Long-term analysis of soil water conservation and crop yield under different tillage systems in Mediterranean rainfed conditions

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Abstract

This study focuses on the quantification of soil water storage and crop yield under different tillage systems in dryland semiarid Mediterranean conditions. Three long-term tillage experiments based on cereal production were initiated in 1987, 1990 and 1992, at three different locations in the Ebro river valley (NE Spain): El Canós, Selvanera and Agramunt, with an increasing degree of aridity. Different tillage intensities were compared in each experiment using different implements: no tillage (NT), minimum tillage (MT), chisel (Ch), subsoiler up to 25 cm depth (Sub-25) and up to 50 cm (Sub-50), and mouldboard plough (Mb). Soil water content (SWC) up to 100 cm, soil water storage (SWS), precipitation storage efficiency (PSE) and crop yield were quantified during 8 (El Canós) and 19 years (Selvanera and Agramunt). The use of MT (at Selvanera) and NT (at El Canós and Agramunt) led to the highest SWC after the storage period (i.e. from previous harvest to crop tillering), with a major role played by the storage of water at deep soil layers. At Agramunt, Mb presented the lowest SWS when compared to Ch, Sub-50 and NT, and, consequently, the lowest post-tillering evapotranspiration. On the contrary, no differences were found between tillage systems on SWS at El Canós or at Selvanera. Significant yield differences were found at Agramunt being: NT > Sub-50 > Ch = Mb. These differences were especially important in years with mean yield below 2000 kg ha⁻¹, in which NT obtained the highest productions. At Selvanera yield was greater under conservation tillage (NT, MT) than under intensive tillage (Sub-50). Contrarily, no yield differences were found between tillage systems at El Canós, the site with the lowest water deficit, where crop residues were removed. A strong linear relationship was found between SWS and yield at Agramunt and Selvanera. At Agramunt the relationship presented a greater slope under Mb. In this site, in years with previous harvest-to-tillering SWS below 100 mm and with precipitation over 100 mm between tillering and anthesis, yields were, as an average, 1245 kg ha⁻¹ higher than in standard years. This study demonstrates that under semiarid rainfed conditions, soil water storage increases with the use of conservation tillage systems, being amplified with the degree of aridity of the site. The

relationship between water stored in the soil and crop yield and its reliability is site-specific. Once determined, it could be used to predict yield at the end of the vegetative phase of the crop to help take management decisions.

Keywords: Soil water storage; No-tillage; Conservation tillage; Intensive tillage; Semiarid dryland.

1. Introduction

The Mediterranean climate is defined by low and variable rainfall. The Ebro river valley (NE Spain) is representative of the arid and semiarid areas of the Mediterranean region. In these areas about 75% of the precipitation falls in two periods, from September to December and from April to May, with higher uncertainty in the second one (Austin et al. 1998). In the autumn and winter months, cold temperatures, low radiation, high relative humidity and low wind-speeds result in low evaporation rates. From September to January rainfall exceeds evaporation and water is stored in the soil, considering this period as the “soil water recharge period”. In the spring and summer months, however, low rainfall and enhanced evaporation by increased radiation and wind-speeds cause high water deficit for agricultural activity (Cooper et al., 1987). Under these conditions, fallow and intensive tillage systems had been a traditional strategy to capture and store out-of-season water. However, in the last two decades conservation tillage (CT) has been increasingly adopted by the farmers as a new alternative to increase water availability and reduce costs (Cantero-Martínez and Gabiña, 2004) making possible the intensification of the cropping system. Regarding to this last, Álvaro-Fuentes et al. (2008, 2009b), in this same geographical area, concluded that the suppression of long fallow periods and the use of no-tillage increases the stability of the soil structure and leads to soil carbon (C) sequestration.

According to Peterson and Westfall (2004), sustainable cropping under water limiting conditions involves maximizing precipitation use efficiency (PUE). PUE is the quotient between

yield (Y) and rainfall (R): $PUE = \frac{Y}{R}$

We can expand this expression by adding the terms water use (WU) and soil water storage

(SWS) in this way: $PUE = \frac{Y}{WU} \cdot \frac{WU}{SWS} \cdot \frac{SWS}{R}$

Y over WU is water use efficiency (WUE), and SWS over R is precipitation storage efficiency (PSE) (Tanaka and Anderson, 1997). The term WU over SWS can be assumed to be 1 as a

mean in semiarid environments (crops tend to use all the water available in the soil). We can simplify then PUE as: $PUE = WUE \cdot PSE$

CT can have a positive effect on PUE because it can improve both WUE and PSE by increasing the infiltration to runoff ratio (Unger and McCalla, 1980) and reducing evaporation (Bond and Willis, 1971). CT can also play an important role to stabilize yields by increasing water stored in the soil during the months of lower evaporative demand by increasing infiltration (Unger and McCalla, 1980), depending on the amount of crop residues left on the soil surface (Smika and Unger, 1986; Tanaka and Anderson, 1997). The improvement of soil structure by the reduction of tillage and the increase of soil organic matter content under CT can also increase the available water capacity of the soil (Hudson, 1994; Plaza-Bonilla et al. 2013).

Different short-term studies in the area proved that CT stored more water than more intensive tillage systems (Lampurlanés et al., 2002; Moret et al. 2006). These results suggest that CT can play an important role in improving the water-trapping process during the soil water recharge period in Mediterranean conditions. As these studies were limited in time (included no more than 4 years), to confirm this hypothesis we present here the results of three experiments with 9, 24 and 27 years of continuous CT use (6 and 19 years of water storage data), the longest tillage experiments in the area. The effect of CT on productivity and water use efficiency were already published (Cantero-Martínez and Lampurlanés, 2007). This work aimed at quantifying the long-term effects of different tillage systems on soil water storage and precipitation storage efficiency and their relationships with crop yield under dryland semiarid Mediterranean conditions.

2. Materials and methods

2.1 Climate and soils of the experimental area

The study was conducted in the Ebro valley (NE Spain). In this area climate is classified as Temperate Continental Mediterranean (Papadakis, 1966) and is representative of a wide extension of the Mediterranean region. Annual rainfall is below 350 mm in the centre of the valley, but reaches 650 mm near the surrounding mountains.

The experimental fields for this study were established at three locations in the Ebro Valley, all three in the Lleida province (Spain): Agramunt, Selvanera, and El Canós, with different long-term mean annual precipitation (382 to 450 mm), and annual water deficit (350 to 423 mm). The soils are classified as Fluventic Xerochrept at Selvanera and El Canós, and Typic Xerochrept at Agramunt (Soil Survey Staff, 1999). Soil texture is loamy at Selvanera, loamy fine at El Canós, and clay-silt-loamy at Agramunt. Plant-available water-holding capacity, up to the sampling depth (1 m), reaches 206 mm at Agramunt, 213 mm at Selvanera, and 225 mm at El Canós. More information about sites, climate and soils can be found in Table 1.

2.2 Experimental design and tillage systems

The experimental plots were established in 1987 at Selvanera and 1990 at Agramunt, by the Extension Services of the Spanish Ministry of Agriculture. At El Canós the study was initiated in 1992 by the Agronomy and Environment in Mediterranean Agroecosystems Research Group of the University of Lleida that manages the three experiments since 1995. The experiments consisted on a randomised block design with three replications at Selvanera and four at El Canós and Agramunt. Plot size was (50 x 7 m) 350 m² at Selvanera, (30 x 6 m) 180 m² at El Canós and (50 x 9 m) 450 m² at Agramunt.

Six tillage systems, mouldboard (Mb) plough, deep subsoiling to 50 cm (Sub-50), shallow subsoiling to 25 cm (Sub-25), chisel (Ch), minimum tillage (MT) and NT were compared across the sites: NT, MT and Sub-50 at El Canós; NT, Ch, Sub-50 and Mb at Agramunt; and NT, MT, Sub-25

and Sub-50 at Selvanera. Intensive tillage (Mb) consisted of one mouldboard ploughing (30–35 cm depth) plus one or two cultivator passes (15 cm depth) in September. Subsoilings (Sub-50 and Sub-25) were carried out in August to depths of 40–50 and 20–25 cm, respectively. The practice of a shallow subsoiling at 25 cm depth was established by the farmer as a way to reduce fuel consumption. Ch consisted of one pass with a chisel plough (20 cm depth) before sowing. The tillage systems enumerated above were completed with a single cultivator pass when soil conditions were appropriate for sowing. MT comprised one cultivator pass (10–15 cm depth) in the same soil moisture condition as the Sub-50 and Sub-25. In NT, crops were sown without tillage (direct drilling) after plots were sprayed with herbicide, 1.5 L ha⁻¹ of 36% glyphosate [N-(phosphonomethyl)-glycine] plus 1 L of 40% MCPA [2-(4-chloro 2-methylphenoxy) acetic acid]. In some years, a roller was used to break clods and promote germination in all systems where some kind of tillage was employed. Sowing was performed with a no-till disc drill in Agramunt and with a no-till hoe drill in Selvanera and El Canós, properly regulated to the soil conditions of each treatment. In the analyses, MT and NT were considered CT systems while the other four systems were considered as intensive tillage treatments.

2.3 Cropping systems and crop technology

Different crop sequences were maintained at individual sites throughout the study according to their yield potential. These crop sequences are shown in Table 2. At Selvanera, owing to its climatic conditions, canola (*Brassica napus* L.) was sufficiently productive to be alternated with winter cereals (barley, *Hordeum vulgare* L.; and wheat, *Triticum aestivum* L.) one each four years after 1996. Moreover, since the 2011-12 cropping season the rotation was diversified with the introduction of winter pea (*Pisum sativum* L.). At El Canós and Agramunt, since growing canola was extremely uncertain (Álvaro-Fuentes et al., 2009a) only cereals were grown. Barley was grown every year at El Canós, while at Agramunt, it was alternated with wheat and triticale since the 2000-2001 season.

Crop management practices, apart from tillage, were similar in all three experiments. Crops were sown earlier at Selvanera (early October for barley and wheat and end of September for canola) than at El Canós and Agramunt (end of October to end of November) because September rainfall in Selvanera permits earlier soil preparation and weed control. Planting density ranged between 400 and 500 seeds m⁻² for barley and wheat and 100–120 seeds m⁻² for canola in rows spaced 17–19 cm apart.

Fertilization was performed according to crop requirements and soil tests. Cow manure and pig slurry (60 kg N ha⁻¹) were annually spread before sowing at Selvanera and Agramunt, respectively. Top dressing mineral fertilizer (50–60 kg N ha⁻¹) using ammonium nitrate (33%) was spread on the soil surface at tillering in Selvanera and, if needed according to soil analyses, at the same growth stage 60 kg N ha⁻¹ of ammonium nitrate was applied at Agramunt. At El Canós, 50 kg N ha⁻¹ of mineral fertiliser was applied, one-third before sowing using ammonium sulphate (21%) and two-thirds at the beginning of tillering using ammonium nitrate (33.5%). Additional P and K fertilizers were applied before sowing following soil tests at El Canós.

After the emergence of the crop and before tillering, grass and broadleaf weeds were controlled by herbicides. A rotation of products, of low toxicity, was applied only when necessary. No treatments were required for pests or diseases.

Grain harvest was carried out with a standard medium sized combine that chopped and spread straw at Agramunt. At El Canós and Selvanera cut straw was removed because of the large amounts that were produced in some years. At these sites, however, the stubble was cut higher than traditionally-practiced by farmers (i.e. 20-25 cm).

2.4 Measurements and derived variables

Rainfall and temperature were monitored daily at standard weather stations situated at or near the experimental fields. Soil cores were taken from 0–25, 25–50, 50–75 and 75–100 cm depth before sowing, at tillering, anthesis and after harvest every year, in two replicates per plot. Soil water

content (SWC) was determined gravimetrically on these cores after drying them to constant weight in a forced-draft oven at 105 °C (Campbell and Mulla, 1990).

The growing season was divided into two periods: the water storage period, from previous harvest to tillering, and the water consumption period, from tillering to harvest, both divided again in two sub-periods as shown in Fig. 1. For every period or sub-period, soil water storage (SWS) was calculated as SWC at the end (SWC_e) minus SWC at the beginning (SWC_b). Precipitation storage efficiency (PSE) was calculated as the quotient between SWS and rainfall (R), negative values were set to 0 and values over 100 were set to 100. Evapotranspiration (ET) was calculated with a simplified soil water balance for each sub-period: $SWC_b + R = ET + SWC_e$ (in the three sites slope can be considered negligible, preventing runoff and there is not enough rain for deep drainage). Then, $ET = R + SWC_b - SWC_e = R - SWS$. Crop yield was determined weighing the grain obtained from the harvest of each plot and converting it to 10% humidity.

2.5 Statistical analysis

Linear regression and variance analyses were computed using the “lm” function of the R language for statistical computing (R Development Core Team, 2015) and the “Anova” function of the “car” package (Fox and Weisberg, 2011) to test the main effects of the year (YEAR) and tillage system (TIL) and its interaction. Mean separations for significant effects were conducted using the least significant difference (LSD) contrast ($P=0.05$) with the “LSD.test” function of the “agricolae” package of R (de Mendiburu, 2014).

3. Results

3.1 Precipitation during the experimental period

July to June precipitation was highly variable during the experimental years (Fig. 2). The driest seasons (below 300 mm) were 2004-05, 2005-06, 2010-11 and 2011-12. The wettest (over 500 mm) were 1995-96, 1996-97, 2003-04, and 2009-10. Mean annual precipitation over the studied seasons was 427 ± 94 mm at El Canós, 421 ± 123 mm at Agramunt, and 398 ± 100 mm at Selvanera, with an annual water deficit of 370, 434 and 402 mm respectively. However, taking into account ET, from driest to wettest the sites ordered Agramunt > Selvanera > El Canós. In addition, the precipitation distribution pattern was different at El Canós, compared with Agramunt and Selvanera (Fig. 3). Up to 68% of the precipitation (293 mm) fell during the storage period at El Canós whereas only 52% at Agramunt (230 mm) and 55% at Selvanera (221 mm). At El Canós, intense rainfall in autumn flooded the experimental field in two seasons: 1994-95 (sowing had to be repeated in February) and 1995-96 (no yield was obtained).

3.2 Soil water content, soil water storage and precipitation storage efficiency

Significant differences between tillage systems were found on SWC at El Canós at sowing, tillering and harvest and throughout the season at Agramunt and Selvanera (Table 3). On average (all cropping seasons), NT showed the highest SWC at El Canós and Agramunt whereas MT at Selvanera. TIL*YEAR interaction was significant at Agramunt and Selvanera at sowing, and tillering. At Agramunt, at tillering, the stage with the greatest SWC, NT presented greater SWC than Mb in 11 out of 19 years (Fig. 4a). These differences were found not only at the surface but throughout the soil profile, especially in seasons with more than 200 mm rainfall during the storage period. At Selvanera (Fig. 4b), NT overpassed the most intensive tillage system (i.e. Sub-50) only in 4 out of 17 years. No significant differences were found in the remaining years.

As an average of the different tillage systems and years, the SWS and the PSE during the water storage period (i.e. from previous harvest to tillering) was lower at El Canós (83 mm and 32%

respectively, Table 4) and Agramunt (81 mm and 37% respectively, Table 5) than at Selvanera (99 mm and 49% respectively, Table 6). PSE was very similar at all locations during the previous harvest to sowing sub-period (around 30%), but greater and different at the sowing to tillering sub-period: 38% at El Canós (Table 4), 46% at Agramunt (Table 5), and 61% at Selvanera (Table 6).

At El Canós, no differences were found in SWS or PSE between tillage systems (Table 4). Contrarily, great differences were found for both variables at Agramunt (Table 5). On the whole period, Mb was the system with the lowest mean SWS (70 mm) compared with Sub-50 (82 mm), Ch (84 mm), and NT (87 mm). At Agramunt, 13 out of 19 years received less than 250 mm of precipitation during the soil storage period (Fig. 4a). In half of those years (i.e. 6 out of 13), Mb stored significantly less water than NT. Accordingly, mean PSE was lower for Mb (32%) than for Sub-50 (37%), Ch (38%) or NT (42%). Year by year comparisons of tillage systems for PSE followed the same pattern as SWS: Mb showed significantly lower values than the other tillage systems in half of the years with less than 250 mm rainfall during the soil recharge period. At Selvanera (Table 6), differences between tillage systems on SWS were not statistically significant, but NT showed significantly greatest PSE. Across sites and years, SWS was positively related with precipitation during the storage period (regression coefficients of 0.15^{***} at El Canós, 0.32^{***} at Agramunt, and 0.40^{***} at Selvanera), and negatively related with SWC at previous harvest (regression coefficients of -0.95^{***} at El Canós, -0.57^{***} at Agramunt, and -0.67^{***} at Selvanera).

3.3 Post-tillering evapotranspiration, yield and its relationships with previous variables

During the consumption period, ET was 227 mm at El Canós (Table 4), 286 mm at Agramunt (Table 5), and 298 mm at Selvanera (Table 6), as an average of tillage systems and years. Differences between tillage systems in post-tillering ET were found only at Agramunt where Mb showed the lowest values (Table 5): 14, 17 and 22 mm less than Sub-50, Ch and NT, respectively. Significant differences between tillage systems on post-tillering ET were observed in 9 out of 19 years. In seven of those nine years, NT presented greater post-tillering ET than Mb. Moreover, post-

tillering ET was positively related to SWS at El Canós (regression coefficient 1.05^{***} , $R^2 = 0.75^{***}$), at Agramunt (regression coefficient 0.75^{***} , $R^2 = 0.16^{***}$) and at Selvanera (regression coefficient 0.86^{***} , $R^2 = 0.33^{***}$).

Mean yield decreased from 4310 kg ha^{-1} at Selvanera (Table 6) to 3239 kg ha^{-1} at El Canós (Table 4), being the lowest at Agramunt: 2644 kg ha^{-1} (Table 5). Significant differences between tillage systems on yield were found at Agramunt which, from greatest to lowest, were: $\text{NT} > \text{Sub-50} > \text{Ch} = \text{Mb}$, ranging between 2929 and 2430 kg ha^{-1} (Table 5). At Selvanera, significant yield differences were observed between conservation tillage (NT : 4393 kg ha^{-1} , Ch : 4355 kg ha^{-1}) and intensive tillage (Sub-25 : 4269 kg ha^{-1} , Sub-50 : 4219 kg ha^{-1}) systems (Table 6). Contrarily, no significant yield differences between tillage systems were found at El Canós (Table 4).

On a yearly analysis, yield differences between tillage systems were found at Agramunt and Selvanera (Fig. 5). At Agramunt, NT over yielded the other tillage systems in 5 out of 19 years and presented the lowest yield only in one of them (1998-99, Fig. 5b). Mb over yielded the rest of treatments in two consecutive years (1997-98 and 1998-99) and under yielded in 8 years. In this site, differences between tillage systems were especially important in years with mean yield below 2000 kg ha^{-1} (2000-01, 2004-05, 2005-06, 2007-08, 2010-11 and 2011-12), the driest of the series, where NT obtained the highest yields (Fig. 5b). At Selvanera, differences between tillage systems were found in the less-productive years (2003-04, 2004-05, 2007-08 and 2011-12) but without consistent advantage of any tillage system (Fig. 5c).

Yield was positively related to SWS at Agramunt and Selvanera (Fig. 6). At Agramunt two groups of years had to be considered to properly model this relationship (Fig 6-a): the standard (mean yield of 2191 kg ha^{-1}) and the over-yielding years (mean yield of 3436 kg ha^{-1}). On the standard years (10 over 18) the slope of the relationship was steepest for Mb ($27.8 \text{ kg ha}^{-1} \text{ mm}^{-1}$) than for the other tillage systems ($18 \text{ kg ha}^{-1} \text{ mm}^{-1}$). The over-yielding years (8 over 18) were the ones with less than 100 mm SWS up to tillering and more than 100 mm of precipitation during the

tillering to anthesis period. In these years, the intercept of the yield to SWS relationship was around 2000 kg ha⁻¹ higher than in the standard years, and the slope 12.1 kg ha⁻¹ mm⁻¹. At Selvanera, the slope of the relationship was 30.4 kg ha⁻¹ mm⁻¹ irrespective of the tillage system (Fig 6-b). No significant relationship was found between SWS and yield at El Canós. At Selvanera, the yield to SWS relationship had the same slope for the different crops, but 1800 kg ha⁻¹ lower intercept for canola, the crop with lower yield potential. At Agramunt, in the standard years wheat had a significantly greater slope than barley or triticale which implies higher sensitivity of its yield to SWS. Similarly than in Selvanera, no significant tillage and crop interaction on the slope of the linear relationship between yield and SWS was found in Agramunt.

4. Discussion

This study was carried out at three different locations within an aridity gradient to be representative of the wide variability in Mediterranean areas. The results obtained highlight the great effect of site-specific conditions like rainfall distribution and soil management system (tillage operations and residue management) on the soil water storage process and, consequently, on yield.

Yield differences between tillage systems increased with aridity. At Agramunt, the driest site according to the annual water deficit, greater yield differences were found between tillage systems, especially in years with yields below 2000 kg ha^{-1} , the driest of the series. In the semiarid areas, under greater water deficits, a greater crop response to the use of conservation tillage systems is usually found (e.g. Cantero-Martínez et al., 2003; Hernanz et al., 2014). This shows the potential of conservation tillage systems which overpass the conventional ones in semiarid conditions.

El Canós, the place with the greatest amount of precipitation during the storage period, showed the lowest PSE because most of this rain falls during the summer months, the period with the highest evaporative demand (i.e. from previous crop harvest to sowing). Therefore, the reduction of the evaporation during this period would be crucial to increase the amount of water available for the crop. As crop residues were removed after harvest in this site, maintaining a greater amount of them over the soil or create a tillage mulch should be considered to increase soil water storage under conditions of high evaporative demand (Lampurlanés et al., 2002; Montenegro et al., 2013). Soil cover with crop residues not only reduces evaporation but mitigates significantly the risks of soil erosion, an aspect of a paramount importance under Mediterranean rainfed agriculture (Delgado et al., 2013; García-Ruiz, 2010). However, to be useful, crop residues must be properly managed to maximize the amount of water stored in the soil. Regarding to this, in a recent work, Swella et al. (2015) concluded that tall-standing residue increases the interception of rainfall and allows a greater penetration of water into the soil when compared to leaving most of the residues horizontal. However, in the least productive environments not enough plant residues could be available to

adequately cover the soil. In turn, under smallholder agriculture, the competition with other residue uses impedes the proper application of no-tillage practices (Lahmar et al., 2012; Plaza-Bonilla et al. 2015). Under those scenarios, or in the case of soil surface seals, some authors advocate for some tillage (Radford et al., 1992; Thomas et al., 2007). Similarly, in some conditions, secondary tillage appears to have a positive effect on soil water conservation at the end of the fallow (Moret et al., 2006).

During the sowing to tillering period precipitation was similar at the three sites (around 140 mm) but SWS was, on average 22/44 mm greater and PSE 15/23% greater at Selvanera than at Agramunt and El Canós, respectively. That result could be explained by differences between sites in evaporative demand (higher at Agramunt), SWS in the previous harvest to sowing period (higher at El Canós), the amount of residue (higher at Selvanera despite being partially removed), and aggregate stability at the soil surface, which is significantly reduced when tillage is used, especially systems that involve any degree of soil inversion (Plaza-Bonilla et al. 2010), which could have affected water infiltrability (that is the case of Agramunt where Mb was used).

Differences between tillage systems on SWS or PSE were appreciable at Agramunt, small at Selvanera and negligible at El Canós. In general, SWS and PSE increased as tillage intensity decreased. The lower values were quantified under Mb, only tested at Agramunt. Mb is not well suited for the dryland Mediterranean agroecosystems because no residues are left over the soil surface, an aspect that could have been aggravated due to the soil texture of Agramunt with 60% of silt, being prone to crust formation (Pagliai et al. 1995). Probably, at Agramunt, lower infiltration rates under Mb promoted water ponding and, concomitantly, evaporation, and limited water availability for the crop. As it has been found in the area, the use of mouldboard plough reduces the stability of the aggregates decreasing the ability of the soil structure to recover after disturbances such as high intensity rains, typical of the Mediterranean climate (Plaza-Bonilla et al. 2010, 2013; Álvaro-Fuentes et al. 2008). Moreover, the lower soil water content under Mb impaired proper crop

establishment in some years, resulting in low yields. Despite not studied here, other aspects such as the reduction of soil quality (e.g. organic C fractions, soil enzymatic activities, etc.) or the increase in the yield-scaled greenhouse gas emissions highlight the importance of avoiding the use of inversion tillage in the Mediterranean dryland areas (Melero et al., 2011; Plaza-Bonilla et al., 2014). On the other side, SWS tended to be greater under NT, especially at Agramunt and Selvanera, the sites with lower rainfall during the storage period. Water was stored deep in the soil profile under this tillage system where, preserved from soil evaporation, remains available for the crop during the consumption period. Similarly, other authors have reported greater water storage at soil depth under conservation tillage in semiarid conditions (O’Leary and Connor, 1997; Su et al., 2007).

Although related, differences in SWC between tillage systems were greater than differences in SWS. Throughout the year, SWC, and hence soil water potential, were in general greater under conservation tillage systems (NT and MT) than under more intensive tillage systems. This could explain the higher WUEs observed under conservation tillage systems, especially at Agramunt (Cantero-Martínez and Lampurlanés, 2007).

The significant relationships found between SWS and yield at Agramunt and Selvanera can be used to predict the yield of the year. This prediction would be more reliable at Selvanera than at Agramunt where yield predictions would fail in years with less than 100 mm SWS and more than 100 mm precipitation between tillering and anthesis (45% of the years). Since SWS can be computed at tillering, this yield prediction can be a valuable tool to decide the amount of N fertilization to be used as top-dressing application.

5. Conclusions

This long-term experiment demonstrates that, under semiarid rainfed conditions, soil water storage increases with the use of conservation tillage systems which leave more crop residues on the soil surface. Moreover, this effect increases when increasing the degree of aridity of the site. Inversion tillage should be avoided in these conditions, especially in soils prone to crust formation, because it can have deleterious effects on infiltration reducing their capacity to store water, leading to reduced crop yield. The relationship between water stored in the soil and crop yield and its reliability are site-specific. Once determined, it can be used to predict crop yield at the end of the vegetative phase of the crop. This can be a valuable tool to take management decisions like N fertilization.

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Table 1. Site and general soil characteristics in the 0–30 cm soil depth of the three experimental sites.

	El Canós	Agramunt	Selvanera
Year of establishment	1992	1990	1987
Latitude	41° 41' N	41° 48' N	41° 49' N
Longitude	1° 12' E	1° 07' E	1° 17' E
Elevation (m)	410	330	480
Mean annual precipitation (mm) ^a	382	432	450
Mean annual ETo (mm) ^a	797	855	800
Mean annual water deficit (mm) ^b	415	423	350
Soil classification ^c	Fluventic Xerochrept	Typic Xerochrept	Fluventic Xerochrept
pH (H ₂ O, 1:2.5)	8.2	8.5	8.3
Soil organic carbon (g kg ⁻¹)	13.9	7.6	10.5
EC 1:5 (dS m ⁻¹)	0.19	0.15	0.16
Equivalent CaCO ₃ (%)	25	40	35
Water-holding capacity (mm) ^d	225	206	213
Particle size distribution (%)			
Sand (2,000–50 µm)	24.9	30.2	36.5
Silt (50–2 µm)	52.7	51.9	46.4
Clay (<2 µm)	22.6	17.9	17.1

^a From Zapater, 1995.

^b Difference between mean annual ETo and mean annual precipitation.

^c According to the USDA classification (Soil Survey Staff, 1999).

^d Up to 1 m (soil sampling depth).

Table 2. Crops at El Canós, Agramunt and Selvanera from 1987 to 2014.

Growing Season	El Canós	Agramunt	Selvanera
1987-1988	-	-	Barley
1988-1989	-	-	Barley
1989-1990	-	-	Barley
1990-1991	-	Barley	Barley
1991-1992	-	Barley	Barley
1992-1993	Barley	Barley	Canola
1993-1994	Barley	Barley	Wheat
1994-1995	Barley	Barley	Barley
1995-1996	Barley	Barley	Barley
1996-1997	Barley	Barley	Canola
1997-1998	Barley	Barley	Wheat
1998-1999	Barley	Barley	Barley
1999-2000	Barley	Barley	Wheat
2000-2001	Barley	Wheat	Canola
2001-2002	-	Barley	Wheat
2002-2003	-	Wheat	Barley
2003-2004	-	Barley	Wheat
2004-2005	-	Wheat	Canola
2005-2006	-	Barley	Wheat
2006-2007	-	Wheat	Barley
2007-2008	-	Triticale	Wheat
2008-2009	-	Barley	Canola
2009-2010	-	Wheat	Wheat
2010-2011	-	Barley	Barley
2011-2012	-	Wheat	Pea
2012-2013	-	Triticale	Wheat
2013-2014	-	Wheat	Canola

Grey data indicate growing seasons not included in the analysis because of lack of data on soil water content.

Table 3. ANOVA for soil water content (SWC) at different crop development stages.

Location		Probability values				
ANOVA factors		Prev. Harvest	Sowing	Tillering	Anthesis	Harvest
El Canós						
	YEAR	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
	TIL	0.008	0.003	0.007	NS	0.004
	TIL*YEAR	NS	NS	NS	NS	NS
Tillage means:						
	NT	188 a	227 a	272 a	212	185 a
	MT	182 b	217 b	265 b	209	180 ab
	Sub-50	180 b	211 b	262 b	204	174 b
Agramunt						
	YEAR	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
	TIL	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
	TIL*YEAR	NS	< 0.0001	0.02	NS	NS
Tillage means:						
	NT	124 a	139 a	214 a	164 a	122 a
	Ch	111 b	126 b	197 b	148 bc	110 b
	Sub-50	112 b	127 b	197 b	152 b	111 b
	Mb	111 b	119 c	181 c	144 c	111 b
Selvanera						
	YEAR	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
	TIL	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
	TIL*YEAR	NS	< 0.0002	< 0.0002	NS	NS
Tillage means:						
	NT	154 b	163 b	254 a	197 ab	153 b
	MT	160 a	177 a	256 a	201 a	160 a
	Sub-25	148 c	158 b	245 b	187 c	146 c
	Sub-50	150 bc	161 b	241 b	192 bc	150 bc

TIL, tillage system: no-tillage (NT), minimum tillage (MT), and subsoiler at 25 and 50 cm depth (Sub-25 and Sub-50, respectively).

NS, no significant at the 0.05 probability level.

Table 4. ANOVA, general mean and tillage means for soil water storage (SWS), precipitation storage efficiency (PSE), post-tillering evapotranspiration (ET), and yield at El Canós.

El Canós	SWS (mm)			PSE (%)			Post-tillering ET (mm)			Yield (kg ha ⁻¹)
ANOVA table	PH to S	S to T	Whole period	PH to S	S to T	Whole period	T to A	A to H	Whole period	
YEAR	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
TIL	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
TIL*YEAR	NS	NS	NS	NS	NS	NS	NS	NS	0.02	NS
General mean	35	48	83	29	38	32	99	116	227	3239±1004
Tillage means										
NT	39	45	84	31	39	33	101	115	227	3304±1040*
MT	35	48	83	30	35	32	98	116	225	3266± 948
Sub-50	31	52	83	27	40	32	99	118	228	3146±1053

ET, evapotranspiration.

* mean values ± standard deviation.

PH to S, previous harvest to sowing.

S to T, sowing to tillering.

T to A, tillering to anthesis.

A to H, anthesis to harvest.

TIL, tillage system: no-tillage (NT), minimum tillage (MT), and subsoiler at 50 cm depth (Sub-50).

NS, not significant at the 0.05 probability level.

Different letters indicate significant differences between tillage systems at $P<0.05$.

Table 5. ANOVA table, general mean and tillage means for soil water storage (SWS), precipitation storage efficiency (PSE), post-tillering evapotranspiration (ET), and yield at Agramunt.

Agramunt	SWS (mm)			PSE (%)			Post-tillering ET (mm)			Yield (kg ha⁻¹)
ANOVA table	PH to S	S to T	Whole period	PH to S	S to T	Whole period	T to A	A to H	Whole period	
YEAR	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
TIL	0.004	< 0.0001	< 0.0001	< 0.0001	0.003	< 0.0001	0.0008	NS	< 0.0001	< 0.0001
TIL*YEAR	< 0.0001	< 0.0001	0.005	< 0.0001	< 0.0001	< 0.0001	0.02	NS	0.01	< 0.0001
General mean	14	70	81	29	46	37	174	125	286	2644 ± 1218
Tillage means										
NT	16 a	76 a	87 a	34 a	50 a	42 a	177 a	127	295 a	2929 ± 1204 a*
Ch	16 a	72 ab	84 a	31 ab	47 b	38 b	178 a	125	290 ab	2508 ± 1055 c
Sub-50	16 a	69 b	82 a	28 b	46 b	37 b	176 a	127	287 b	2708 ± 1180 b
Mb	8 b	62 c	70 b	22 c	42 c	32 c	166 b	121	273 c	2430 ± 1432 c

ET, evapotranspiration.

* mean values ± standard deviation.

PH to S, previous harvest to sowing.

S to T, sowing to tillering.

T to A, tillering to anthesis.

A to H, anthesis to harvest.

TIL, tillage system: no-tillage (NT), chisel (Ch), subsoiler 50 cm depth (Sub-50), and mouldboard plough (Mb).

NS, no significant at the 0.05 probability level.

Different letters indicate significant differences between tillage systems at $P < 0.05$.

Table 6. ANOVA table, general mean and tillage means for soil water storage (SWS), precipitation storage efficiency (PSE), post-tillering evapotranspiration (ET), and yield at Selvanera.

Selvanera	SWS (mm)			PSE (%)			Post-tillering ET (mm)			Yield (kg ha⁻¹)
ANOVA table	PH to S	S to T	Whole period	PH to S	S to T	Whole period	T to A	A to H	Whole period	
YEAR	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
TIL	NS	NS	NS	0.04	NS	0.01	NS	NS	NS	0.05
TIL*YEAR	0.005	0.05	0.002	NS	NS	0.0006	NS	NS	0.03	< 0.0001
General mean	12	92	99	32	61	49	163	135	298	4310±1692
Tillage means										
NT	8	98	104	32 ab	65	51 a	162	126	286	4393±1656 a*
MT	18	87	99	38 a	58	48 b	164	137	300	4355±1733 ab
Sub-25	11	93	97	28 b	60	48 b	166	132	296	4269±1681 bc
Sub-50	9	90	96	28 b	58	46 b	161	135	296	4219±1738 c

ET, evapotranspiration.

* mean values ± standard deviation.

PH to S, previous harvest to sowing.

S to T, sowing to tillering.

T to A, tillering to anthesis.

A to H, anthesis to harvest.

TIL, tillage system: no-tillage (NT), chisel (Ch), subsoiler at 50 cm depth (Sub-50), and mouldboard plough (Mb).

NS, no significant at the 0.05 probability level.

Different letters indicate significant differences between tillage systems at $P < 0.05$.

Figure captions

Fig. 1 Periods and sub-periods of the growing cycle: previous harvest to sowing (PH to S), sowing to tillering (S to T), tillering to anthesis (T to A) and anthesis to harvest (A to H).

Fig. 2 Rainfall from July of the sowing year to June of the harvest year during the different cropping seasons studied at El Canós, Agramunt and Selvanera.

Fig. 3 Mean rainfall distribution at El Canós, Agramunt and Selvanera as an average of the cropping seasons (shown at the top) for different sub-periods: harvest of the previous crop to sowing (PH to S), sowing to tillering (S to T), tillering to anthesis (T to A), and anthesis to harvest (A to H).

Fig. 4 Soil water content (up to 100 cm depth) at tillering (lines) and previous harvest to tillering rainfall (columns) at a) Agramunt and b) Selvanera for the different tillage systems: no-tillage (NT), chisel (Ch), subsoiler at 50 cm (Sub-50), and mouldboard plough (Mb). Within each cropping season, different letters indicate significant differences between tillage systems at 0.05 probability level. In each site, the field capacity (FC) and permanent wilting point (PWP) values are shown in dotted lines.

Fig. 5 Grain yield at a) El Canós, b) Agramunt and c) Selvanera for different tillage systems: no-tillage (NT), minimum tillage (MT), chisel (Ch), subsoiler at 25 cm (Sub-25), subsoiler at 50 cm (Sub-50), and mouldboard plough (Mb). Within each cropping season, different letters indicate significant differences between tillage treatments at

1 0.05 probability level. Capital letters over the bars stand for the crop sown each year:
2 barley (B), wheat (W), triticale (T), canola (C), and peas (P).

3

4 **Fig. 6** Linear relationship between grain yield and soil water storage (SWS) up to
5 tillering in the experiments of Agramunt (a) and Selvanera (b) for the tillage treatments
6 compared (S50, subsoiler at 50 cm; S25, subsoiler at 25 cm; Ch, chisel; NT, no-tillage;
7 MT, minimum tillage; Mb, mouldboard plough). Year 2013 at Agramunt and years
8 2003 and 2011 at Selvanera (in light grey) were excluded from the regressions. Note the
9 different Y-axis scales.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6