocks design were selected for plant measurements at each sampling date. Dry weight of above-ground plant material collected was determined after oven-drying at 65 °C for 48 h. Immediately prior to harvest, total plants from each 0.5 m long row sampling were hand-harvested to determine grain yield and yield components. The ears were counted and, after oven drying, threshed to determine the number of grains per ear and mean grain weight.

2.2.4. Water use and water use efficiency

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

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

$$T = DM\left(e^{*} - e\right)/\,k \qquad (7.1)$$

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

Water use efficiency for both total *DM* produced at harvest (WUE_b) and grain yield (WUE_g) were determined as the respective total biomass and yield weights divided by total *ET*. The precipitation use efficiency index (*PUE*) , defined as grain yield divided by harvest-to-harvest water use (Jones and Popham, 1997), was also calculated for both CC and CF systems. Likewise, the fallow precipitation storage efficiency (*PSE*), defined as the percentage of fallow-season precipitation that is stored as soil water, was calculated for CF as

$$PSE = [(q_f - q_i)/P_F\,] \times 100 \qquad (7.2)$$

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

3. Results and discussion

3.1. Seasonal rainfall and soil water storage

Average annual precipitation for the experimental period (1999-2002) was 362 mm, 7% lower than the long-term average (1954-2002) precipitation (390 mm). Total precipitation recorded from crop sowing to harvest during the 1999-2000 (205 mm), 2000-2001 (164 mm) and 2001-2002 (216 mm) crop-season periods was 24, 28 and 5% below the long-term average, respectively (Fig. 7.2a). Rainfall patterns were contrasted among growing seasons, with monthly totals irregularly distributed over each crop cycle period. Thus, whereas the 1999-2000 and 2001-2002 seasons showed a dry autumn-winter period (November-March) (62 and 89 mm, respectively) and a wet spring (April-May) (107 and 95 mm, respectively), an opposite pattern characterised the 2000-2001 season (171 mm from November to March and 56 mm from April to May). Likewise, different amount of effective rainfall ($\geq$ 10 mm day^{-1}) were also observed among the experimental growing seasons. Thus, whereas the 2000-2001 season showed the highest effective rainfall in the autumn-winter period, the effective rainfall in spring was significantly higher in the 2001-2002 season than in the 1999-2000 and the 2000-2001 seasons (Fig. 7.2a).

As expected, the soil water content during the different crop growth phases was influenced by seasonal rainfall pattern. Figures 7.2a, 7.2b and 7.2c show the evolution of water content in the soil profile (0-70 cm) over the entire experimental period for the different tillage and cropping systems. Whereas a dry autumn in 1999 and 2001 (Fig. 7.2a) determined a low soil water content at seeding (Figs. 7.2b and 7.2c), a wet autumn in 2000 allowed an important water recharge (Figs. 7.2b and 7.2d). Tillage and crop rotations also affected soil water content. Thus, on average, the crop-fallow rotation (CF) stored at seeding 19, 32 and 17 mm more water than the continuous cropping (CC) for the conventional tillage (CT), reduced tillage (RT) and no-tillage (NT) treatments, respectively (Chapter 5, Table 5.4). Overall,

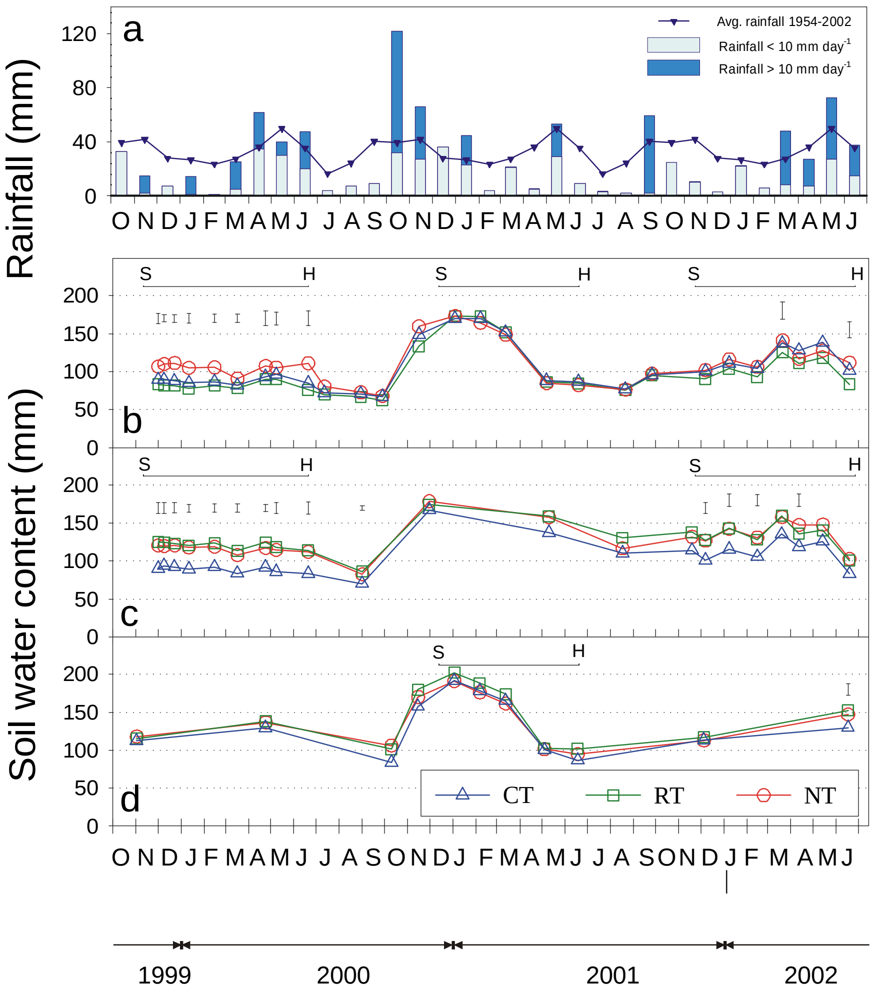

Figure. 7.2. Monthly rainfall for the experimental period (1999-2002) vs. long-term average (1954-2002) (a) and dynamics of soil water content (0-70 cm) for conventional tillage (CT), reduced tillage (RT) and no-tillage (NT) under continuous cropping (b) and crop-fallow rotation (c) and (d). S and H indicate sowing and harvest dates, respectively. Vertical bars indicate LSD ($P < 0.05$).

CT showed to be the most inefficient system to store water over the growing season. At harvest, a substantial depletion of water content in the soil profile was observed under both CC and CF systems (Fig. 7.3). The soil water profile was also affected by the different tillage systems. In agreement with findings by Lampurlanés et al. (2002) in eastern Ebro valley and Chan and Heenan (1996) in southern Australia, soil water content in the upper 20 cm was generally higher under NT than under CT and RT (Fig. 7.3) (Chapter 5).

3.2. Crop performance

3.2.1. Crop establishment and growth

Table 7.1 summarises the percentage of crop emergence and seed depth as affected by tillage and crop systems for the three experimental growing seasons. Firstly, results show that rainfall regime during the growing season had a significant influence on emergence percentage. Favourable weather and soil conditions (high water content at sowing) during the germination period in 2000-2001 (Fig. 7.3), resulted in significantly higher percentages of crop emergence than in 1999-2000 and 2001-2002. Statistical differences in crop emergence were also observed at $P < 0.1$ between crop systems. The extra water stored at the end of the 16-18 month fallow period in the CF rotation resulted in a slight decrease of crop failure in this system, especially in seasons with a dry fall (1999-2000 and 2001-2002) (Austin et al., 1998b). On the other hand, as Chan and Heenan (1996) observed, the greater water content in the NT topsoil at sowing (Fig. 7.3) did not induce significant differences in crop emergence among tillage systems. During the three experimental years, the smallest seed depth was measured in NT plots. This shallow seed placement should be associated with a more compacted soil surface under NT (Chapter 4). No significant differences in seed depth were observed between cropping systems (Table 7.1).

Figure 7.4 shows the seasonal changes in aboveground dry-matter (*DM*) and

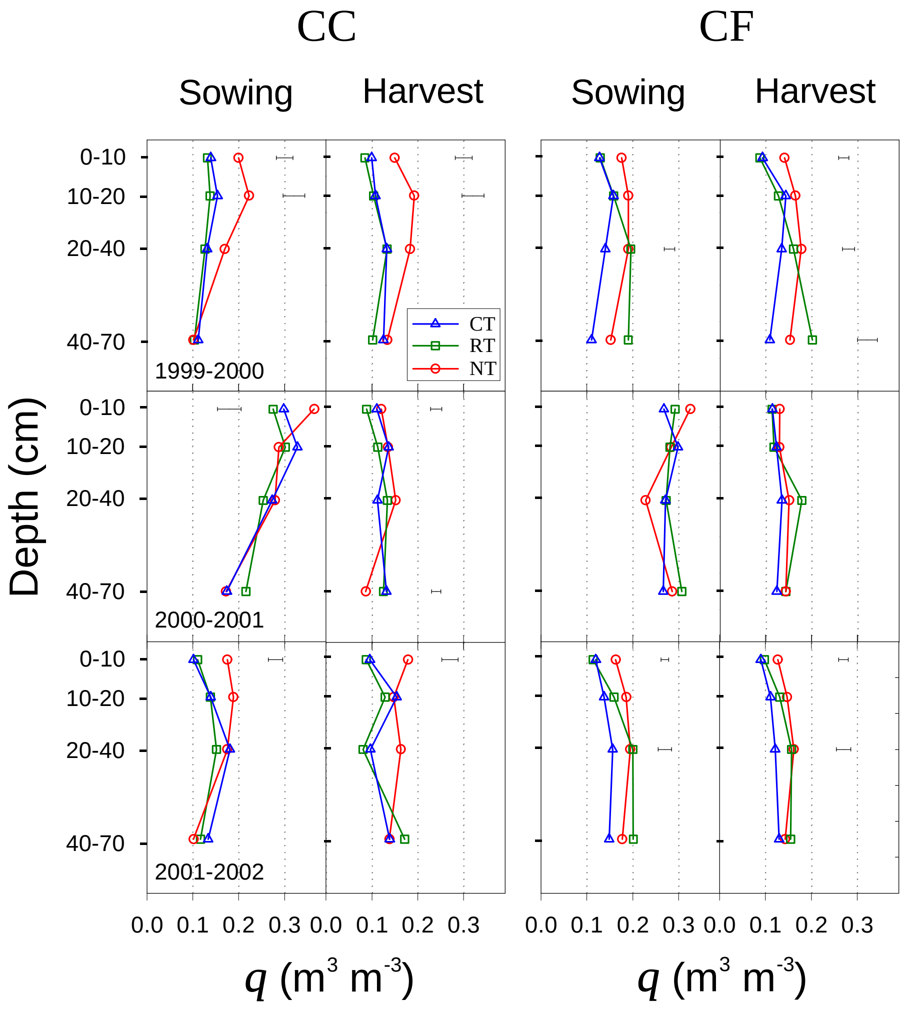

Figure 7.3. Soil water (*q*) profiles at sowing and harvesting of barley as affected by tillage (CT, conventional tillage; RT, reduced tillage; and NT, no-tillage) under continuous cropping (CC) (left) and crop-fallow rotation (CF) (right) in the 1999-2000, 2000-2001 and 2001-2002 growing seasons. Horizontal bars indicate LSD ($P < 0.05$).

Table 7.1. Crop establishment of barley as affected by tillage (conventional tillage; CT, reduced tillage, RT; and no-tillage NT), and cropping system (CC, continuous cropping; CF, cereal-fallow rotation) in the 1999-2000, 2000-2001 and 2001-2002 growing seasons.

Growing season	Cropping system	Tillage treatment	Emergence (%)	Seed depth (cm)
1999-2000	CC1	CT	50.7	5.1
		RT	45.8	4.4
		NT	62.9	3.5
		LSD[†]	NS	1.1
	CF3	CT	67.1	3.3
		RT	67.1	3.2
		NT	66.8	3.5
		LSD	NS	NS
2000-2001	CC1	CT	79.5	3.9
		RT	83.3	3.7
		NT	82.3	2.6
		LSD	NS	NS
	CF2	CT	79.1	4.6
		RT	81.9	4.1
		NT	93.3	2.7
		LSD	NS	NS
2001-2002	CC1	CT	47.5	5.3
		RT	55.9	5.6
		NT	65.2	2.6
		LSD	NS	1.6
	CF3	CT	61.3	5.8
		RT	69.4	4.4
		NT	67.9	1.8
		LSD	NS	1.4

[†] Least significant difference, $P<0.05$. NS, not significant.

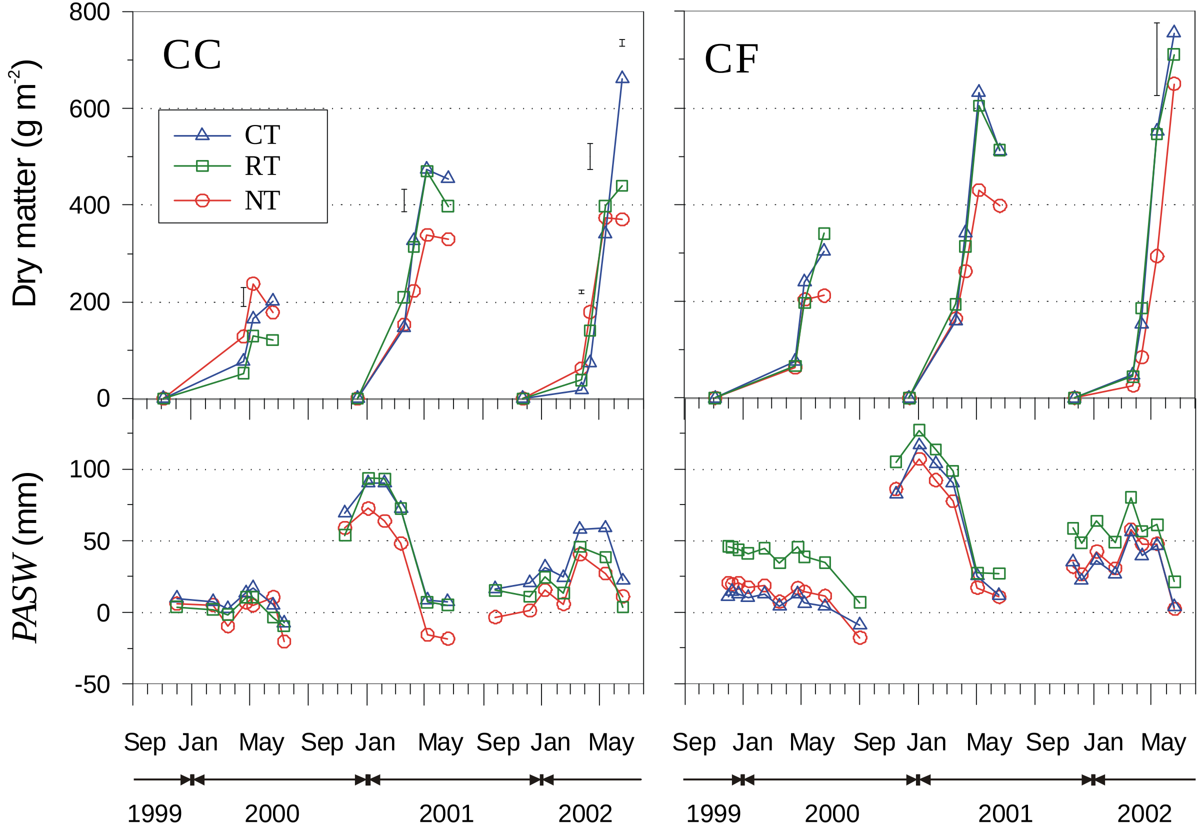

Figure 7.4. Seasonal changes in total above-ground dry matter and plant available soil water content (*PASW*) (0-70 cm) as affected by tillage (CT, conventional tillage; RT, reduced tillage; and NT, no-tillage) under continuous cropping (CC) and crop-fallow (CF) rotation during the 1999-2000, 2000-2001 and 2001-2002 growing seasons. Vertical bars indicate LSD ($P < 0.05$).

plant available soil water content (*PASW*) as affected by season, cropping system and tillage treatment. Vegetative growth of barley occurred from sowing to mid-March, while reproductive period extended to late April. Regardless of tillage and cropping systems, aboveground dry matter production was significantly different in the three growing seasons, which were characterised by a different rainfall pattern. In 1999-2000, the low *PASW* between November 1999 and March 2000, due to a depleted soil water profile at seeding (Fig. 7.3) and a low precipitation in that period (68 mm), would explain the low *DM* during the early stages of crop development up to stem elongation. On the other hand, the low effective rainfall recorded in April-May 2000 (38 mm) (Fig. 7.2a) was not enough to recharge the soil water profile, which would explain the lowest *DM* production (226 g m^{-2}) at harvest with respect to 2001 and 2002 (Fig. 7.4). In 2000-2001, high *DM* measured up to anthesis was connected with a high *PASW* in that period (November-March) (Fig. 7.4), as a consequence of the important precipitation before sowing and during the early stages of crop development (Fig. 7.2a). Average *DM* at harvest was 433 g m^{-2}. Finally, in 2001-2002, crop growth was markedly different between autumn-winter (low *DM*) and spring (vigorous crop growth from stem elongation to harvest) periods (Fig. 7.4). These results can be explained by a low *PASW* from November to beginning of March (41 mm of effective rainfall) and a later increase in *PASW* in spring according to a greater effective precipitation in March-May (109 mm). *DM* production at harvest was the greatest (597 g m^{-2}) of the three growing seasons.

On average, *DM* production under CF was 28% higher than under CC (Fig. 7.4). This difference, also observed in others studies (French, 1978; Carr et al., 2000; López-Bellido et al., 2000; Díaz-Ambrona and Mínguez, 2001; Lampurlanés et al., 2002), may be related to greater *PASW* values under CF, which determined a better crop establishment and growth (Fig. 7.4).

As it can be observed in Fig. 7.4, NT treatment produced less *DM* than CT and RT treatments. As López et al. (1996) suggested, crop growth under NT could have been limited by a more compacted NT topsoil that restricts root growth. Likewise, a lower *PASW* under NT during the crop development (Fig. 7.4) could also explain the poorer crop growth under NT. These results are similar to those reported by Hamblin et al. (1982) in semiarid western Australia and López-Bellido et al. (2000) in southern Spain, but differ from results obtained in semiarid Morroco by Mrabet (2000), who found under NT the highest *DM* values. A significant cropping system x tillage interaction was also observed for total *DM* production.

3.2.2. Crop yield

As found in previous studies (McAneney and Arrúe, 1993; Cantero-Martínez et al., 1995; Austin et al., 1998b; Díaz-Ambrona and Mínguez, 2001), barley yields (Table 7.2) were highly dependent on seasonal rainfall. However, in agreement with findings by Smika (1970) in the semiarid Grain Plains of USA, crop yield was more influenced by the rainfall distribution over the crop growing season than by the total precipitation. Hence, and regardless of tillage and cropping systems, barley yield in 1999-2000 was 61% less than yield in 2001-2002 for a similar seasonal rainfall in both growing seasons. The high yield in 2001-2002 (Table 7.2) can be related to a large effective rainfall in March-May (109 mm), (Fig. 7.2a) that favoured ear and grain development. In 1999-2000, low yields (Table 7.2) were associated to a low effective rainfall during flowering (58 mm in March-May; Fig. 7.2a), which determined a poor grain development through a lower number of ears x m^{-2} and grain weight (Table 7.2). These results agree with those of Amir et al. (1991) and Day et al. (1987) who found lower grain production when there is a water shortage during the grain-filling period. In the 2000-2001growing season, characterised by a contrasting seasonal rainfall distribution (wet fall and dry spring), barley yields were also low. A low *PASW* in April-May (Fig. 7.4), due to a high soil water consumption by the crop in the pre-anthesis period, along with a low precipitation in those months (only 25 mm of effective rains), stressed the crop during ear

Table 7.2. Grain yield and yield components of barley as affected by tillage (conventional tillage, CT; reduced tillage, RT; and no-tillage NT), and cropping system (CC, continuous cropping; CF, cereal-fallow rotation) in the 1999-2000, 2000-2001 and 2001-2002 growing seasons.

Growing season	Cropping system	Tillage treatment	Grain yield (kg ha^{-1})	Ears per m^2	Grains per ear	Grain weight (mg)	Harvest index
1999-2000	CC1	CT	859	183.4	17.4	27.8	0.43
		RT	484	122.6	14.4	27.5	0.36
		NT	633	145.0	16.3	27.8	0.35
		LSD[†]	165	NS	NS	NS	0.06
	CF3	CT	1442	255.9	18.6	31.2	0.50
		RT	1567	239.2	21.2	32.3	0.49
		NT	839	210.8	14.5	28.9	0.36
		LSD	NS	NS	2.6	NS	NS
2000-2001	CC1	CT	1409	246.6	13.9	37.5	0.28
		RT	1188	236.8	13.6	35.2	0.28
		NT	902	148.7	20.4	31.5	0.27
		LSD	NS	NS	NS	NS	NS
	CF2	CT	1475	284.6	14.1	44.8	0.25
		RT	1347	224.5	16.7	33.4	0.24
		NT	1242	236.1	20.9	26.7	0.26
		LSD	NS	NS	NS	NS	NS
2001-2002	CC1	CT	2599	457.7	17.2	33.6	0.39
		RT	1782	350.5	14.9	33.2	0.39
		NT	1494	263.0	17.1	28.1	0.32
		LSD	NS	NS	NS	NS	NS
	CF3	CT	3096	528.2	15.6	34.5	0.40
		RT	2751	374.8	22.1	36.7	0.43
		NT	3190	570.7	17.7	36.1	0.56
		LSD	NS	NS	4.0	NS	0.11

[†] Least significant difference, $P<0.05$. NS, not significant.

development, which resulted in a decrease in the number of ears per square meter and, therefore, in low yields (Table 7.2). Comparable results were found in south Australia by French (1978), who observed that yields were poorly correlated with soil water content at sowing but highly influenced by rainfall during the growing season. However, a higher amount of stored water at sowing in the 2000-2001 season provided some insurance against plant water stress in spring so that grain production was higher than in the dry 1999-2000 season.

Overall, grain yield in the CF rotation (1883 kg ha^{-1}) was 49 % greater than in the CC system (1261 kg ha^{-1}) (Table 7.2). This yield increase in CF is higher than the 25% measured by López and Arrúe (1997) and the 15% estimated by Austin et al. (1998a) in the study area, and the 24 and 31% reported by López-Bellido et al. (2000) and French (1978) for wheat in south Spain and south Australia, respectively, but lower than the 63% obtained by Díaz-Ambrona and Mínguez (2001) in semiarid central Spain for barley in two contrasting years and the 105% found by Amir et al. (1991) in semiarid Israel for wheat in years with below-average rainfall. In our study, since the growing season rainfall was low (195 mm on average), the yield gain in CF could be explained by the additional water stored at sowing. French (1978) in south Australia and López and Arrúe (1997) in central Aragón found that the yield response under CF was related positively to this extra water. The mean yield gain in CF was 28 kg ha^{-1} per mm water conserved. This grain yield increase is greater than the 11 or 8 kg ha^{-1} per mm water conserved obtained by French (1978) and López and Arrúe (1997), respectively. In other experiences, however, the yield gain after long fallowing has been attributed to an increase in soil nitrogen availability and control of cereal root diseases and not to any increase in soil water storage (Incerti et al., 1993; Amir et al., 1991). In our water limiting conditions, where cereal crops might be more sensitive to soil pathogens, the higher crop yield under CF could be related to an improvement in soil sanitation.

On the other hand, an interaction between cropping system and rainfall distribution during the growing season was observed. Differences in crop yield were small (16%) in 2000-2001 (wet autumn and dry spring) and more significant in 1999-2000 (95%) and 2001-2002 (54%) (dry autumn and wet spring in both seasons). These results suggest, as Austin et al. (1998a) pointed out, that in years with wet autumns (i.e. the 2000-2001 campaign), farmers could beneficially sow without long-fallowing (i.e., after the minimum 5-month fallow). On the contrary, in years with a dry autumn, where the risk of crop failure is high, fallowing for a further year could result in additional root zone soil water at sowing and a better crop establishment thus decreasing the risk of crop failure. In 2001-2002, the higher yield under CF could be also explained by additional water stored at sowing below 70 cm depth due to deep percolation during the preceding overwinter fallow period (Chapter 6 (Fig. 6.5). When grain production was adjusted to an annual basis including fallow time, the CC system was more efficient at using precipitation, producing, on average, 34% more grain than the CF rotation.

Although small differences in grain yield were observed among tillage systems in the three experimental years, NT yielded 24 and 8 % less grain than CT and RT, respectively, as a result of a smaller number of grains per unit of area (grains per ear x ears per m^2) (Table 7.2). A reduction of 53 and 43% in grain yield with NT compared to CT and RT was found by López and Arrúe (1997) in central Aragon after two years of trial. In principle, a lower grain production under NT could be related to a greater soil compaction at the surface horizons in this treatment that restricts root growth and access to water and nutrients in deeper layers (López et al., 1996). These results are comparable to those obtained by López-Bellido et al (2000) in southern Spain, but differ from those found by Mrabet (2000) in semiarid Morocco and Lampurlanés et al. (2002) in northeastern Spain, who reported a significant yield increase with NT compared to CT and RT treatments.

The harvest index, which was not much affected by crop and tillage systems, was relatively low in 2000-2001 (Table 7.2). As mentioned before, in this season, an important vegetative growth during the early crop development stages, along with a drought period during ear formation (Fig. 7.4), limited the amount of soil water available for grain development, which resulted in low yield and harvest index values. This result is in agreement Amir et al. (1991) who found that the harvest index is strongly related to the post-anthesis water supply.

3.3. Crop water use

3.3.1. Total water use

Overall, 60% of total water use (*ET*) occurred by anthesis and 40% from anthesis to maturity (Fig. 7.5). Over the three experimental years, dry matter production (*DM*) was related to *ET* ($DM = 68ET - 10597$, $R^2 = 0.61$). On the other hand, although a poor relationship was found, grain yield tended to increase with *ET*. A significant influence of both seasonal precipitation and cropping system on *ET* was found. In 1999-2000, small differences between *ET* and seasonal rainfall indicate that during the entire growing period the crop mostly used this rainfall. Additionally, the low *ET* in 1999-2000 (on average, 16% lower than *ET* in 2000-2002 and 2001-2002) would explain the poor crop growth and development in that season. In contrast, in 2000-2001, *ET* up to anthesis (ZGS 60) was 40% higher than the rainfall received in that period (Fig. 7.5). This result is consistent with the high soil water content at seeding (Fig. 7.2) and would also explain the high *DM* production during the vegetative period (Fig. 7.4). As high pre- to post-anthesis *ET* ratio indicate, the rainfall collected during the last phases of crop development (from anthesis to harvest) was not enough to satisfy the water needs of a well-developed crop, which resulted in low yields. Cantero-Martínez et al. (1995) also found that in dry years water is preferentially consumed in the pre-anthesis period. In 2001-2002, *ET* up to tillering (ZGS 22) was about two times lower than the

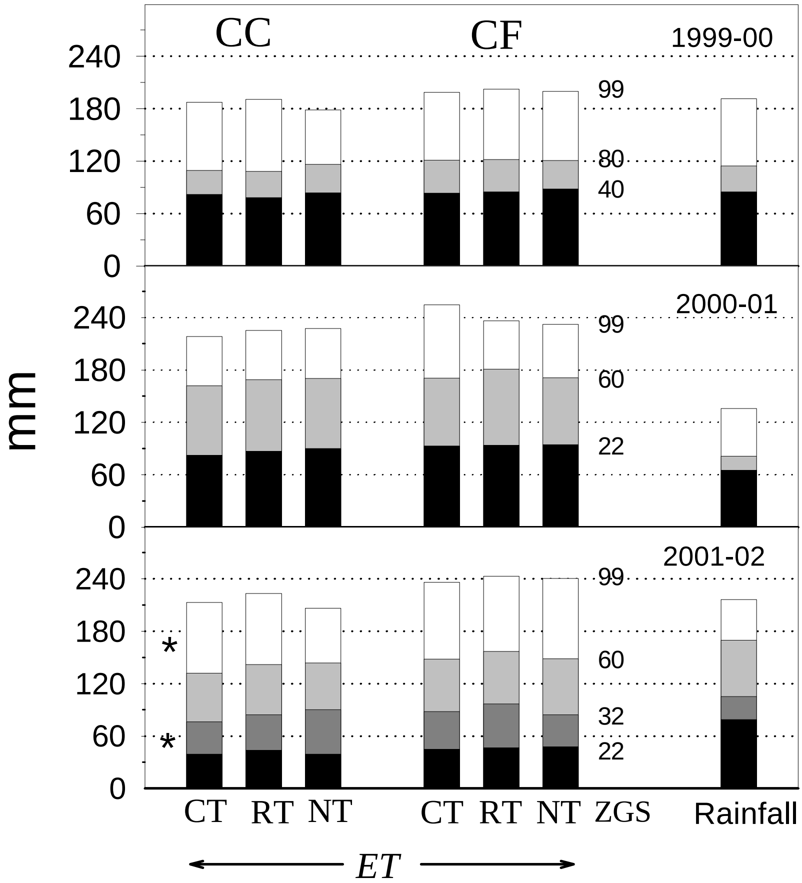

Figure 7.5. Crop water use (*ET*) during different phases of barley growth as affected by tillage (CT, conventional tillage; RT, reduced tillage; and NT, no-tillage) under continuous crop (CC) and crop-fallow rotation (CF) and seasonal precipitation during the 1999-2000, 2000-2001 and 2001-2002 growing seasons. ZGS indicates Zadoks growth stages. An asterisk indicates significant differences among tillage treatments at P<0.05 for a given growth phase and crop system.

corresponding rainfall (Fig. 7.5), which can be attributed also in this case to a poor crop establishment and early growth (Table 7.1; Fig. 7.4). The extra soil water not consumed by the crop by tillering was subsequently used, which would explain high biomass production from tillering to harvest (Fig. 7.4) and high grain yields in the 2001-2002 season (Table 7.2).

Regardless of tillage treatment, the CF rotation used 15-26 mm more water than the CC system. Although a consistent relationship between the extra water used by the CF crop and the additional water content at sowing was not found, the average *ET* is in agreement with the average 22 mm water gained at sowing by the CF system (Chapter 5, Table 5.4). These results are comparable with those obtained by French (1978) and Latta and O'Leary (2003) in south Australia. The difference in *ET* between CF and CC was more important in seasons with a dry autumn (i.e., 1999-2000 and 2001-2002).

There were no significant differences in *ET* among tillage treatments. This unexpected result, also observed by Singh et al. (1998), is not consistent with the lower yields measured under NT.

3.3.2. Crop transpiration and soil water evaporation

Estimates of *T*, its contribution to *ET* and the transpiration efficiency for grain yield, *TE*, are shown in Table 7.3. The partitioning of *ET* into its components showed that a large proportion of *ET* occurred as *E*. This would explain the similarity in total *ET* for the three tillage treatments, despite the differences observed in crop growth and yield. Overall, the contribution of *E* to *ET* showed a significant variation among growing seasons, ranging from 31% of *ET* in 2001-2002 (wet spring) to 69% of *ET* in 1999-2000 (dry spring). On the other hand, *T* was significantly greater under the CF rotation than under the CC system. The average *T*/*ET* ratio under CF (0.57) was 30% higher than under CC (0.44), similar to the 39% obtained by Amir et al (1991) in arid Israel. These differences can be

Table 7.3. Crop transpiration (*T*), its contribution to water use (*T/ET*) and transpiration efficiency for grain yield (*TE*) of barley, estimated from vapour pressure deficit (e^* - e) and above-ground dry matter (*DM*) for conventional tillage (CT), reduced tillage (RT) and no-tillage (NT) under continuous cropping (CC) and cereal-fallow (CF) rotation in the 1999-2000, 2000-2001 and 2001-2002 growing seasons.

Growing season	Cropping system	Tillage treatment	(e^* - e) (Pa)	*ET* (mm)	*DM* (g m^{-2})	*T* (mm)	*T/ET* (%)	*TE* (kg ha^{-1} mm^{-1})
1999-2000	CC1	CT	850	187	202	56.0	28.6	15.7
		RT		190	121	33.1	16.6	13.3
		NT		178	178	48.7	26.0	12.9
		LSD[†]		NS	NS	8.8	4.8	2.3
	CF3	CT	850	199	303	86.0	41.4	17.8
		RT		202	340	93.1	45.8	17.7
		NT		200	212	58.0	29.1	13.1
		LSD		NS	NS	NS	NS	NS
2000-2001	CC1	CT	858	219	453	125.7	57.2	10.1
		RT		225	398	110.2	48.7	10.0
		NT		228	329	91.1	40.0	9.8
		LSD		NS	NS	NS	8.7	NS
	CF2	CT	858	253	510	137.6	58.9	10.0
		RT		237	512	142.0	59.6	8.8
		NT		233	397	109.9	47.8	10.0
		LSD		NS	NS	NS	NS	NS
2001-2002	CC1	CT	805	214	661	171.7	80.5	15.0
		RT		223	440	114.3	51.0	15.0
		NT		206	370	96.0	46.2	12.2
		LSD		13	151	NS	18.6	NS
	CF3	CT	805	235	754	196.0	82.9	15.2
		RT		243	710	184.4	75.7	16.4
		NT		241	649	169.2	70.2	21.7
		LSD		NS	NS	NS	NS	4.1

[†] Least significant difference, P<0.05. NS, not significant.

attributed to a lower crop biomass under CC, which favoured soil water evaporation. Although no significant differences in *T* were observed among tillage treatments, high *E* values under NT resulted in a low *T*/*ET* ratio (Table 7.3). This could be attributed to a lower ground cover by the crop during crop growth (López and Arrúe, 1997) and higher water content at the surface in the NT soil profile, which may enhance soil water evaporation in this treatment. The average value of *TE* computed over the three experimental years (13.6 kg ha^{-1} mm^{-1}) was within the range found by López and Arrúe (1997) for barley (7.4-23.8 kg ha^{-1} mm^{-1}) and below the potential ratio (16.7 kg ha^{-1} mm^{-1}) estimated by McAneney and Arrúe (1993) for wheat in central Aragon.

3.3.3. Quantitative indices of water use and precipitation use efficiency

Water use efficiency for above-ground biomass at harvest (WUE_b) and grain yield (WUE_g) were affected by seasonal rainfall, tillage treatment and cropping system (Fig 6). Overall, WUE_b values ranged between 6.1 and 32.2 kg ha^{-1}mm^{-1} and were comparable to those found for wheat by other authors (French, 1978; French and Schultz, 1984; Amir et al.,1991). Years with a wet autumn and a dry spring (i.e., 2000-2001), but also with a dry autumn and effective rains in spring (i.e., 2001-2002), showed high WUE_b values. In 1999-2000, on the contrary, the lowest values of WUE_b could be related with a less effective precipitation recorded during the entire crop growing season.

A different behaviour was observed in WUE_g. Small WUE_g values obtained in 1999-2000 and 2000-2001 (Fig. 7.6) were due to low *PASW* during the ear formation phase (Fig. 7.4), which could have limited the translocation of the pre-anthesis carbohydrate reserves to the grain (López and Arrúe, 1997). On the contrary, higher *PASW* from March to May in 2001-2002 (Fig. 7.4) determined higher WUE_g values in this year (Fig. 7.6). WUE_g varied from 2.3 to 14.9 kg ha^{-1} mm^{-1}, being consistent with the range of values reported in the literature for cereal

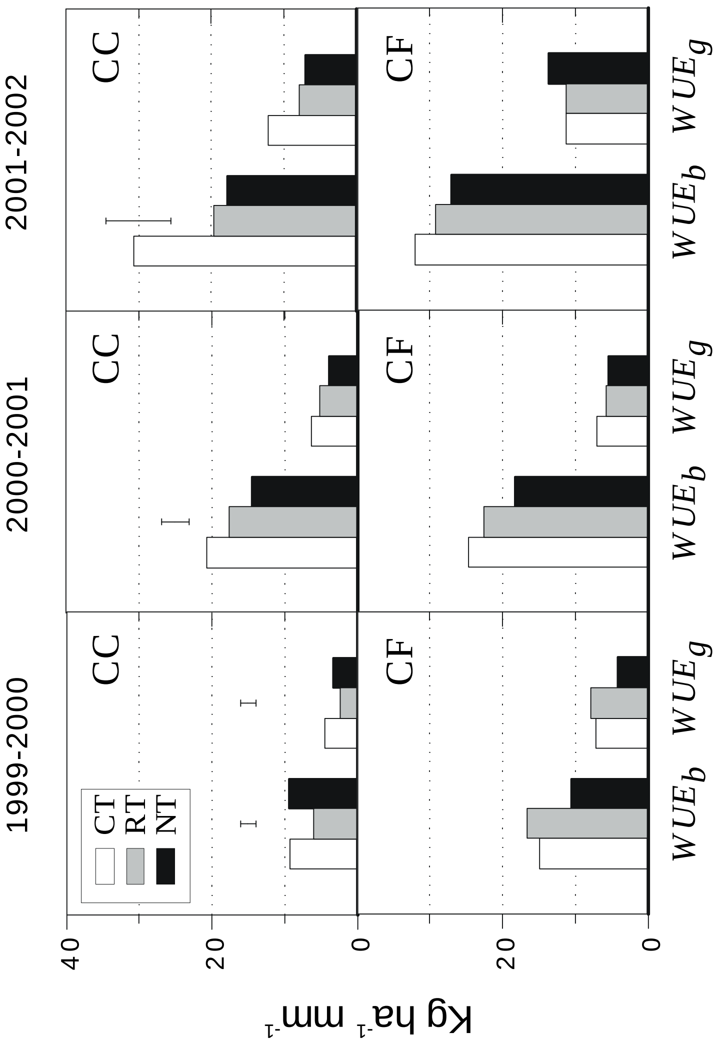

Figure 7.6. Water use efficiency for above-ground biomass (WUE_b) matter (*DM*) and grain (WUE_g) of barley as affected by tillage (CT, conventional tillage; RT, reduced tillage; and NT, no-tillage) under cropping system (CC, continuous cropping; CF, crop-fallow rotation) in the 1999-2000, 2000-2001 and 2001-2002 growing seasons. Vertical bars indicate LSD ($P < 0.05$).

crops in similar semiarid environments. French (1978) cited WUE_g values of 0.8-11.4 kg ha^{-1} mm^{-1} for wheat in south Australia and Cantero-Martínez et al. (1995) and López and Arrúe (1997) obtained for barley in two areas of the Ebro River valley WUE_g values that ranged from 5.9 to 9.5 kg ha^{-1} mm^{-1}, in the first case, and from 0-7 to 17.0 kg ha^{-1} mm^{-1}, in the second. Mrabet (2000) found WUE_g values from 2.5 to 10.7 kg ha^{-1} mm^{-1} in semiarid areas of Morroco.

In agreement with data reported by Cooper and Gregory (1987) and results by French (1978), Amir et al. (1991) and Latta and O'Lery (2003), in the present study average values of both WUE_b and WUE_g were 26 and 29% greater, respectively, under the CF rotation than under the CC system. However, this difference between cropping systems was more significant in seasons with a dry autumn (1999-2000 and 2001-2002), in which the growing-season precipitation was low and not favourably distributed. Although, in general, tillage did not significantly affect water use efficiency, NT tended to show the lowest *WUE* values (Fig. 7.6) due to greater soil water evaporation losses under this treatment. This result differs from that obtained in semiarid Morocco by Mrabet (2000), that is greater *WUE* values under NT compared to CT and RT.

As water use efficiency measurements are limited to the growing season, for comparison of cropping systems with fallow periods of different length, the precipitation use efficiency (*PUE*) index proposed by Jones and Popham (1997) can be alternatively used (Table 7.4). Our results show that this index substantially increased when most of the effective rainfall occurred in the last months (March-May) of crop development (i.e., 2001-2002). On the other hand, although no significant differences in *PUE* were observed between the CF and CC systems, *PUE* tended to increase under CC. This would indicate (Farahani et al., 1998) that a shorter fallow season in the CC system allows using for crop transpiration the water that would otherwise be lost during long fallowing by soil water evaporation, runoff, or deep percolation.

Table 7.4. Precipitation use efficiency (*PUE*) of barley (grain yield divided by harvest-to-harvest crop water use) as affected by tillage (CT, conventional tillage; RT, reduced tillage; NT, no-tillage), and cropping system (CC, continuous cropping; CF, cereal-fallow rotation) in the 1999-2000, 2000-2001 and 2001-2002 growing seasons.

Growing season	Cropping system	Tillage treatment	Rainfall† (mm)	*ET*‡ (mm)	*PUE* (kg ha^{-1} mm^{-1})
1999-2000	CC1	CT	335	335	2.6
		RT		360	1.3
		NT		316	2.0
		LSD§			0.9
	CF3	CT	620	619	2.3
		RT		611	2.6
		NT		611	1.4
		LSD			NS
2000-2001	CC1	CT	386	383	3.7
		RT		378	3.1
		NT		415	2.2
		LSD			NS
	CF2	CT	721	723	2.0
		RT		718	1.9
		NT		716	1.7
		LSD			NS
2001-2002	CC1	CT	320	304	8.5
		RT		321	5.6
		NT		290	5.1
		LSD			NS
	CF3	CT	706	708	4.4
		RT		720	3.8
		NT		715	4.5
		LSD			NS

† Harvest to harvest precipitation
‡ Harvest to harvest crop water use
§ Least significant difference ($P<0.05$). NS, not significant.

Finally, the relationship between precipitation fallow storage efficiency (*PSE*) of the CF rotation and crop yield was established for the three experimental years (Fig. 7.7). The lack of correlation between *PSE* and yield would indicate that under CF grain yield is mainly related to the amount of effective rainfall during the last months of crop development (March-May), rather than to the gain in soil water storage at sowing after a long 16-18 month period of fallow.

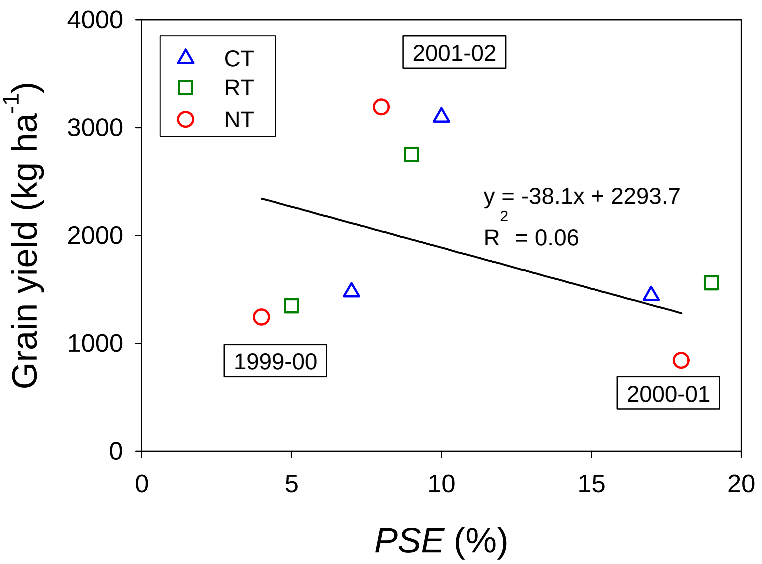

Figure 7.7. Barley yield for the crop-fallow rotation in the 1999-2000, 2000-2001 and 2001-2002 growing seasons *versus* precipitation storage efficiency (*PSE*) (CT, conventional tillage; RT, reduced tillage; and NT, no-tillage).

4. Conclusions

Results from three growing seasons showed that growth, water use efficiency and yield of a winter barley crop were influenced by both the amount and distribution of seasonal precipitation and cropping system, and to a lesser extent by the type of tillage. Above-ground dry matter production and corresponding water use efficiency (WUE_b) were high in years with significant effective rainfalls (>10 mm day^{-1}) either in autumn or in spring. However, greater values of water use efficiency for grain (WUE_g) and grain yields were found to be mainly linked to effective rainfall from stem elongation to harvest.

Despite the similarity in crop water use (*ET*) found under conventional tillage, reduced tillage and no-tillage, the lowest biomass values were provided, in general, by no-tillage. This response can be attributed to a greater soil water content in the untilled surface horizons over the growing season, which favoured a greater soil water loss by evaporation and less water for transpiration (*T*), as the lowest *T*/*ET* ratio values under no-tillage indicate. However, there were no clear differences in crop yield among tillage treatments for the study period. This finding suggests that conventional tillage can be substituted by conservation tillage for fallow management in semiarid dryland cereal production areas in central Aragon.

Overall, the crop-fallow rotation (CF) provided the highest values of crop biomass and water use, yielding about 49% more grain than the continuous cropping (CC) system. Although, in principle, these differences could be attributed to the additional soil water storage at sowing under CF, this extra water resulted in a significant yield increase only under dry, water limiting conditions during the early crop growth stages. However, other factors, such as the incidence of specific pests and diseases, that could be prevented in the CF system, should be further investigated. On the other hand, though no significant differences in precipitation use efficiency (*PUE*) were observed between the CF and CC systems, *PUE* tended to increase under CC, which yielded 34% more grain than the CF rotation when yields are adjusted to an annual basis. Results also showed that crop yields under CF were not dependent on the soil water stored at sowing after a long 16-18 month period of fallow. Further research on alternative crop rotations and cropping intensification to improve the efficient use of precipitation is needed to the sustainability of dryland agriculture in central Aragon.

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Capítulo 8

Conclusiones generales

Conclusiones generales

Avances metodológicos en la medida de las propiedades hidráulicas del suelo

1. El sistema desarrollado para la medida del nivel de agua en la columna de Mariotte de alimentación de un infiltrómetro de disco, utilizando la técnica de Reflectometría de Dominio Temporal (TDR), ha permitido:
   i) automatizar las lecturas del flujo de infiltración facilitando, con ello, un mejor registro de datos y eliminando los errores asociados al procedimiento habitual de lectura manual;
   ii) efectuar medidas simultáneas de infiltración y contenido de humedad del suelo utilizando una misma técnica; y
   iii) realizar determinaciones simultáneas de infiltración en varios puntos de observación utilizando un sistema de mutliplexión.

2. El nuevo diseño de infiltrómetro de disco propuesto, con el depósito de Mariotte alimentador de agua independiente del disco, supone un avance metodológico con respecto a diseños similares ya que:
   i) reduce sensiblemente el peso del infiltrómetro sobre la superficie de infiltración; y
   ii) permite fijar una tensión de infiltración constante con independencia de la posición del disco con respecto al depósito de Mariotte de alimentación.

3. La aplicación de la técnica de infiltrometría de discos en suelos muy sueltos (i.e. suelos recientemente labrados) ha permitido demostrar que el peso del

infiltrómetro colapsa la débil estructura del suelo en condiciones próximas a saturación, afectando directamente a las medidas de infiltración. En estos casos, ni la reducción del peso del infiltrómetro, ni su completa eliminación con la ayuda de soportes han dado resultados satisfactorios. En conclusión, la infiltrometría de discos no es una técnica adecuada para la caracterización de la conductividad hidráulica en suelos recientemente labrados, ya que subestima el flujo de infiltración en condiciones próximas a saturación.

4. El índice de poros propuesto para caracterizar la fracción de poros de transporte de agua (número de poros efectivos y porosidad efectiva) a partir del tamaño de poro representativo para dos tensiones consecutivas elimina la inconsistencia asociada a la aplicación de la teoría de ascenso capilar para estimar el número de poros transmisores de agua. Los resultados demuestran, tras verificar la solidez de este nuevo índice, que el método del ascenso capilar subestima el radio de los macroporos y sobrestima de número de poros y la porosidad efectiva de los macro- y mesoporos del suelo.

Sistema de laboreo y propiedades hidrofísicas del suelo durante el periodo barbecho

5. Tras 8-10 años de comparación de sistemas de laboreo, el horizonte superficial del suelo (0-10 cm) bajo el sistema de siembra directa o no-laboreo (NT) presenta, en comparación con los sistemas de laboreo convencional (CT) y laboreo reducido (RT): i) una mayor densidad aparente; ii) curvas características de retención de agua con menor contenido de humedad a saturación y de agua disponible para las plantas y un mayor contenido de humedad a capacidad de campo (-10 kPa) y punto de marchitez permanente (-1500 kPa); y (iii) macroporos de mayor diámetro pero una menor

conductividad hidráulica a tensiones próximas a saturación debido un menor número de macroporos y mesoporos. No se observaron diferencias significativas en propiedades hidrofísicas entre CT y RT.

6. Las labores primarias aplicadas en CT y RT: i) reducen la densidad aparente del horizonte superficial del suelo; ii) incrementan la humedad a saturación y la fracción de poros de aireación y reducen el agua disponible para las plantas; y iii) reducen el tamaño de poro representativo y aumentan significativamente el número de poros para el rango de tensiones entre –4 y –14 cm, lo que se traduce en un aumento significativo en la conductividad hidráulica del suelo.

7. Las lluvias registradas tras las labores primarias en CT y RT reestructuran el suelo: i) incrementando la densidad aparente en superficie; ii) reduciendo la humedad a saturación y la porosidad de aireación; y iii) aumentando el tamaño de poro representativo pero disminuyendo el número de poros para el rango de tensiones comprendidas entre –4 y –14 cm, lo que lleva a una reducción de la conductividad hidráulica del suelo para ese rango de tensiones. Estos cambios son más pronunciados cuanto más intensas son las lluvias registradas tras las labores.

8. A diferencia del suelo bajo NT, que presenta valores similares de propiedades hidrofísicas en la superficie y a 40 cm de profundidad, el suelo bajo CT y RT muestra un horizonte profundo más compacto, con menor porosidad de aireación, menor contenido de humedad a saturación y menor conductividad hidráulica.

9. En general, la distribución del contenido de agua en el perfil del suelo en NT se caracterizó por presentar un mayor contenido de agua en superficie, frente al suelo en CT y RT que tiende a acumular más agua en profundidad.

Manejo del suelo y balance de agua durante el periodo de barbecho

10. Las labores primarias aplicadas en CT y RT durante el periodo de barbecho en la rotación cebada-barbecho favorecen las pérdidas de agua por evaporación a corto plazo (24 horas después de las labores). El valor medio de estas pérdidas bajo CT y RT, 14 y 11 mm, respectivamente, fue mayor al observado en NT (1 mm).

11. Las pérdidas medias de agua por evaporación durante las primeras 24 horas tras las labores secundarias fueron menores (3.9 mm en CT y 3.8 mm en RT) que las observadas tras las labores primarias. Sin embargo, las labores secundarias en CT y RT favorecen la conservación del agua a medio plazo al reducir la tasa de evaporación por debajo de los valores medidos en NT.

12. La eficiencia del barbecho para la acumulación de agua en el suelo (*PSE*) fue baja en el periodo experimental (11 %) y claramente influida por el régimen pluviométrico registrado en los distintos periodos de barbecho. Los mayores valores de *PSE* coinciden con aquellos periodos en los que gran parte de la lluvia se concentra en los dos últimos meses del barbecho.

13. El sistema de laboreo no tuvo efectos significativos sobre la eficiencia en el almacenamiento de agua al final del barbecho.

14. Como promedio, el sistema de cultivo de "año y vez" almacenó al final del barbecho 22 mm más de agua que el sistema de cultivo continuo. Esto supone que la eficiencia del barbecho largo (16-18 meses) con respecto al barbecho corto (5-6 meses) es de tan sólo un 5.2%. Estos resultados cuestionan la viabilidad del barbecho largo como práctica agronómica para acumular agua para el cultivo siguiente.

15. La aplicación del modelo SiSPAT para simular el balance de agua durante el periodo de barbecho resultó altamente satisfactoria. Los resultados muestran que en ausencia de labores la evaporación acumulada al final del barbecho es mayor bajo NT que bajo CT y RT, tratamientos que favorecen el drenaje profundo.

16. La simulación también ha evidenciado que los valores más altos de *PSE* y de drenaje profundo coinciden con aquellos periodos en los que las lluvias se concentran principalmente en la primera fase del barbecho, con baja demanda evaporativa. Por el contrario, los periodos de barbecho con una primavera muy lluviosa presentan un valor de *PSE* inferior.

17. Tras comparar la *PSE* medida en campo con la estimada por el modelo SiSPAT, en el supuesto de ausencia de alteración del suelo, se ha observado cómo en años con una primera fase de barbecho muy lluviosa las labores favorecen la evaporación del agua del suelo, reduciendo la *PSE*.

Manejo del barbecho y rendimiento del cultivo de cebada

18. La producción de biomasa y su correspondiente eficiencia en el uso de agua incrementaron en años en los que las lluvias fueron abundantes tanto en otoño

como en primavera. Sin embargo, el rendimiento de cebada fue más elevado en años con abundantes lluvias efectivas en primavera, independientemente de las lluvias registradas en otoño.

19. Aunque el uso total de agua por el cultivo fue similar en los tres sistemas de laboreo, el cultivo bajo NT produjo menos biomasa que bajo CT y RT, lo que indica que en NT las pérdidas de agua por evaporación son más elevadas. No se observaron diferencias claras en rendimiento entre sistemas de laboreo.

20. El rendimiento medio en grano en el sistema de cultivo de "año y vez" fue un 49 % más alto que en el sistema de cultivo continuo de cebada. Estas diferencias fueron más significativas en años con un otoño seco. Sin embargo, el cultivo continuo rindió un 34% más que el cultivo en "año y vez" cuando la producción de grano se ajustó a una base anual considerando la precipitación entre dos cosechas consecutivas y la duración del periodo de barbecho.

21. Dados los bajos rendimientos del sistema de cultivo continuo de cebada, la viabilidad económica de este sistema en comparación con el sistema de "año y vez" es también cuestionable. Este hecho, junto al largo periodo improductivo (16-18 meses) en el sistema de "año y vez", justifican la necesidad de buscar nuevas rotaciones de cultivo que permitan mejorar la productividad y sostenibiliad de los secanos semiáridos de Aragón.