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WATER USE OF WHEAT, CORN AND SUNFLOWER IN THE SEMIARID PAMPAS

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ABSTRACT

Crop water use in semiarid environments allows designing management strategies to improve water use efficiency. Our objective was to estimate wheat (*Triticum aestivum* L.), maize (*Zea mays* L.) and sunflower (*Helianthus annuus* L.) water use in the Semiarid Pampas of Argentina and to identify the relative contribution from soil and from in-season rainfall. Data were collected from 138 field experiments conducted during 2000-2013 over an area of 15 Mha. Soil water content was measured 3-4 times during the crop growing season, in a total of 552 soil profile moisture determinations. Soil samples were taken every 20 cm in the entire rooting zone. Gravimetric water content was converted to stored water using measured bulk density. Rainfall during crop growing cycle was measured at each experimental site. Crop water use was calculated as the difference between soil water content at sowing minus the soil water content at harvest plus rainfall received during the growing season. Runoff and drainage were estimated and discounted from crop water use. Water use efficiency was estimated as the ratio between grain yield and crop water use. Water losses as runoff and drainage rounded 15% among the three crops. Average water use was 319 mm for wheat, 487 mm for maize, and 443 mm for sunflower while respective water use efficiencies were 7.3, 18.6 and 5.6 kg DM grain ha^{-1} mm^{-1} respectively. Approximately 90% of water used by crops corresponded apparently to the in-season rainfall whereas the contribution from stored soil water at sowing was relatively low, except in dry years when it represented around 25% of in-season crop water use.

Key words. Crop water use, water use efficiency, Argentine Pampas.

USO DEL AGUA POR TRIGO, MAÍZ Y GIRASOL EN LA REGIÓN SEMIÁRIDA PAMPEANA

RESUMEN

La determinación de los requerimientos hídricos de los cultivos permite diseñar estrategias de manejo orientadas a un uso eficiente del agua. Nuestros objetivos fueron estimar el uso consuntivo de trigo (*Triticum aestivum* L.), maíz (*Zea mays* L.) y girasol (*Helianthus annuus* L.) en la Región Semiárida Pampeana y particionar el aporte del agua del suelo y la precipitación. Adicionalmente, calculamos la eficiencia de uso del agua para esos cultivos. Se utilizó información generada en 138 ensayos realizados entre 2000 y 2013 distribuidos en un área de 15 Mha. Se realizaron 552 muestreos de humedad del suelo hasta una profundidad de 140 cm o hasta el límite superior de la capa petrocálcica en capas de 20 cm. La medición de agua gravimétrica se transformó a lámina usando la densidad aparente de cada capa de suelo. En cada sitio experimental se midieron las precipitaciones durante el ciclo de los cultivos. El uso consuntivo se calculó como la diferencia entre el nivel de agua del suelo a la siembra y a la cosecha más las precipitaciones. Las pérdidas de agua por escurrimiento y drenaje fueron estimadas y restadas al uso consuntivo. La eficiencia de uso del agua se calculó como la relación entre el rendimiento y el uso consuntivo. El uso consuntivo promedio fue de 319 mm en trigo, 487 mm en maíz y 443 mm en girasol y las eficiencias de uso del agua fueron de 7,3; 18,3 y 5,6 kg MS mm^{-1} respectivamente. Aproximadamente 90% del uso consuntivo fue aparentemente cubierto por las precipitaciones en los tres cultivos, siendo el aporte del agua del suelo en general pequeño excepto durante años secos en que alcanzó un 25% del uso consuntivo.

Palabras clave. Uso consuntivo**,** eficiencia del uso del agua, Región Pampeana.

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INTRODUCTION

In water-limiting environments, crop productivity is mostly determined by crop water use *(CWU)* and water use efficiency *(WUE)* (Fisher & Turner, 1978; Oweis *et al.*, 2000). Hence, their accurate estimation is critical for assessing crop performance as rainfall amount is scarce and very variable (Loik *et al.,* 2004). Crop water use depends on one hand on soil water supply, which is mainly determined by stored soil water in the root zone at sowing time an in-season rainfall (Passioura, 1977), and on the other hand on type of crop and the cultivar characteristics (Noellemeyer *et al.*, 2013; Puckridge & O´toole, 1980). Thus, degree of water limitation is determined by the balance between water supply and atmospheric demand (Tao *et al.,* 2003). Water use efficiency is regulated by the same controls of and additionally it is impacted by other factors that control crop yield, between them, the agronomic management. Understanding the relative contribution of soil water at sowing and in-season rainfall to the total crop water use is important to design flexible management practices that can help avoid or mitigate the adverse effects of rain-free periods on crop yields (Cayci *et al.*, 2009). In these water-restricted environments there is ample space for management and genetic improvements that increase and subsequently crop yield (Passioura, 1977; Sadras & Angus, 2006). Between the management practices than can affect and , nitrogen fertilization and different tillage systems are usually adopted in dryland agriculture. Nitrogen fertilization may lead to better (Cooper *et al.,* 1987; Oweis *et al.* 2000) while tillage system effects may be year dependent (Azooz & Arshad, 1998).

The Pampas of Argentina is a vast plain of around 50 Mha (Alvarez & Lavado, 1998) considered as one of the most suitable areas of grain crop production in the world (Satorre & Slafer, 1999). Agriculture is performed on well-drained soils, mainly Mollisols in the semiarid and humid portions (MAGYP, 2016). The semiarid portion covers almost half of this region and a low-input agriculture (Viglizzo *et al.*, 2001) has developed with wheat (*Triticum aestivum* L.), maize (*Zea mays* L.) and sunflower (*Helianthus annuus* L.) accounting for 50% of the area devoted to grain crops.

Previous results showed that, in the region, average and rounded 360 mm and 6.3 kg DM ha^{-1} mm^{-1} respectively for wheat (Fagioli *et al.*, 1985a) and 530 mm and 5.0 kg DM ha^{-1} mm^{-1} for sunflower (Bono *et al.,* 1999). The possible effects of nitrogen fertilization and tillage systems has not been evaluated except in a few experiments from which no clear effects of management practices can be summarized and extrapolated to the whole region (Fagioli *et al.*, 1985b; Gregoret *et al.*, 2006; Noellemeyer *et al.*, 2013; Scianca *et al.*, 2006).

Also, during some years when stored soil water at sowing is large, can exceed rainfall received during the crop growing cycle (Quiroga *et al.*, 1998a); showing the importance of the soil component on water use. Productivity of sunflower in the area had been shown to be linearly related to evapotranspiration (Grassini *et al.*, 2009) and the yield of the crop is linearly related to soil available water content (Funaro *et al.*, 2006). Some of these studies were based on one or a few experiments in which different methodologies were used or were performed using data generated around 20 years ago and regional estimations of and are not available in the Semiarid Pampas in recent years. Data for maize are especially scarce in the region. Our objectives were: 1) to estimate regional wheat, maize and sunflower and in the Semiarid Pampas using the results of numerous experiments widespread over the region, 2) to quantify the apparent contribution of stored water in the soil at seedling and of the rainfall received to the depending on the climate scenario, and 3) to evaluate the impact of nitrogen fertilization and tillage systems on and of the three crops.

MATERIALS AND METHODS

Between 2000 and 2013 three fertilization experimental networks were carried out with wheat (78 experiments), maize (22 experiments) and sunflower (38 experiments) in the semiarid portion of the Pampas, which have been detailed described previously (Bono & Álvarez, 2006; 2007; 2012). These broadly distributed experiments covered an area of ca. 15 Mha which represented almost half of the Semiarid Pampean Region and were located to the West of the annual 800 mm isohyet (Fig 1).

The experimental networks tested different fertilizer effects on yield and generally the design was with randomized blocks with four replications located ad random in each block. Plots had an average size of 5 m by 10 m (50 m^2) for wheat and 10 m by 10 m (100 m^2) for corn and sunflower. Next to the unfertilized control treatments of each experiment a pit was dug for profile description and three samples were taken from the walls of the pit at the middle of every soil layer of 20 cm up to 140 cm or up to the upper limit of the petrocalcic layer, when present, for bulk density determination via the cylinder method (Blake & Hartge, 1986), using steal cylinders of 250 cm^3. At sowing, tillering or V4-V6, flowering and maturity unfertilized control plots were sampled with an auger in layers of 20 cm to 140 cm depth or up to the petrocalcic layer. Three sites were randomly selected for sampling per plot and timing. Soil water content of samples was measured by gravimetry. Wheat sowing was concentrated from early June to early July, corn from early October to end of November and sunflower from early October to early November.

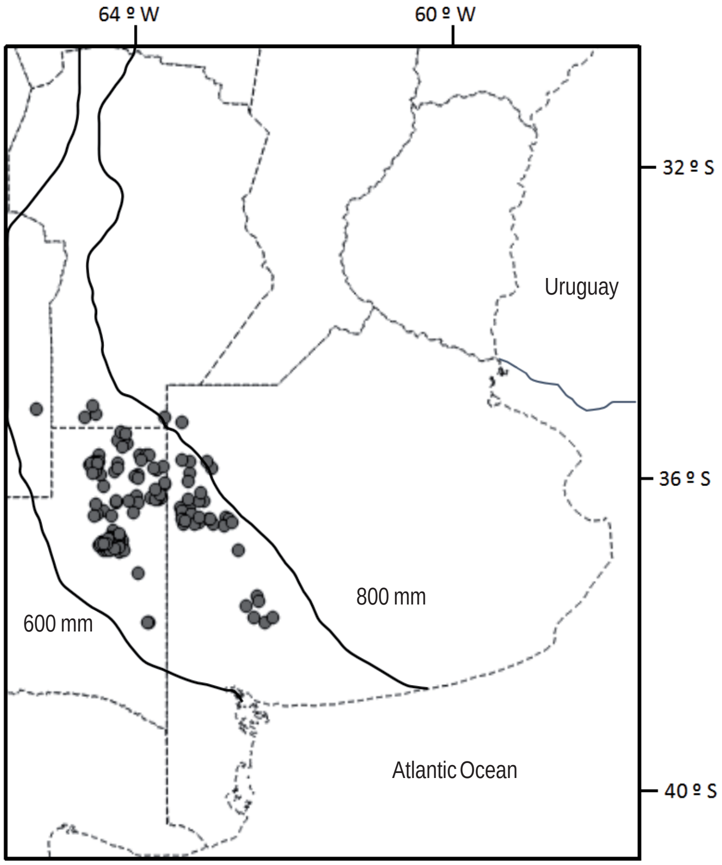

Figure 1.
Geographical location of 138 experiments carried out and comprised in this study. The lines represent the 600 and 800 mm isohyets.

Figura 1.
Ubicación geográfica de los 138 experimentos usados en este estudio. Las líneas indican las isoyetas de 600 y 800 mm.

In the upper 20 cm of the soil profile, texture (Gee & Bauder, 1996) and organic matter (Allison, 1965) were determined. Soil nitrates were measured at seeding by the chomotropic acid method (West & Ramachandran, 1966) every 20 cm and up to a depth of 60 cm. In each experiment the amount of received rainfall during the entire crop growing cycle was registered daily with pluviometers installed not farther away than 1000 m from the experiments. Additionally, dry grain yield (0% humidity) was determined by hand harvest of one microplot per experimental plot. In wheat, 10 rows where harvested and in corn and sunflower three rows were harvested. In all cases, microplots had 5 m long. Harvest was performed after crops attained physiological maturity and before commercial harvest

Crop management was similar to farmer's management in each case and therefore representative of the region. The majority of the experiments of maize and sunflower were carried out under no-till while many of the experiments with wheat were produced under conventional tillage where soil was ploughed with harrows and discs (Table 1). Almost half of the sampled soils in the experiments with wheat presented a petrocalcic layer within the sampling depth and this physical impediment was also present in ca. 25% of the soils with sunflower while maize was produced always in deep soils. In cases in which the petrocalcic layer was present, soil was sampled to the upper limit of that layer. Predominant soils were coarse-textured Haplustolls (67%) and Hapludolls (28%) according to Soil Taxonomy (USDA, 2003) with low organic matter contents. Soil nitrates in the upper 60 cm, sand content and organic matter exhibited large variation among sites. Rainfall amount received by the three crops was also very variable with the lowest rainfall amount received during the wheat growing cycle. The large variability of soil and climate conditions resulted in large yield ranges (Table 1). Crop water use was determined using the following model modified from the general model proposed by Doorenbos and Pruitt (1990):

$$CWU = (SWS - SWM) + (R_a - R_u - D) \qquad \text{Eq. 1}$$

where: SWS is the stored water at seeding (mm), SWM is the stored water at maturity (mm), R_a (mm) is the rainfall received during the crop growing season accounted for between seeding and maturity, R_u (mm) in the water lost by runoff and D (mm) is the water lost by deep drainage. The variable $(R_a - R_u - D)$

Table 1. Number of experiments performed per crop, experiments managed under no-till, average values of some measured soil properties, rainfall received during crop growing cycles and achieved yields. Numbers in parenthesis indicate minimum and maximum values of each variable.

Tabla 1. Número de experimentos realizados, cantidad de experimentos realizados bajo siembra directa, propiedades de suelo, precipitaciones y rendimientos medios logrados. Los números entre paréntesis indican valores mínimos y máximos de cada variable.

Crop	Experiments (n)	No-till (n)	Petrocalcic layer (n)	Sand (%)	Organic matter (%)	N-nitrates (kg N ha^{-1})	Rainfall (mm)	Yield (kg DW ha^{-1})
Wheat	78	23	37	58	1.8	55	356	2010
			(30 - 83)	(0.1 - 2.8)	(16 - 222)	(38 - 527)	(190 - 5070)	
Maize	22	17	0	66	1.9	77	481	7820
			(44 - 85)	(1.1 - 3.3)	(18 - 202)	(147 - 784)	(1570 - 13300)	
Sunflower	38	22	9	58	2.3	89	448	2300
			(24 - 86)	(0.4 - 5.7)	(22 - 343)	(198 - 684)	(730 - 4500)	

accounts for the rainfall water entering the soil and retained within the profile. Possible water table contribution to crop absorption was monitored taken into account water table intrusion in the rooting depth during the growing season. For this objective soil was sampled for water content determination not only at seeding and at the end of the cycle but also in intermediate crop growing phases.

For wheat and corn, soil samples for measuring water content were taken during sowing, tillering or V4-V6, flowering and maturity. For sunflower, samples were taken at seedling, V4-V6 and maturity. In total, 552 profile soil moisture determinations were performed. Gravimetric moisture content was converted to stored water using bulk density. Water content at field capacity (-33 kPa) and permanent wilting point (-1500 kPa) matric potentials were determined using the Richards methodology (Gardner, 1986). Stored water content over the wilting point was also calculated. The runoff water losses were estimated by the curve number method (Huang *et al.,* 2006; USDA, 1986). Estimations were performed for soil of the Group A (sand, loamy sand and sandy loan) using the curve number 65 (cropped soils). Drainage water losses were estimated by a daily water balance (Allen *et al.*, 1998). Drainage was calculated as the difference between soil water content in a day and the soil water retention capacity when soil is at field capacity. The soil water content was calculated as the sum of the water content of the previous day plus the difference between $(R_a - R_u)$ and crop evapotranspiration. For estimating crop evapotranspiration, data of potential evapotranspiration calculated by the Penman-Montheit equation of the Anguil Experimental Station (INTA) were used obtained from the Instituto de Clima y Agua-INTA Castelar. This station was in a central location referred to most of our sampled sites and is the only station with complete records in the sampled area. Crop potential evapotranspiration was estimated using kc values for the different crop growth stages obtained from Zeljkovich & Perez (1994) for wheat and Della Maggiora *et al.* (2000) for corn and sunflower. Crop evapotranspiration was calculated assuming that the ratio crop evapotranspiration/ crop potential evapotranspiration was linearly related to the fraction of available water content of the soil and that evapotranspiration was not constrained in our sandy soils when available water content was 50% or more of the soil retention potential (Allen *et al.,* 1998). Water use efficiency *(WUE)* (kg DM ha^{-1} mm^{-1}) was calculated as follows:

$$WUE = \frac{Y}{CWU} \qquad \text{Eq. 2.}$$

where: Y is the crop yield (kg DW grain ha^{-1}).

Regression analysis was performed to evaluate associations between variables and the F test was used with $P< 0.05$ for determining statistical significance. In order to separately identify the apparent contribution of rainfall to *CWU* , the $(R_a - R_u - D)/CWU$ ratio was calculated. The apparent contribution from soil to *CWU* was estimated as 100 - $(R_a - R_u - D)/CWU$. The data set was partitioned taken into account rainfall received along the growing season in three percentiles: lower 33%, intermediate 33% and upper 33%. Significant differences between means of, *CWU*, change in soil water content between seeding and harvest (Δ stored water), $(R_a - R_u - D)/CWU$ and WUE between different rainfall percentiles and tillage systems were accounted for by a two sample t-test ($P< 0.05$). Standard errors were calculated as a measure of variability. Yield and graphs were constructed for inspection of the relationship between both variables. A boundary function was fitted using quantile regression fitting a strait line to the upper 10% of data for determining the maximum efficiency of crops in transforming available water into grain.

RESULTS

Despite the ample range of variation of soil properties and yield, correlation between these variables was low ($R^2 < 0.3$) and generally not significant. Yields of wheat and sunflower tended to be lower in shallow soils (P= ns), organic matter was negatively correlated with sand ($R^2 = 0.25$, $P < 0.05$) and positively with the nitrate-N content ($R^2 = 0.09$, $P < 0.05$) when all soils were pooled (n= 138). Other possible relationships between variables were not significant.

Average stored water content decreased from sowing to maturity in almost all soil layers for the three crops (Fig 2). For the entire rooting zone (140 cm) stored water over the wilting point decreased 22% in wheat, 36% in maize and 27% in sunflower in average. Water depletion patterns differed between wheat and summer crops. While for wheat small differences between layers of stored water reduction was observed (20-27%), water depletion in summer crops was much greater in deep soil layers than in the topsoil, ranging the decrease below 60 cm between 40-45% in maize and 37-40% in sunflower.

Water losses in runoff rounded 4-5% of incident rainfall and drainage losses ranged from 7 to 11% of rainfall depending on the crop (Fig 3). The mean overall water losses did not exceeded 15% of rainfall in any case. The possibility that the water table acted as a source of water seemed unimportant in wheat and sunflower. Sampled data during the sowing, vegetative growing period, flowering and maturity showed that soil moisture in the deeper layers did not exceed field capacity by 100% (which is compatible with the presence of the water table) in 85-90% of the cases for these two crops. Conversely, in 50% of the maize sites, water content doubled field capacity in the 120-140 cm layer in at least one of the sampling times, indicating that the water table was an additional source of water for the crop, not accounted in our calculations. The largest amount of was registered for the summer crops first maize followed by sunflower (Table 2). Summer crops had about 40-50 % larger than wheat. Changes in soil water stored during the growing cycle were small representing only 15% or less of the for the three crops (Table 2). Water use efficiency was nearly 3-fold greater in maize than in the other two crops (Table 2). Correlation analysis showed only weak ($R^2 < 0.4$) and generally not significant relationships of and with soil properties and yield. The only remarkable association was found between and soil depth for sunflower ($R^2 = 0.35$, $P = 0.05$). Water use efficiency decreased in shallow soils.

When partitioning our data set into rainfall percentiles, it was possible to detect that during years with rainfall

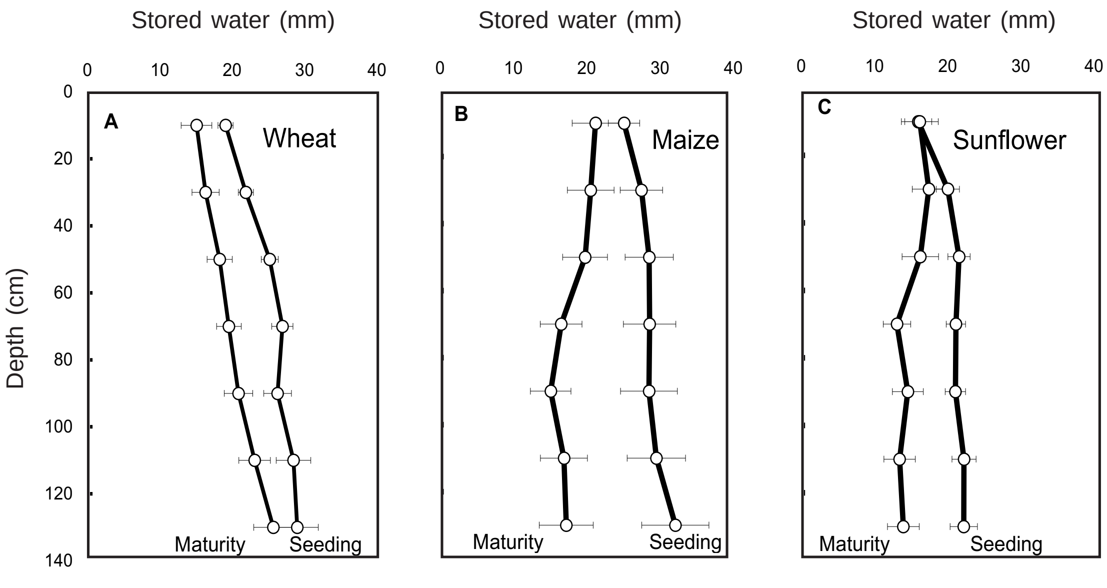

Figure 2. Stored water content of soil over the wilting point content at crop seeding and maturity. Each point indicates de average measured value for all the experiments of the corresponding network calculated for 20 cm soil layers. Bars indicate standard errors.

Figura 2. Agua almacenada en el suelo por encima del punto de marchitez a la siembra y a la madurez de los cultivos. Cada punto es el promedio de los valores de todos los experimentos de la red correspondiente calculado para capas de 20 cm de suelo. Las barras indican el error estándar.

Table 2. Crop water use *(CWU)*, reduction in stored soil water between seeding and maturity (Δ stored water), ratio (rainfall-runoff-drainage)/crop water use (Ra-Ru-D)/), and water use efficiency *(WUE)* of crops. Means and standard errors are reported.

Tabla 2. Uso consuntivo *(CWU),* reducción de la cantidad de agua almacenada en el suelo entre siembra y madurez (Δ stored water), relación (precipitación-escurrimiento-drenaje)/uso consuntivo ((Ra-Ru-D)/), y eficiencia del uso del agua *(WUE)* de los cultivos. Se reportan medias y errores estándar.

Crop	*CWU* (mm)	Δ stored water (mm)	$\frac{\text{Ra-Ru-D}}{CWU}$	*WUE* (kg DW grain ha^{-1} mm^{-1})
Wheat	319 ± 11.9	34 ± 10.5	0.89 ± 0.090	7.3 ± 0.87
Maize	487 ± 19.1	73 ± 18.7	0.85 ± 0.034	18.6 ± 1.92
Sunflower	443 ± 10.0	35 ± 12.1	0.92 ± 0.042	5.6 ± 0.39

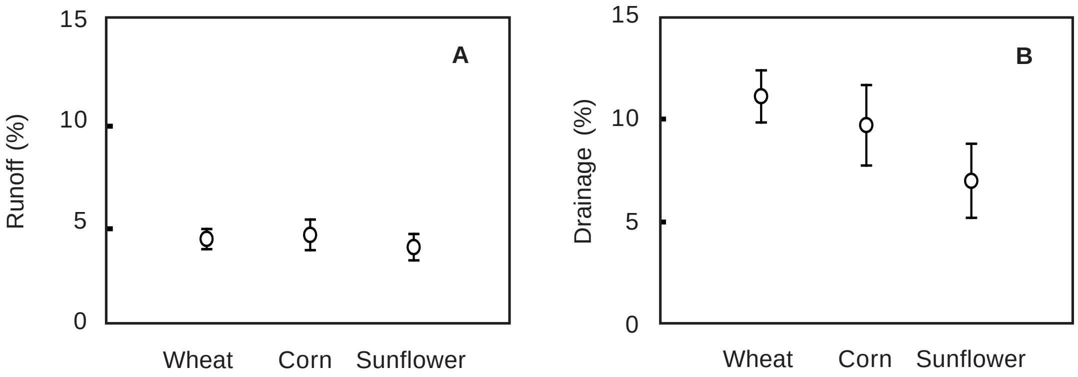

Figure 3. Average runoff (A) and drainage (B) estimations in the experimental networks as percent of incident rainfall. Bars indicates standard errors.

Figura 3. Escurrimiento (A) y drenaje (B) promedio estimados en las redes experimentales. Las barras indican el error estándar.

amount within the lower 33% percentile, was lower in corn and sunflower than in humid years, with no significant effects in wheat (Fig 4 A, B and C). In contrast, D stored water decreased in the three crops as rainfall was greater (Fig 4 D, E and F). For the upper 33% percentile D stored water approached zero, showing only minimal differences between initial and final soil water contents along the growing season. Based on the / ratio it was estimated an apparent soil water contribution to rounding 25% of the total water use in dry years (Fig 4 G, H and I). Under average to high rainfall scenarios (comprising the middle 33 % percentile and the largest 33% percentile), average was similar to and the apparent soil contribution became very low. The ratio /approached to 1 in the most humid years. When rainfall received was low this ratio rounded 0.7. As the ratio / increased decreased in corn and sunflower indicating that in humid growing season summer crops were less efficient in using water for grain production (Fig 4 J, K and L). This fall in during wet years compared to dry ones was particularly strong in maize but also very variable as marked by the standard errors of the estimations; a possible consequence of the smaller dataset available for this crop. The of wheat and sunflower were similar and around one third of maize values (Table 2). When data were partitioned taken into account tillage system, was greater in experiments managed under no-till than compared to those under tillage in the three crops but differences were only significant for sunflower (Table 3). For this later crop was 47% higher in no tilled experiments. Boundary functions fitted by quantile regression showed that maximum attained was around 60% greater than average values (slopes of regression lines in Figures 5, A, B and C) for all crops.

DISCUSSION

The methodology used for estimation had some limitations. First, changes of soil water stored below 140 cm depth were not measured. Maize, wheat and sunflower

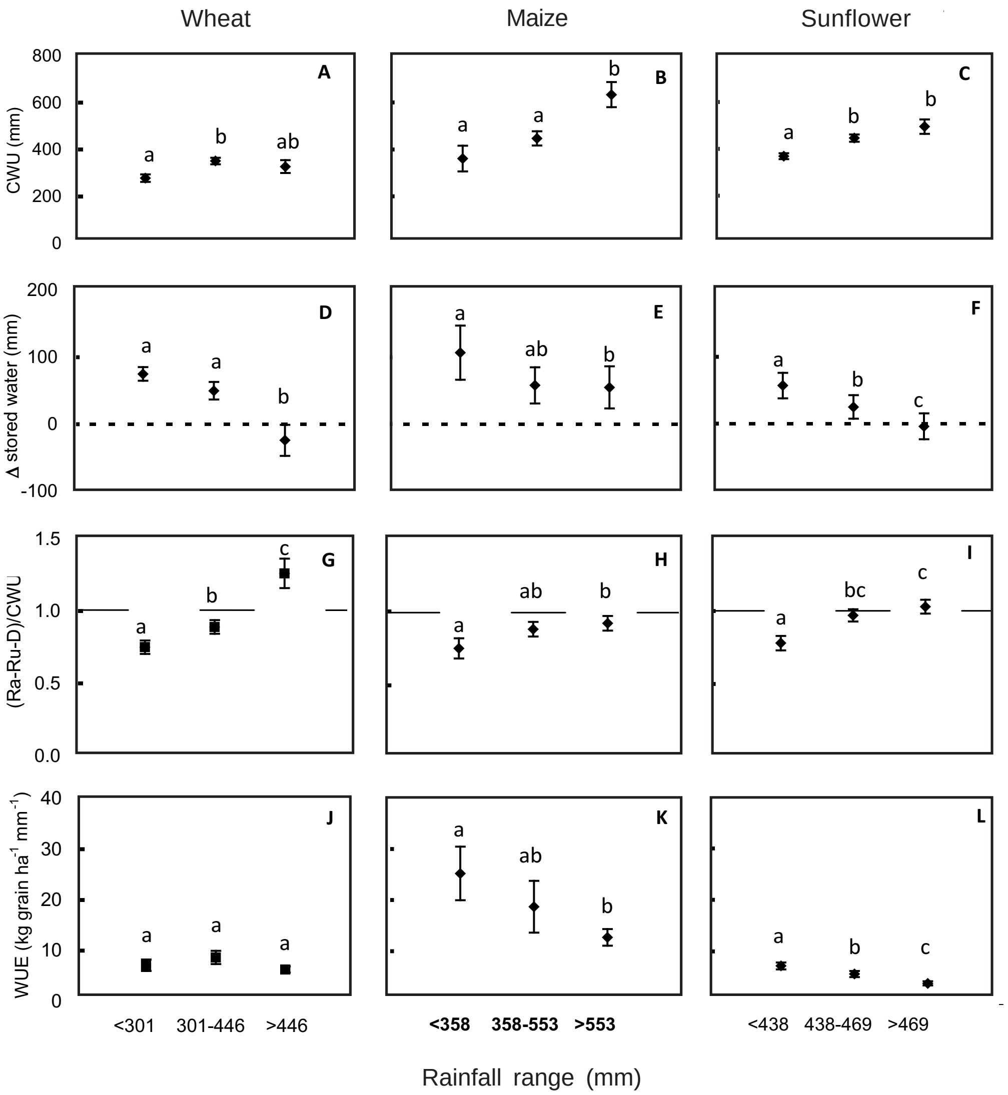

Figure 4. Relationships between crop water use *(CWU)*, change in soil water content between seeding and harvest (Δ stored water), the ratio rainfall-runoff-drainage and crop water use (Ra-Ru-D/*CWU*) and the water use efficiency *(WUE)* with the rainfall amount received during crop growing cycle partitioned in 33 % percentiles. Bars indicate standard errors. Different letters indicate significant differences ($P< 0.05$) between rainfall percentiles.

Figura 4. Relación entre el uso consuntivo *(CWU)*, el cambio del contenido de agua del suelo entre siembra y madurez (D stored water), el cociente precipitación-escurrimiento-drenaje/uso consuntivo (Ra-Ru-D/*CWU*) y la eficiencia en el uso del agua *(WUE)* con la precipitación recibida durante los ciclos de los cultivos particionados en percentiles del 33%. Las barras indican errores estándar. Letras diferentes indican diferencias significativas ($P< 0,05$) entre percentiles de precipitación.

Table 3. Water use efficiency *(WUE)* of the crops as a function of tillage system.

Tabla 3. Eficiencia del uso del agua *(WUE)* en función del sistema de labranza.

Crop	(kg DM grain ha^{-1} mm^{-1})		Significance
	No-till	Conventional tillage	
Wheat	7.9	7.0	ns
Maize	20.0	13.9	ns
Sunflower	6.2	4.7	$P< 0.05$

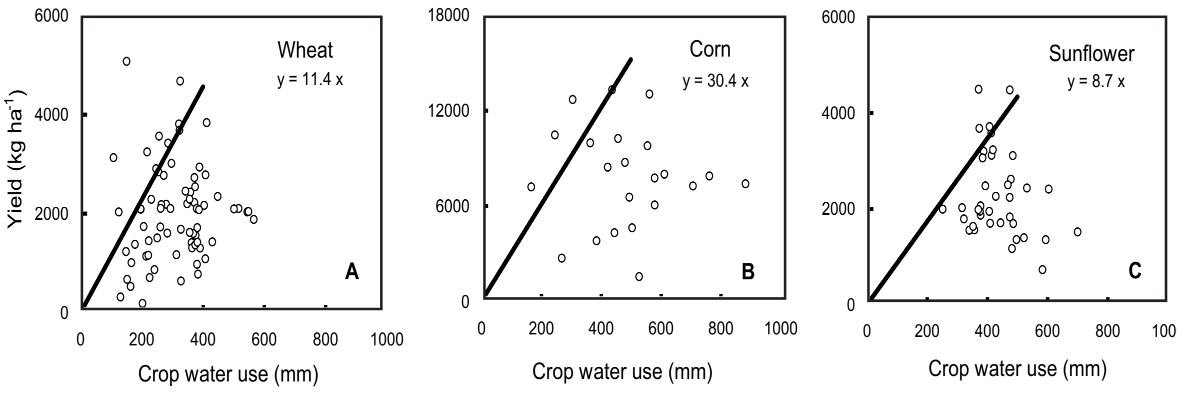

Figure 5. Quantile regression models fitted to the upper 10% yield data as a function of crop water use.
Figura 5. Modelos de regresión de quantiles ajustados al 10% superior de los datos de rendimiento en función del uso consuntivo de los cultivos.

can extract water below 140 cm in the Semiarid Pampas and measurements beyond 200 cm would have been necessary to find the point of zero water extraction, especially for summer crops (Dardanelli *et al.,* 1997; 2004). However, not accounting for this soil water input would not substantially affect the estimated *CWU* and therefore the thinkable underestimation would not be substantial. For example, if water absorption below 140 cm would increase D stored water by 50% in Eq. (1), estimated *CWU* would have been underestimated only by 4-8% depending on the crop. Second, possible absorption from the water table, that had been reported in the region before (Nosetto *et al.,* 2009), was ignored. This water flux seemed not to be an important phenomenon in most of the sites with wheat and sunflower as the water table did not intruded the upper 140 cm of the profile. Conversely, as in 50% of the maize sites, the water table was detected in the 120-140 cm layer in at least one of the sampling times, for this crop the water table may be a source of available water. Assuming that absorption from the water table increased the total water absorption from soil (D stored water) 100% in half of the maize sites, this would produce an average contribution of 37 mm across all maize sites and a sub-estimation of *CWU* in Eq. (1) of 8%.

The most widely used methodology for *CWU* estimation had been a simplification of the model in Eq. (1) in which runoff and drainage are not taken into account (Allen *et al.*, 2011; Sadras & Angus, 2006).This methodology has the main limitation of overestimate *CWU* when runoff and drainage losses are important, and can subestimate it if capillary ascend is intense (Allen *et al.*, 2011). This simple methodology have been commonly used previously in the Semiarid Pampa for *CWU* and *WUE* calculation for winter (Fagioli *et al.,* 1985a; Noellemeyer *et al.*, 2013; Scianca *et al.,* 2006) and summer (Bono *et al.*, 1999; Gregoret *et al.*, 2006) crops. We introduced in the calculation of *CWU* estimations of runoff and drainage losses in order to obtain more accurate results. As it can be expected for semiarid areas when no irrigation is applied (Oweis *et al.*, 2000), water losses were small. Because soils of the experimental sites were sandy textured with high infiltration and in general did not present high slope, which was always lower than 0.5%, average runoff did not exceeded 5% of rainfall. Drainage losses doubled runoff and were produced only after high rainfall events. Grassini *et al.* (2009) using the simulation model OILCROP-SUN estimated water losses by runoff and drainage for sunflower in 47 sites with climatic records located in the Semiarid Pampa. The average runoff calculated was 32 mm and the average drainage loss was 43 mm. These values are not far from our estimations of 18 mm and 31 mm respectively.

Stored soil water was depleted after crop growing seasons and some similar results were reported previously for the region. In an Entic Haplustoll, this soil water reduction along the growth of different crops was observed (Dardanelli *et al.*, 1997) and surface stored water at harvest was lower than at sowing for different summer and winter crops (Quiroga *et al.*, 1998 a; b). In average of all the experiments, soil water depletion to 140 cm depth was measured in our three experimental networks. Although most of crop root biomass is found in the upper soil layers (Fagioli, 1973), the absorbing activity of deep crop roots is very important in the soils of the region (Fagioli, 1983). These results are compatible with the average results reported here where the soil water content decreased sharply below even 100 cm depth, especially in summer crops. However, a strong year effect exists on D stored water. In wet years, D stored water may be near zero (Fig 4 F) or even more water may be found at maturity than at seedling (Fig 4 D).

Our results also showed that *CWU* of summer crops is greater (53% for corn and 39% for sunflower) than wheat. *CWU* Previous comparative analysis of the water requirements of different crops in other agricultural regions showed that winter crops had commonly lower *CWU* than summer crops (Cabelguenne & Debaeke, 1998). Conversely, little differences were observed in the average $(R_a \_ R_u \_ D)/CWU$ ratio and the average proportion of *CWU* apparently becoming from stored soil water between the three crops. Additionally, in drier years the contribution of soil water to *CWU* increased in the three crops. Changes in precipitation patterns will directly affect soil-moisture storage and evapotranspiration (Tao *et al.,* 2003). During the last century approximately 20 La Niña years were reported in South America (Grimm *et al.*, 2000; NOAA, 2016) during which water restrictions to summer crop were intense. During these dry years the soil contribution to *CWU* would be greater and management practices would be-come crucial for storing water in the soils. In our dataset, rainfall during La Niña years did not differed from the overall average for wheat (9 experiments) but was 18% lower for corn (8 experiments) and 38% lower for sunflower (4 experiments).

Our average *WUE* seem appropriate to characterize the region but it must be considered that these were based on unfertilized control plots measurements. Previous average values of *WUE* of unfertilized crops, calculated using a network of 10 experiments and without computing runoff and drainage in wheat was 6.3 kg DM grain ha^{-1} mm^{-1} (Fagioli *et al.*, 1985a), and using a network of 44 experiments in sunflower was 5.0 kg DM grain ha^{-1} mm^{-1} (Bono *et al.*, 1999). Our data are around 12-15% greater for both crops which seemed the consequence of the imputation of water losses in our model. We also determined that corn *WUE* tripled these efficiencies in the region. Root density and yields of fertili-zed crops in semiarid environments are higher and consequently crops may extract more water from the soil profile than unfertilized crops (Cooper *et al.*, 1987). However, in the Semiarid Pampas some experiments had shown that fertilization increased WUE of wheat because of the higher yields attained but had only minimal effects on *CWU* (Fagioli *et al.*, 1985b) and another one had shown no impact of nitrogen fertilization on both variables (Scianca *et al.*, 2006). In one experiment it had been reported that corn *WUE* may be greater when nitrogen fertilizer is applied than in non fertilized crops (Gregoret *et al.*, 2006). No-till management impacted positively *WUE* of sunflower but not those of wheat and maize in our dataset. Under no-till greater soil water storage had been measured in the region during some growing season (Bono *et al.*, 2008; Quiroga *et al.*, 1998b), leading to higher crop yields (Bono *et al.*, 2008; Noellemeyer *et al.*, 2013). This seems the cause of previous observations but care must be taken when interpreting these results because our experimental networks were not balanced and confounding effect may arise, especially in the case of maize. For this later crop only five experiments under conventional tillage were performed.

The boundary function analysis showed that attainable *WUE* is around 60% greater that average values in the Semiarid Pampa for the three crops evaluated. This indicates that there is an ample space for yield and *WUE* improvements. To a similar conclusion had reached a previous study performed in the region with sunflower which used a dataset generated before the year 2000. Management improvements are still need to attain this goal as in other dry areas of the world (Sadras & Angus, 2006).

In semiarid regions such as the Semiarid Pampas the availability of soil water and rainfall is variable and difficult to predict; consequently it is necessary to assess results during several years before reaching to average *CWU* and *WUE* values (Day *et al.*, 1978). Our results can be used as regional averages because of the size of the experimental networks used to make estimations and the long time period during which they were obtained. For this purpose a simple estimation methodology was needed that allowed its application on experimental networks despite its shortcomings. When rainfall amount does not match the crop requirements during dry years, the water flux provided by the soil is of relevance in the region and it is important to account for agricultural strategies that increase stored water leading to yield improvements. No-till seems a management option to attain this goal.

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