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FIELD-6636; No. of Pages 9
ARTICLE IN PRESS
Field Crops Research xxx (2016) xxx–xxx
Contents lists available at ScienceDirect
Field Crops Research
journal homepage: www.elsevier.com/locate/fcr

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

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ARTICLE INFO

Article history:
Received 29 October 2015
Received in revised form 18 January 2016
Accepted 10 February 2016
Available online xxx

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

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.

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

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http://dx.doi.org/10.1016/j.fcr.2016.02.010
0378-4290/

Please cite this article in press as: Lampurlanés, J., et al., Long-term analysis of soil water conservation and crop yield under different tillage systems in Mediterranean rainfed conditions. Field Crops Res. (2016), http://dx.doi.org/10.1016/j.fcr.2016.02.010

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):$PUE = Y/R$

We can expand this expression by adding the terms water use (WU) and soil water storage (SWS) in this way: $PUE = \left(Y/WU\right) \times \left(WU/SWS\right) \times \left(SWS/R\right)$

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: $PUE = WUE \times PSE$

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 (382–450 mm), and annual water deficit (350–423 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 × 7 m) 350 m^2 at Selvanera, (30 × 6 m) 180 m^2 at El Canós and (50 × 9 m) 450 m^2 at Agramunt.

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_2O, 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 (2000–50 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).