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Assessing the cover crop effect on soil hydraulic properties by inverse modelling in a 10-year field trial

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ABSTRACT

Cover cropping in agriculture is expected to enhance many agricultural and ecosystems functions and services. Yet, few studies are available allowing to evaluate the impact of cover cropping on the long term change of soil hydrologic functions. We assessed the long term change of the soil hydraulic properties due to cover cropping by means of a 10-year field experiment. We monitored continuously soil water content in non cover cropped and cover cropped fields by means of capacitance probes. We subsequently determined the hydraulic properties by inverting the soil hydrological model WAVE, using the time series of the 10 year monitoring data in the object function. We observed two main impacts, each having their own time dynamics. First, we observed an initial compaction as a result of the minimum tillage. This initial negative effect was followed by a more positive cover crop effect. The positive cover crop effect consisted in an increase of the soil micro- and macro-porosity, improving the structure. This resulted in a larger soil water retention capacity. This latter improvement was mainly observed below 20 cm, and mostly in the soil layer between 40 and 80 cm depth. This study shows that the expected cover crop competition for water with the main crop (evapotranspiration) can be compensated by an improvement of the water retention in the intermediate soil layers and a reduction of drainage loses. This may enhance the hydrologic functions of agricultural soils in arid and semiarid regions which often are constrained by water stress.

1. Introduction

Water availability in the soil root zone is a critical agriculture production factor in semiarid and arid conditions. This water availability (defined here as the difference between soil water content at field capacity and permanent wilting point, 33 and 1500 kPa respectively) is mainly determined by the field scale soil water balance and controlled by hydraulic properties in the soil root zone. The properties of the soil pores, such as soil pore size distribution, connectivity and tortuosity, are directly related to several soil processes, such as soil water infiltration, retention and drainage. Macropores (500–50 µm equivalent diameter) are related to water and air movement, whereas mesopores (50–5 µm) are related to soil water retention capacity (Carter and Ball, 1993). Both abiotic (e.g., tillage, drying and wetting) and biotic factors (e.g., roots, earthworms) influence the size, shape and continuity of the soil pores that affect the soil hydraulic processes and in turn the field water balance (Kay and VandenBygaart, 2002). Soil management can control these factors (Van Es et al., 1999), including the soil root zone water availability.

Introducing conservation practices such as minimum tillage after the long-term traditional use of mouldboard ploughing is now well known to induce changes in soil properties (Strudley et al., 2008). Initially, an increase in soil bulk density may occur (Moret and Arrúe, 2007; Rücknagel et al., 2016). However, in the long term, organic matter and aggregate stability increase, soil pore size distribution changes and, often, the soil water retention capacity increases (Strudley et al., 2008). Moreover, Hargrove (1991) observed that plant cover helped to reduce soil compaction and soil erosion under no-tillage conditions. Cover crops (CCs) have been recognized as a successful method for improving nutrient availability (Thorup-Kristensen et al., 2003), controlling nitrate leaching (McCracken et al., 1994), reducing weed infestation (Leavitt et al., 2011) or disease suppression (Abawi

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and Widmer, 2000). But CC have been also recognized for soil quality improvement (Kuo et al., 1997) and soil erosion control (Langdale et al., 1991; Bowman et al., 2000). Leaving the soil fallow will increase soil erodibility and bulk density, which is critical for runoff initiation (Cerdà et al., 2009). Maintaining a CC between main summer crops, when the majority of the yearly rainfall occurs under Mediterranean conditions, protects soil from the impact of rainfall, reducing aggregate slaking and disruption (i.e., crusting). Moreover, CC residues after the termination date provide a mulch on the soil surface that may prevent the direct loss of soil water through evaporation and hence increase soil root zone water availability. These benefits may counteract the possible competition for water with the main crop, which is one of the main drawbacks of CCs application (Unger and Vigil, 1998).

During the last few years, several publications have tried to quantify the effects of CCs on soil properties (Celette et al., 2008; Ward et al., 2012; Gabriel et al., 2014). However, given the high complexity of the CC-main crop-soil-weather system, those studies do not often reach the same conclusions. Most of the publications focused on the increase in soil organic matter and its related effect on aggregate stability and soil structure (Peregrina et al., 2010; García-González et al., 2016; Rorick and Kladivko, 2017). Other studies focused on soil hydraulic properties. For example, Celette et al. (2008) measured an increase in soil water infiltration under CC and also observed an enhancement in soil aggregate stability, whereas Quemada and Cabrera (2002), Ward et al. (2012) or Basche et al. (2016) reported an increase in soil water holding capacity when CCs were used. However, most of these studies elucidated impacts of CCs either on the soil surface or in the short term. Thus, there is a need to study the effects of CCs on soil hydraulic properties in the long term and along the soil profile. This effect is critical for evaluating the sustainability of CCs in agro-ecosystems under current and future climate conditions, even more when the availability of water is not assured and models are predicting less rainfall in Mediterranean regions (Kaye and Quemada, 2017).

Numerical models based on physical equations and knowledge of the soil hydraulic properties allow the quantification of water fluxes and water balance state variables in the soil-crop-atmosphere continuum, including water drainage (Muñoz-Carpena et al., 2008). However, complex models (simulating soil-water-plant continuum) involve a large number of parameters, with the final prediction success relying on their accurate identification and on the model's sensitivity to them (Šimůnek et al., 1999). Inverse modelling can be used to try to overcome this limitation problem, allowing the identification of soil hydraulic parameters (Ritter et al., 2003). The process consists of a search for the best set of parameters, varying them iteratively and comparing the numerical prediction of the soil water state variable provided by the model with the actual value measured under field conditions (Šimůnek et al., 1999). Consequently, the main advantage of this procedure is that the results are based on directly monitored variables (Ritter et al., 2003). In this study, the approach is made possible owing to the development of multisensor probes (placed at different depths and in different points), which allow the continuous monitoring of soil water content at different depths with minimum soil disturbance (Fares and Alva, 2000). Inverse modelling allows the identification of parameters of the soil-crop system that are consistent with monitored soil water and crop parameters in the field and will ultimately result in lower model prediction uncertainties, trying to reduce these uncertainties as much as possible to the intrinsic natural soil uncertainty. If soil-crop management dynamically affects the soil hydraulic properties and hence the soil water dynamics, then inverse modelling should enable the dynamics of soil hydraulic properties to be unravelled based on the monitoring of soil water dynamics. However, interferences between crop and hydraulic properties should be identified in order to avoid equifinality problems.

The main objective of this study was to assess the medium-term effect of cover crops on soil hydraulic properties over the soil profile using the inverse modelling of a mechanistic model based on continuous soil moisture measurements in a field experiment. The secondary objective was to analyse if the change in the soil hydraulic properties could reduce the water competition with the main crop.

2. Material and methods

2.1. Field experimental setup

The study was conducted in an experimental field station located in the Tajo River Basin (40°03′N, 03°31′W and 550 m a.s.l., in Aranjuez, close to Madrid, Spain). The slope was close to zero and runoff was not observed along the experiment. The soil was classified as a *Typic Calcixerept* (Soil Survey Staff, 2014) and it has a silty clay loam texture. Other soil chemical and physical properties (0–120 cm depth) are shown in Gabriel et al. (2010). Climate is classified as cold steppe arid (Bsk) according to Köppen-Geiger classification (Peel et al., 2007). Weather information (temperature, humidity, wind speed, precipitation and solar radiation) were recorded hourly using a field Campbell Scientific station (Campbell Scientific, Logan, UT, USA) placed in the experimental field during the study period.

The field experiment consisted of a 10-year crop rotation (from October 2006 to September 2016), with or without a winter CC between consecutive main summer crops. The main crops were sown during April and harvested around September and they were maize (*Zea mays* L.; the summers of 2007, 2008, 2009, 2010, 2013, 2014 and 2016) and sunflower (*Helianthus annuus* L.; the summers of 2012 and 2015). In the summer of 2011, the field was fallow to control weeds and finished with a maize monoculture. The experimental plots consisted of eight square 144 m^2 plots randomly distributed between the two treatments with four replications. Each plot received the same treatment throughout the 10-year period. The CC was barley (*Hordeum vulgare* L.) and was sown every year during the first half of October and killed during the second half of March. Barley was sown by broadcasting, incorporated with a 5-cm shallow cultivator, terminated with one application of glyphosate and chopped before main crop sowing, leaving the residues over the ground. The main crops were directly sown over the CC residues. Then, the soil was not tilled except for the first 5 cm once per year. Other cropping techniques applied to the main crops, such as fertilization, irrigation, or weed control, were equal in both treatments and adjusted to crop demands or weed infestation. More details can be found in García-González et al. (2016).

2.2. Field measurements

The soil water content was monitored daily (averaging hourly measurements) using EnviroSCAN® capacitance probes (Paltineanu and Starr, 1997). Six access tubes were installed in the 10-year experiment, three per treatment. Each access tube consisted of a plastic extrusion with 6 sensors from 0.1 to 1.1 m in depth every 0.2 m. Sensors were previously normalized, calibrated (under field and laboratory conditions) and validated following Gabriel et al. (2010). This validation included punctual response of the sensor to fast wetting events and the following drying period but also the consistence of the field measurements along the first 3 years of the present experiment. During the 3 years there was no decrease in the accuracy or the precision on the sensor measurements (Gabriel et al., 2010).

Different soil properties were measured at the beginning of the experiment. Four layers were defined (0–20, 20–40, 40–80 and 80–120 cm depths) based on the soil description in two trenches dug on the sides of the experimental field in 2006 (Gabriel and Quemada, 2011). Ten 100 cm^3 (50 mm in diameter) undisturbed soil cores for each layer were taken in 2006. The soil hydraulic conductivity (K_s) was measured using a laboratory constant head permeameter (Klute and Dirksen, 1986), and the saturation soil water content (θ_s) was obtained as the porosity measured in the soil cores. The residual soil water content (θ_r) was obtained from the lowest water content observed in each EnviroSCAN® probe after dry summer periods. The van Genuchten curve-shape initial hydraulic parameters α and n (van Genuchten, 1980; Mualem, 1976) were obtained with the RETC model (van Genuchten et al., 1991). The α and n were adjusted based on the soil water content data observed at saturation (based on the porosity), field capacity (as the water content observed in the EnviroSCAN® after 48 h from a heavy rainfall event; Arrequi and Quemada, 2006) and θ_r (from the EnviroSCAN® probes) for each core and probe. These results provided a range in which soil hydraulic property values estimated by inverse modelling should be included.

Climatic conditions (temperature, humidity, radiation, photosynthetically active radiation, rainfall and wind) were measured by a weather station located < 100 m from the field trial. Cover crop biomass was measured just before glyphosate application. Four 0.5 m × 0.5 m squares were randomly harvested from each plot, cut by hand at ground level, oven-dried at 65 °C and weighed as dry matter (d.m.). Soil cover was monitored every 15 days by taking digital images in 5 permanent points per plot that were analysed using techniques following Ramirez-Garcia et al. (2012). The root depth was estimated based on the differential water extraction between day and night at each depth observed in the EnviroSCAN® hourly measurements, following Gabriel et al. (2012).

2.3. WAVE model

The Water and Agrochemicals in soil, crop and Vadose Environment (WAVE_ model (Vanclooster et al., 1996) describes the water flow and solute movement in the vadose zone. The model numerically solves the one-dimensional isothermal Richard's equation parameterized with the van Genuchten (1980) water-retention curve and the Mualem (1976) unsaturated hydraulic conductivity. More details can be found in Gabriel et al. (2012). In this case, a Matlab® (The MathWorks Inc., Natick, MA, USA) version of the model was used. A crop subroutine was also included, principally based on the WOFOST crop model (van Diepen et al., 1989) and the previous SUCROS code (van Keulen, 1982; Spitters et al., 1988).

The climatic input data of the model are temperature and photosynthetically active radiation (assuming equal to 50% of the total radiation). Radiation is converted to an increase in biomass (based on light interception, maintenance rate and conversion efficiency) and an increase in biomass in leaf area index (LAI) (based on partitioning coefficients and leaf morphology coefficients). The subroutine discriminates assimilate partitioning at different phenological stages: from sowing to emergence (phase 0), from emergence to flowering (vegetative phase or phase 1) and from flowering to the dead leaves phase (reproductive phase or phase 2). The phenological stage and the simulated crop height were both based on thermal time. The model considers a bounded temperature range in which thermal time is accumulated. Crop growth is also corrected by temperature, water or nitrogen stresses, reducing crop growth and increasing the senescence rate. Root development considers a triangular distribution of root biomass by depth, increasing the depth based on the thermal time until a maximum root depth. The crop subroutine parameters (Supplemental material 1) were calibrated prior to the identification of soil hydraulic properties (based on previous hydraulic soil parameters defined by Gabriel et al. (2012)) using observed crop data from the first year of the experiment and validated with data from the remaining years. Phenology development rate parameters were adjusted first in order to fit the observed phenology in the field. Subsequently, growth parameters (LAI, aerial biomass, root depth and root biomass) were adjusted to the crop growth field observations.

Previous versions of the WAVE model included potential evapotranspiration as a climatic input. In this case, a subroutine was included to calculate the potential evapotranspiration described by Allen et al. (1998), based on the dual coefficient. This dual coefficient considers two coefficients multiplying the reference evapotranspiration (instead of just a single coefficient), one for evaporation and the other for transpiration, considering also the percentage of soil covered by residues or plants. Evaporation only occurs on the surface that is not covered with crop biomass, whereas transpiration only occurs on the surface covered with crop biomass. Three scenarios were considered: i) soil with crops growing and transpiring; ii) soil without crops; and iii) soil covered with dead crop residues. When the crops are transpiring, evaporation and transpiration are estimated independently. The evaporation is the result of the multiplication of the reference evapotranspiration by 1 (as the FAO coefficient suggestion for bare soil) and by the proportion of soil not covered by crops. The transpiration is the result of the multiplication of the reference evapotranspiration by the basic crop coefficient following the plateau model described by Allen et al. (1998). This model uses an initial value (for soils covered by less than 10%) for the basic crop coefficient, followed by a linear increase until a maximum value is reached when the crop covers more than 80% of the total surface. After this plateau, there is a linear decrease of the basic crop coefficient until a final value at harvest time is reached. When the soil is not covered by any crop or residue, the transpiration is equal to 0 and the evaporation is equal to the reference evapotranspiration. When the soil is covered by some dead residue, the transpiration is equal to 0 and the evaporation is calculated for the bare soil but multiplied by the fraction of soil that is not covered. The soil cover fraction was obtained from the LAI simulated and corrected following Ramirez-Garcia et al. (2012). The WAVE model corrected the final potential evapotranspiration supplied by this new module considering the internal restriction by solving the flow problem (considering surface and root depth soil water content for evaporation and transpiration respectively).

2.4. Soil hydraulic parameter identification

The inverse calibration of the soil hydraulic parameters was done based on the daily soil water content measurements. Each year, the soil hydraulic parameters were adjusted for the fallow and the CC treatments independently. The simulations started on the cover crop planting date, considering the measured soil water content at each depth and treatment as the initial condition for the model, and finished on the following April 15th. The following soil hydraulic parameters were considered to be affected by CCs and identified with a Monte Carlo based inverse modelling procedure: Ks (cm day^{-1}), θ_s ($cm^3\,cm^{-3}$), θ_r ($cm^3\,cm^{-3}$), α (cm^{-1}) and n, and all of them were affected for each of the four depths. The bottom boundary condition was fixed as free drainage, as water table was always below 4.5 m. For the automatic inversion, the WAVE model was coupled to the Shuffled Complex Evolution Metropolis algorithm for optimization and uncertainty assessment of hydrological model parameters (SCEM-UA, Vrugt et al. (2003). This global optimization algorithm is a Bayesian method based on the Markov chain Monte Carlo method (Gilks et al., 1998) that uses the Metropolis Hastings strategy (Metropolis et al., 1953) to evolve the population of possible parameter sets. The method reaches both the most likely parameter set and its underlying posterior probability distribution, conditioned to observed soil water data, within a single optimization run of the 3860 parameter dataset tried by the SCEM-UA. The fit of the simulations to the observed data was evaluated by the coefficient of efficiency (Ceff; Nash and Sutcliffe (1970)) and the root mean squared error (RMSE), as proposed by Ritter and Munoz-Carpena (2013), for the 3860 parameter dataset obtained for each treatment and year. This process was repeated for all the access tubes in both treatments and for each of the individual years in order to assess the dynamic evolution of the soil hydraulic properties over time. Newer indexes as Willmott et al. (2012) could have be used, but the Ceff was chosen for a better comparison with the previous work done in the experiment (Gabriel et al., 2012). Data were analysed using the SAS statistical package for analysis of variance PROC MIXED (SAS Institute, Inc., 2013). "Cover crop" treatment was considered the fixed effect

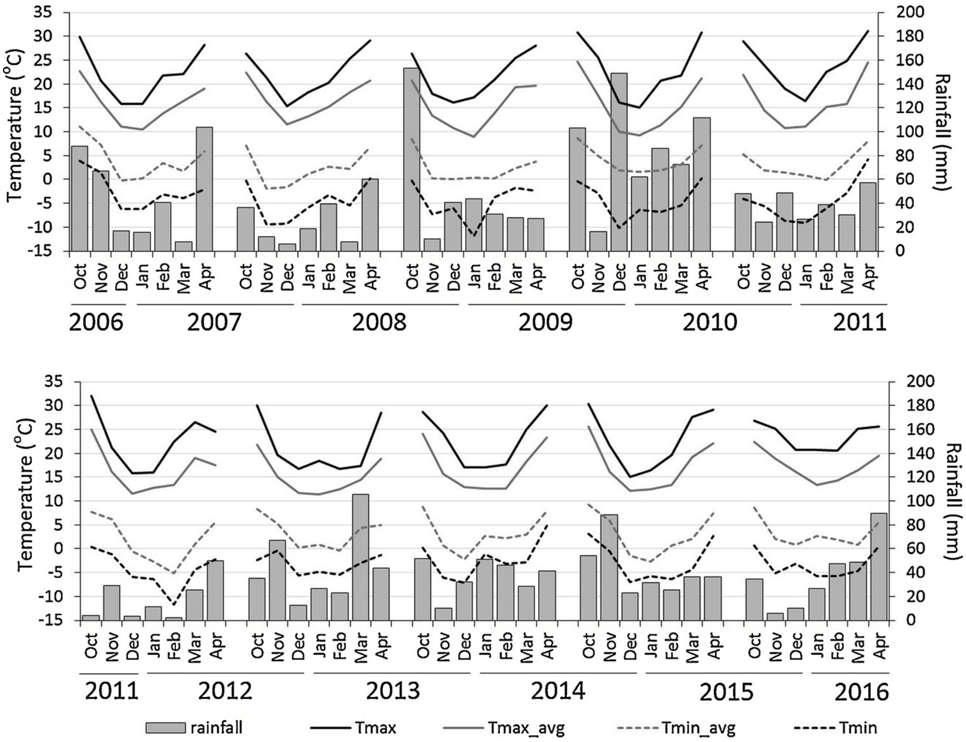

Fig. 1. Monthly climatic conditions during the ten simulated periods. Tmax and Tmin are the absolute maximum and minimum temperature, respectively, observed within a month. Tmax_avg and Tmin_avg are, the monthly average of the daily absolute maximum and minimum temperatures, respectively.

whereas "Year" was considered a repeated effect, as measurements were always done on the same plot over time. Separation of means was tested with the DIFF option of the LSMEANS statement with a significance level of $p < 0.05$.

Once the model was calibrated and the final parameters defined, the water balance was analysed. The water balance was obtained from the WAVE simulation of the ten years and the two treatments as during the calibration, starting on the cover crop planting date, considering the measured soil water content at each depth and treatment as the initial condition for the model, and finishing on the following April 15th. The water balance results compared were the total drainage, the total evaporation, the total transpiration and the final soil water content. This water balance analysis was important in order to see the real impact of the cover crop on the possible water competition with the following main crop.

3. Results and discussion

3.1. Weather conditions and crop development

The weather conditions for the field trial are illustrated in Fig. 1. The weather conditions during the cover cropping period changed from year to year, presenting different conditions for barley development and allowing a test of the model in a broad range of environmental conditions. The weather conditions varied from humid seasons (e.g., 2009/10 had 612 mm of rainfall accumulated between October and April) to very dry seasons (e.g., 2011/12 had just 124 mm of rainfall in the same period), all of them compared with the 222 mm in an average year in the region. Moreover, there were also differences in the cumulative rainfall during late autumn, winter or the beginning of spring. Usually, the winter is dry, as is typically observed in Mediterranean climates, but the autumn and spring are very variable, with years in which one, both or none of them are dry or wet. Temperature conditions were also different between years. Even when the soil never got frost, there were winters in which the minimum temperature average was below 0 °C during three consecutive months (i.e., 2011/12) and others where it was always above 0 °C (i.e., 2009/10 or 2015/16). Both rainfall and temperature distributions affected the soil water dynamics and soil water balance terms. The 10-year weather series considered in this study was able to represent the diversity of weather situations that may occur under these Mediterranean conditions.

The crop parameters were calibrated during the 2006/07 cropping season (Supplemental Material 1), and these values were applied during the entire study. The results of crop growth modelling of the field experiment are illustrated in Fig. 2. Final observed CC dry matter (d.m.) production varied from 1145 to 5117 kg d.m. ha^{-1}, and WAVE was able to predict this crop development with an $R^2 = 0.67$ and a root mean squared error (RMSE) = 1382 kg d.m. ha^{-1}, whereas the average

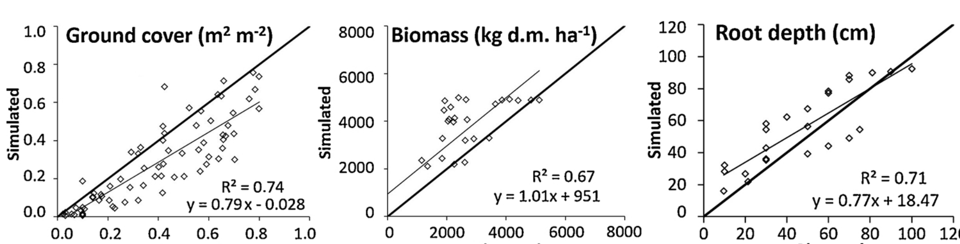

Fig. 2. Simulated versus observed ground cover, aerial biomass and root depth in the field.

observed standard error was 928 kg d.m. ha^{-1}. A tendency to overestimate the aerial biomass was also observed. This fact needs to be considered in further studies, but it seems to be produced because the model did not consider many biotic or abiotic parameters as weeds, pests, germination problems, nutrient deficiencies, etc. So, some of them could be included in further versions. The predicted ground cover (%) throughout the 10 years at different crop dates after sowing matched the observed ground cover with an $R^2 = 0.74$ and an RMSE = 16%. A tendency to underestimate the ground cover was also observed, and needs to be considered in further studies. Predicted root depth adjusted with observations had an $R^2 = 0.71$ and an RMSE = 15.8 cm. Crop simulations were always within the range of variation observed in the field, with RMSE values similar to the natural field variability. The relative RMSEs were 24, 35 and 33% for biomass, ground cover and root depth, respectively, similar or smaller to the 35% presented by Coucheney et al. (2015) as acceptable when evaluating crop components of an integrated agro-hydrological model. The correct simulation of these three variables under different growing conditions is a key factor in order to achieve an accurate estimation of evapotranspiration. And this consideration is possible because, as previous authors said, CC biomass was well correlated with total transpiration (Ritchie and Johnson, 1990), ground cover with direct soil evaporation and rainfall water interception (Tanner and Jury, 1976) and root depth with the total soil water availability for the plant (Doorenbos and Kassam, 1979).

3.2. Soil hydraulic parameter evolution

The model adjusted soil water content with a general coefficient of efficiency (Ceff) equal to 0.79 for fallow and 0.83 for barley treatment, combining all years and depths. Considering individual years, Ceff ranged from 0.77 to 0.57 under fallow and from 0.81 to 0.64 under barley. The similar behaviour in both treatments could be suggesting that the water balance simulated by the crop module is not including any extra noise in the hydraulic parameter estimation. Analysing layer by layer, the best adjustment was obtained in the surface (0–20 cm) of the fallow treatment, with a Ceff = 0.81, whereas the worst was in the 40–80 cm soil layer, with a Ceff = 0.64. In the barley treatment, the best adjustment was in the 20–40 cm layer, with a Ceff = 0.84, and the worst was in the 0–20 layer, with a Ceff = 0.72. The Ceff obtained for all years and treatments were in the same range as the one obtained by Gabriel et al. (2012) for the same soil during 2006/07.

The time course of the soil hydraulic properties presented two different phases (Fig. 3). In the first phase, there was a clear effect on hydraulic properties at the beginning of the study (from one to three years depending on the parameter and the depth), mainly driven by the conversion of the field site from standard reference tillage towards minimum tillage. During these first years, both CC and bare soil treatments followed a similar pattern, specially in the upper layers, those with a previous higher ploughing activity. There was a reduction in the residual soil water content (θ_r) at 20–40 cm, in the saturation soil water content (θ_s) at 0–20 and 40–80 cm and in the soil hydraulic conductivity (K_s) at 20–40 cm, suggesting soil compaction. A similar effect was observed by other authors, such as Rücknagel et al. (2016), who reported an initial compaction under both CC and fallow treatments during the first years under minimum tillage in several locations around Germany. In the second phase, after two to four years, depending on parameter and depth, the evolution of soil parameters changed, starting to demarcate differences between CC and the bare soil treatment.

The effect on θ_r at 0–20 cm throughout the ten years was reduced to a constant increment from the first year to the fifth (and significant from the third year respect to the first one), probably induced also by the minimum tillage (Fig. 3). At 20–40 cm, there was a decrease in both treatments during the second year. In this case, the CC favoured the increase in θ_r, recovering at the third year, whereas bare soil needed three extra years to recover the initial values. Differences between treatments or years at deeper layers were smaller. The effects of CCs on θ_r during the experiment can be explained by the effect of roots on the development of micropore structure i.e. due to both micro-fissuring produced by wetting-drying process enhanced by the presence of roots, and by radial pressures exerted by roots themselves (Scanlan, 2009; Bodner et al., 2014). Although, due to barley`s relatively thin roots, the effect of the CC on the micropore structure development was more pronounced in upper layers, where barley root density was higher. This suggests small differences in the micropore structure between fallow and CC treatments in deeper layers.

The effect of CCs on the time course of θ_s was more significant compared with the effect on the time course of θ_r. There were no significant differences between treatments for the 0–20 cm depth, but some trends were observed at 20–40 cm. This trend became significant in the 40–80 cm and 80–120 cm soil layers. In this case, the θ_s of the CC treatment increased by an average of 0.06 $cm^3\,cm^{-3}$ for the 40–80 cm soil layer and by 0.05 for the 80–120 cm soil layer since 2008/09 (being higher in the CC treatment than in the first year from 2007/08 for the 80–120 cm depth and from 2009/10 for the 40–80, but never in the fallow). These results suggested an increase in macroporosity produced by biopores from dead roots and by improvements in soil structure. This result is consistent with observations from other authors who reported that macroporosity could increase in cover cropping systems (Cresswell and Kirkegaard, 1995; Bodner et al., 2014; Yu et al., 2016). Moreover, some authors have reported that CCs increased organic matter and aggregate stability (Six et al., 2006; Peregrina et al., 2010), providing more stability to this structural improvement. In our study, the difference in θ_s between treatments was only significant in deeper soil layers. Irrigated maize roots may have homogenised the macroporosity in the first 40 cm soil depth.

Van Genuchten parameters (α and n) followed inverse trends. The α value was variable, but, in general, we found lower values under the bare soil treatment than under CC or the initial conditions. The CC treatment presented more stable values along the studied period and even tended to increase with respect to the initial conditions throughout the soil profile. The n value was less variable along the 10 years of the study, although under barley treatment n value tended to decrease compared with the initial value (significant at 0–20 cm on 2001/12, 2014/15 and 2015/16, at 20–40 from 2009/10 to 2011/12, at 40–80 only on 2008/09 and at 80–120 from 2009/10 to 2014/15). In this case, the CC treatment presented lower n values than the bare soil treatment after the first 3 years, becoming significant during the last 3–4 years, depending on the soil layer.

An increase in α and a decrease in n in the CC treatment were consistent with the porosity development in this treatment, and it is in consonance with the equation defined by Kosugi (1994), relating α and n, considering m equal to 1 - 1/n. Indeed, when α increases, the air entry value decreases which occurred when the new soil macroporosity was developed. Additionally, n measures the distribution of pore sizes. When n increases, which occurred under bare soil treatment, the variation in pore sizes decreases, suggesting that some pore size classes became dominant. Both effects, together with the impacts of CC on θ_s and θ_r, suggest considerable differences in the time course of the water retention curve between treatments (Fig. 4). In the two upper layers, the CC soil water retention curves were slightly risen and flattened, which was a result of soil with larger macroporosity development, increasing water infiltration to deeper layers and reducing crop available water in some years (calculated as the difference between field capacity and wilting point soil water content). In our field experiment, García-González et al. (2016) and García-González et al. (2018) measured an increase of soil organic carbon and water-stable aggregates in the CC treatment at different dates in the upper layer, supporting our results. Muñoz-Carpena et al. (2008) also showed a similar effect on the van Genuchten hydraulic parameters in a Sunn hemp (*Crotalaria juncea* L.) cover cropping experiment, suggesting that an increase in organic matter improved soil aggregation. However, below 40 cm in depth, the

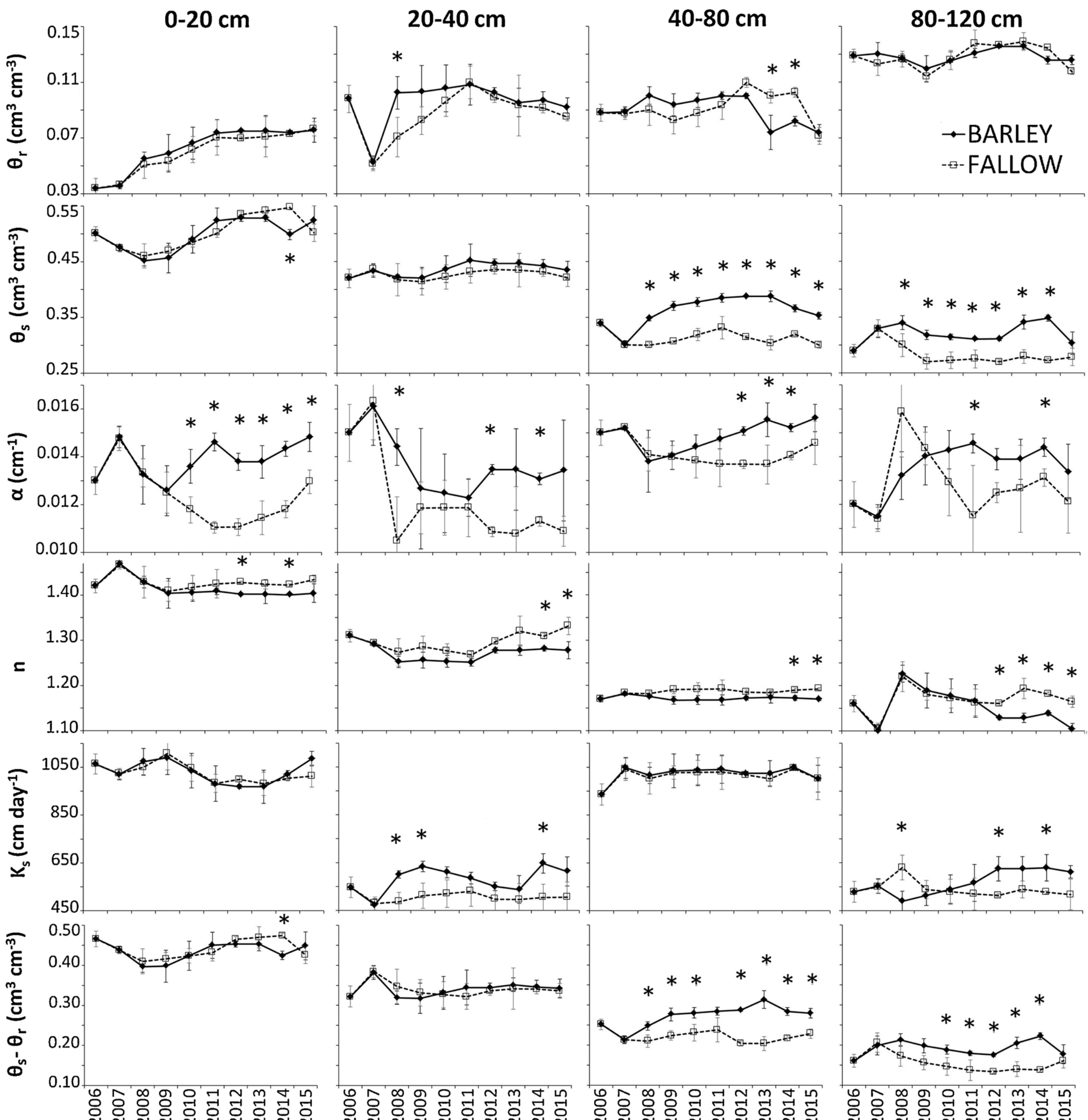

Fig. 3. Evolution of optimized soil parameters at different depths and throughout the ten studied years. θ_r is the residual soil water content, θ_s is the saturation soil water content, α and n are the van Genuchten curve-shape hydraulic parameters and K_s is the soil hydraulic conductivity. * Symbol represents statistical differences between treatments within a year ($p < 0.05$).

crop available water (as the difference between soil water content at field capacity and permanent wilting point, 33 and 1500 kPa respectively) increased by an average of 20% from the third to the last year. This effect, together with the faster infiltration from the upper layers, could result in larger crop available water, not only in the entire profile but also in the upper 80 cm, where the main crop explores more efficiently. Even when there were not many available results on the direct effect of CCs on soil water retention curves, Palese et al. (2014) also reported an increment in soil water retention in a cover cropped olive orchard in the deeper layers. However, they concluded that this increment was only the result of better infiltration, resulting in a reduction of water loss. Therefore, a CC can be a competitor with the main crop for water, but the improvement in soil water retention in the intermediate zone of the soil profile could minimize this competition or even turn it into an advantage in arid and semiarid regions.

Finally, the CC treatment was also able to enhance the soil hydraulic conductivity in the layers with lower K_s. This effect was first observed in 2008/09 at 20–40 cm and was maintained until the end. However, at this depth, differences respect the first year were only observed during 2009/10 and 2014/15 for the CC treatment. At 80–120 cm depth, the effect appeared later, in 2012/13 but was also persistent in time (also significant respect the initial year since 2012/13). In our field experiment, García-González et al. (2018) measured an increase of water infiltration rates in the CC treatment at different dates in the upper layer, supporting our results. Similar increases in infiltration rates in the upper layers of CC soil were observed by other authors (Palese et al., 2014; Yu et al., 2016). Moreover, Gish and Jury (1983) concluded that the pores generated by roots present high connectivity and facilitate water transport through the soil. Again, CC root development and improvement in the structure and pore size distribution seem to be responsible for this increase, reducing the runoff risk and the erosion problems even under the gentle slopes commonly found in semiarid and arid regions. As the model does not consider preferential flow, the K_s obtained comprises both, the matrix flux and other preferential fluxes. Moreover, the capacitance sensors used in the experiment were neither capable to distinguish between macropores or matrix water content.

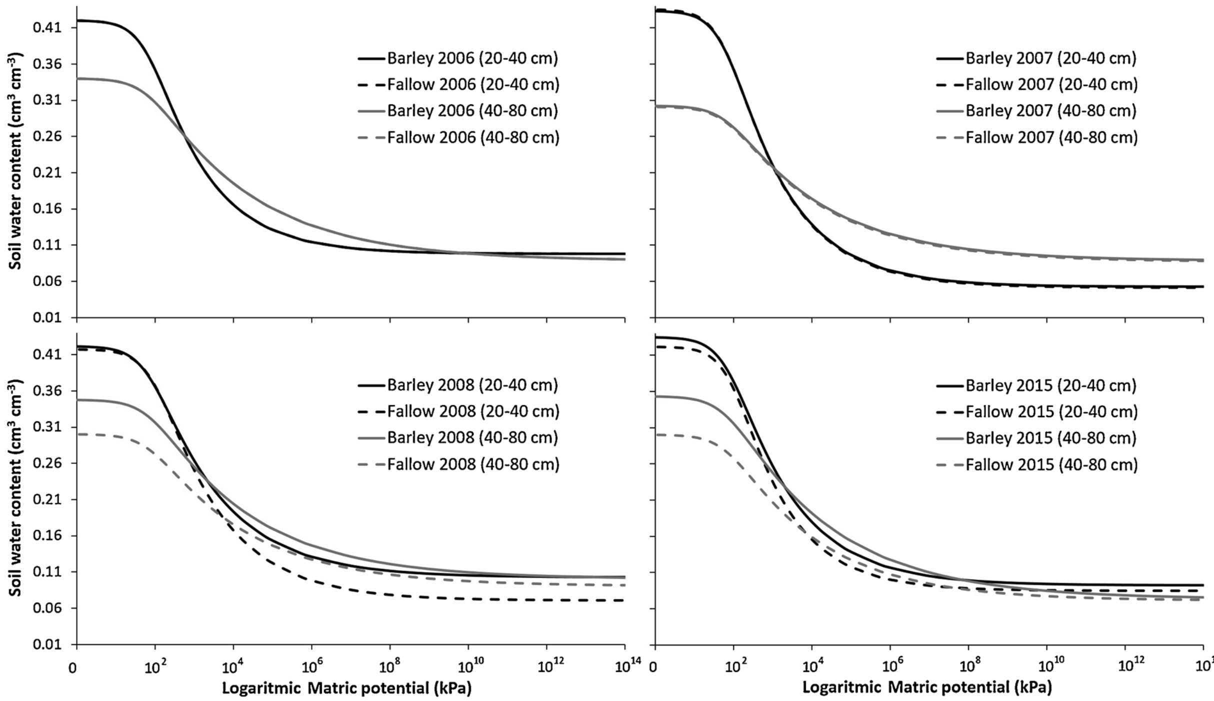

Fig. 4. Optimized soil retention curves at two different depths at the beginning of the experiment (2006) and after 1 (2007), 2 (2008) and 10 years (2015) of a minimum tillage cover crop experiment.

These two factors, together with the daily time step of the observations, made it almost impossible to distinguish between preferential and matrix water flux. This could be a great inconvenient in soils heavily marked by crops with very pivoting root systems, or in well-structured soils, or in shrinking-swelling soils. Yet, this is not the case in this experiment, where the fragile structured soil has a very low content in expansive clay and is cropped with barley as cover crop, exhibiting very fasciculate root systems. In this case, the matrix flux is expected to dominate the preferential flux. It is however suggested to develop further research in order to confirm the actual relevance of preferential flow under these conditions.

Some other hydraulic parameters, such as the tortuosity or hysteretic parameters, could also be included in the inversion analysis. For instance, roots can alter pore geometry and connection, affecting the tortuosity. However tortuosity was not considered to be strongly affected by the CC treatment in this study based on Kool and Parker (1987), and because that effect was masked in the model by the daily time step. We also considered that the CC treatment would not influence the hysteresis effects and therefore it was ignored in the analysis. We, therefore, decided to fix all these parameters to reduce identification problems in the inverse analysis. However, these hydraulic properties, or even additional ones, could be included in future research on the effects of CCs on soil hydraulic properties. Moreover, while inverse modelling allows inferring complex system parameters from ready available observations of dynamic system state variables, it is possible that the obtained parameter values suffer from equifinality. We reduced this equifinality problem by different methods: i) by constraining the confidence interval of each parameter (based on the initial sensitivity analysis of the model, as presented by Gabriel et al. (2012)), ii) by using different and independent parameter chains in the Markov chain methodology, iii) by considering the mean and the standard error of the different EnviroSCAN® access tubes for each parameter and year and iv) by combining the calibration (based on continuous soil water content measurements) with an independent validation (based on crop development). Finally, we also considered the possibility that the parameter evolution could be more influenced by variations in the sensor measurement than by actual soil properties. If this would be the case, the changes along the 10-years of experiment should be similar in both treatments. Since this was not observed, we conclude that no significant bias due to a potential sensor effect affects our observations. In addition, the sensor calibrations as illustrated in Gabriel et al. (2010) did not exhibit drift. Indeed, the most important differences in the soil properties appeared during the first 3 years of experiments. The sensor readings during this period were validated in the field in both treatments at seven different dates. During this period, the accuracy and the precision remained constant at all depths. The rather reliable validation of the sensor readings in this case can be explained by the fact that we are analysing volumetric soil water content inferred from dielectric data at the macroscopic scale. Even when soil particles could be redistributed in many ways and modify soil structure between treatments, it is suggested that this occurs at scales smaller than the capacitance probes footprint and hence does not dominate the sensor calibration. Based on that, we assume that the sensor measurements are not interfering with the hydraulic properties identification.

3.3. Water balance analysis

The slope of the experimental field was close to zero and no visual signals of runoff were observed during the 10 years. Because of that, runoff was considered negligible. The CC treatment did not increase the simulated total water losses compared to the fallow treatment throughout the 10 years studied (Fig. 5). As expected, these total losses were obviously highly correlated with the amount of rainfall (R^2 equal to 0.82 and 0.85 for barley and fallow respectively). However, the weight of evapotranspiration and drainage on these losses was different for CC and fallow treatments. Rainfall correlated better with fallow than with CC drainage (R^2 equal to 0.64 and 0.45, respectively), but better with CC evapotranspiration than with fallow (R^2 equal to 0.85 and 0.79, respectively). The CC treatment increased the simulated evapotranspiration with respect to bare soil (235 vs. 162 mm year^{-1} on average, respectively). However, this increase was compensated by a decrease in the simulated water drainage below 120 cm in depth. The bare soil simulated drainage was on average 60.7 mm year^{-1} larger than the drainage of the CC treatment, but this difference reached

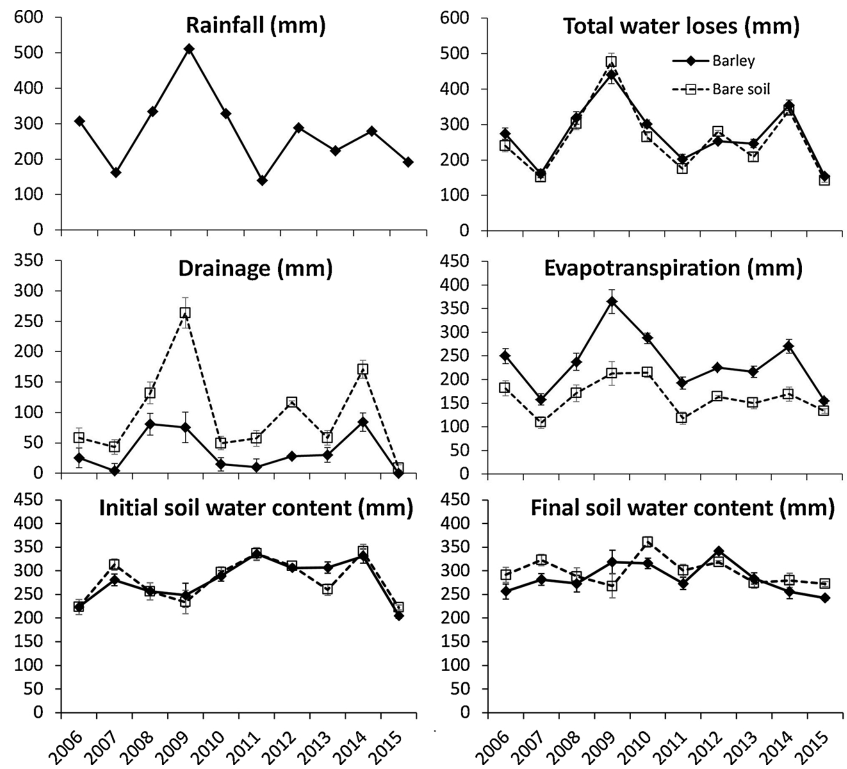

Fig. 5. Soil water balance (from October to April) evolution with and without a cover crop in the 120-cm depth of the soil profile and throughout the ten studied years.

188 mm in very rainy years as 2009/10. These results support previous research on CCs that concluded that good management of the CC would not lead to water competition with the subsequent cash crop even during dry years as 2007 and 2011 (Clark et al., 1997; Alonso-Ayuso et al., 2014). Moreover, this result supported the theory that CCs not only reduce leaching of nitrate and other solutes but also reduce intensive drainage (Thorup-Kristensen et al., 2003). Therefore, CCs can be considered a useful tool for enhancing environmental services linked to agricultural soils, such as the protection of groundwater from nitrate and pesticide pollution from agricultural sources without a large reduction of the water availability. However, in years when rainfall does not occur between the CC termination date and the cash crop seeding, there might arise a problem of water competition if we only take seedbed water content into account (Clark et al., 2007). This water limitation can be observed in the final soil water content in April (Fig. 5), but also in the correlation between rainfall and CC evapotranspiration, showing that CC can grow more when water is available.

4. Conclusions

Using data collected in a 10-year field trial of an agricultural rotation including a CC versus fallow treatment between cash crops, we were able to elucidate by inverse modelling the impact of CCs on the medium-term evolution of the soil hydraulic properties. The cover crops were demonstrated to be a useful tool for improving the soil hydraulic functions of the agricultural system. This improvement could be principally based on a more compensated distribution among macro- to micropores, reducing soil compaction and increasing soil water retention and crop available water. Moreover, the resulting soil could be less prone to runoff and drainage losses, compensating (and even reversing) the possible water competition of the cover crop with the subsequent cash crop. This fact has special relevance in semiarid regions, where water is the most limiting factor in agricultural production.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.agwat.2019.05.034.

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