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Article

Crop and Tillage Effects on Water Productivity of Dryland Agriculture in Argentina

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Abstract: Rising demands for food and uncertainties about climate change call for a paradigm shift in water management with a stronger focus on rainfed agriculture. The objective here was to estimate water productivity of different crops under no-till (NT) and conventional till (CT), in order to identify rotations that improve the water productivity of dryland agriculture. We hypothesized that NT and cereal crops would have a positive effect on overall water productivity. Crop yield and water use data were obtained from a 15 year experiment (1993 to 2008) on an entic Haplustoll in the semiarid Pampa, Argentina, with a rotation of wheat (*Triticum aestivum* L.), corn (*Zea mays* L.), sunflower (*Helianthus annus*), and soybean (*Glycine max* L. Merr.). The results indicated an improved water productivity of all crops under NT compared with that of CT; however, the response of cereals (corn +1.0 kg ha^{-1} mm^{-1}, wheat +1.3 kg ha^{-1} mm^{-1}) was higher than that of sunflower (+0.3 kg ha^{-1} mm^{-1}) and soybean (+0.5 kg ha^{-1} mm^{-1}). Crop type had a higher impact on water productivity than did tillage system. In agreement with our hypothesis, cereal crops were more efficient (corn 9.8 and wheat 6.9 kg ha^{-1} mm^{-1}) compared with soybean 2.4 and sunflower 3.9 kg mm^{-1}, but the economic water productivity of sunflower (0.9 US$ ha^{-1} mm^{-1}) almost equaled that of wheat (1.1 US$ $ha^{-1}mm^{-1}$) and corn (1.2 US$ ha^{-1} mm^{-1}). We concluded that the use of the synergy between NT and water efficient crops could be a promising step towards improving food production in semiarid regions.

Keywords: water productivity; cereals; oilseeds; trade price; energy contents

1. Introduction

There is increasing concern about agricultural water use in the context of rising demand for food and feeds. Rockström *et al.* [1] call for a paradigm shift for water management with a stronger focus on rainfed agriculture, since they visualize few chances of further expansion of large-scale irrigation. The largest gaps between potential and on-farm yields are also most common in these regions. According to de Fraiture *et al.* [2], the biophysical constraints that cause low yields in developing countries can be overcome with appropriate management; better farm-level management might mitigate agricultural droughts and crop failures. Bossio *et al.* [3] highlighted the connection between land degradation and water efficiency in a recent review. This is largely because degradation diminishes soil organic matter content, thus reducing water infiltration and water holding capacity [4]. The improvement of soil physical conditions and effective nutrient management are important tools to enhance the crop's water productivity [5].

In many semiarid regions only a proportion of rainfall is used for transpiration and Rockström *et al.* [6] mentioned that on average 50% of rainfall is lost from the fields. In semiarid regions rainfall usually does not cover the crops' requirements [7]. This is the reason why in these regions fallowing is one of the most common practices to accumulate water in the soil to meet the crops' water requirements. Fallow efficiency is influenced by tillage system and residue cover since in conventional tillage (CT) and with low residue cover the recovery of rainfall during fallow rarely exceeds 20%, while high residue cover as attained with no-till (NT) can improve this value up to 40% [8]. Little is known about how different crops make use of this additional water under NT and whether there are significant differences in water productivity related to that. We therefore hypothesized that NT and the use of water efficient crops would have a positive effect on water productivity of dryland agriculture. The objective of the present work was to estimate water productivity of different crops under NT and CT in a semiarid region, in order to identify soil and crop management that improves the overall water productivity of dryland agriculture.

2. Materials and Methods

The tillage experiment began in 1993 near Dorila, La Pampa, Argentina, on a sandy-loam entic Haplustoll, with a typical profile of A (0–0.18 m), AC (0.18–0.46 m), C (0.46–1.00 m) and C_k (1.00–1.86 m) horizons over a calcium carbonate hardpan. The experimental plots were established in August 1993, with two treatments (NT and CT) in a paired strip design with three replicates. Each of the six plots measured 15 m by 200 m, and they were cultivated with standard agricultural equipment. The crop sequence from 1993 until 2008 was: sunflower (*Helianthus annuus*), wheat (*Triticum aestivum* L.), oats (*Avena sativa)*, corn (*Zea mays* L.), sunflower, wheat, four years of pasture of alfalfa (*Medicago sativa*) and tall fescue (*Lolium arundinaceum* (Schreb.) Darbysh. = *Schedonorus arundinaceus* (Schreb.) Dumort), soybean (*Glycine max* (L.) Merr.), sunflower, corn, soybean, soybean, and corn. Cereal crops were corn, oats, and wheat; oilseeds were sunflower, and soybean a pulse crop. Summer

and winter crops were grown on the same plots in the sequence. The growing season for summer crops (sunflower, soybean, and corn) is from October to February, for winter crops (oats, wheat) the season is from July to November. Under NT all crops and the pasture were established after herbicide fallow with glyphosate with a direct drill; CT consisted of the use of a disk plow (0.18 m depth) and spine harrow (0.15 m) for fallowing and before seeding (two passes each per crop).

Gravimetric water contents of soils were determined at seeding and harvest of all crops. For this purpose soil samples were taken at 0.2 m depth intervals to a total depth of 1.40 m, with three replicates per plot. Field capacity (30 kPa) and permanent wilting point (1500 kPa) water contents were determined once on the same samples in the Richards pressure device (Soil Moisture Equipment Co., Santa Barbara, CA, USA). Available water was defined as the gravimetric water content minus gravimetric water content at permanent wilting point.

Crop production was determined by manual harvest of three sub-samples of each treatment, representing 1 m^2 for wheat and 2 m^2 for corn, sunflower and soybean. For further analyses, mean yield (average of all three plot yields for each tillage treatment) was used. Water productivity, *i.e.*, grain production per unit of water used, was calculated from rainfall data and the change in soil water storage during growing periods of crops according to the following equation [9]:

$$WP = \frac{Y}{CWU} \quad (1)$$

Where WP is water productivity (kg $ha^{-1}mm^{-1}$), Y is mean grain yield of each crop (kg ha^{-1}); CWU (mm) is the crop's apparent mean consumptive water use, which was calculated according to the following formula:

$$CWU = AWi - AWf + R \quad (2)$$

Where AW_i is the initial available water content of the soil at seeding (mm); AW_f is the final water content of the soil at harvest (mm) and R is rainfall during the growing season (mm); all water contents measured to 1.4 m depth. This definition includes water consumption by crop transpiration, as well as runoff, deep drainage, and soil evaporation. All values used for calculations were the means of the three subsamples per treatment (crop, tillage, year). Economic water productivity (EWP, USD ha^{-1} mm^{-1}) was calculated as follows:

$$\text{EWP} = \frac{CY \times TP}{CWU} \quad (3)$$

Where CY is crop yield, TP is trade price.

Crops were not limited by nitrogen or phosphorus, and all crops were fertilized with both elements at rates of 10 kg ha^{-1} of P and 40–60 kg ha^{-1} of N. Soil properties at the end of the growing season 2008 are shown in Table 1.

The historical rainfall data (series from 1921 to 2009) were obtained from the meteorological register of INTA Experimental Station at Anguil, La Pampa, Argentina. During the experiment, rainfall was measured with an automatic weather station at the experimental site. The probability of rainfall was calculated from the monthly average rainfall values for the period between 1921 and 2009. The sum of rainfall during October to February was used for summer crops, and July to November for winter crops (Figure 1). The probability was calculated assuming the theoretical Gamma distribution (Thom, 1958),

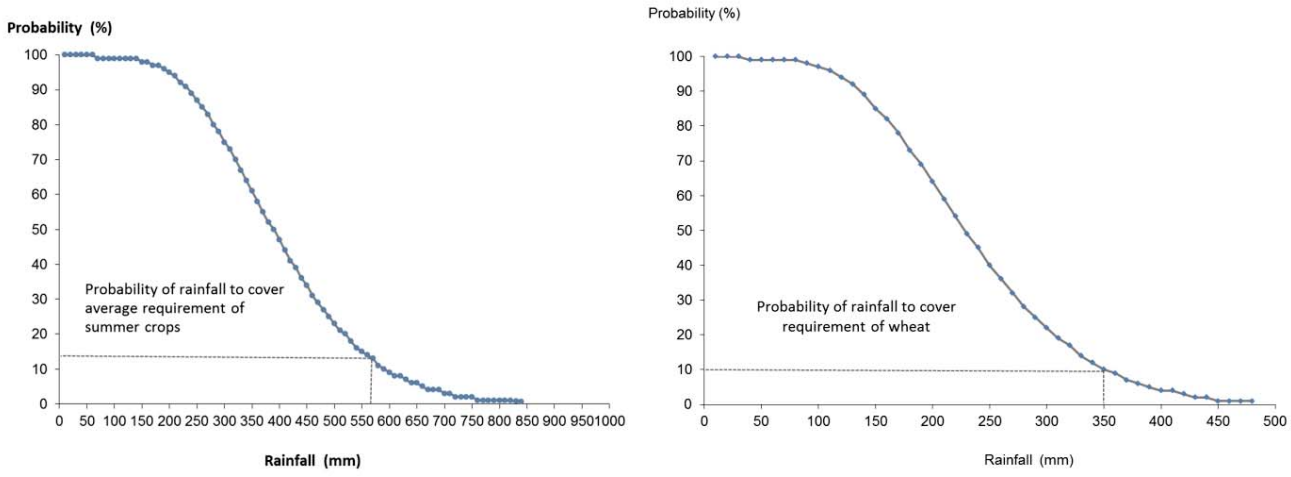
using the MATLAB software. Crop water requirement was estimated according to the total accumulated evapo-transpiration reported by Dardanelli *et al.* [10] as 350, 600, 560 and 530 mm for wheat, soybean, corn and sunflower, respectively. The historical mean annual rainfall (1921–2009) was 703 mm, while from 1993 to 2009 annual average was 842 mm. The probability that rainfall is sufficient to meet the crop's requirements is very low (Figure 1); in only 14% of the years in the case of summer crops and 10% for winter crops were these conditions met.

Table 1. Bulk density (BD), water content at permanent wilting point (PWP) and at field capacity (FC), clay plus silt contents (particles <50 μm diameter), total organic carbon (C), available phosphorus (P) and total nitrogen (N) of conventional (CT) and no till (NT) treatments (Average values for 0–0.18 m depth).

	BD ($Mg\ m^{-3}$)	PWP (mm)	FC (mm)	Clay + Silt ($g\ kg^{-1}$)	C ($Mg\ ha^{-1}$)	P ($Mg\ ha^{-1}$)	N ($Mg\ ha^{-1}$)
CT	1.18a	6.7b	11.9b	459a	13.8b	0.20b	1.26b
NT	1.14a	7.4a	13.8a	441a	15.8a	0.35a	1.37a

Different letters in the same column indicate significant differences ($p < 0.01$).

Figure 1. Probability of occurrence of historical rainfall (1921–2009) in summer crops (October to February) and winter crops (July to November). The arrows indicate the probability of the occurrence of rainfall that covers the crops' minimum requirements (560 mm and 350 mm for summer and winter crops respectively).



Statistical analyses of the data were carried out with InfoStat/P software and consisted of paired *t*-tests comparing the yield, consumptive water use, and water productivity for each crop in each year between CT and NT, considering tillage treatment and crop as main effects. The same procedure was applied for comparison of the average data for summer and winter crops. The paired *t*-test is a statistical procedure which compares the means of two paired datasets, and a minimum of three pairs of observations is needed to carry out this procedure. This test is applicable for cases where data from

different years, sites, or other factor effects are to be compared. The test compares among pairs and thus eliminates the possible effect of year (in our case) since the comparison was between data of the same crop in the same year. For soybean and wheat we had only two years of yield data, and this statistical analysis could not be carried out, since it requires at least three pairs of observations.

3. Results and Discussion

3.1. Water Content of Soils

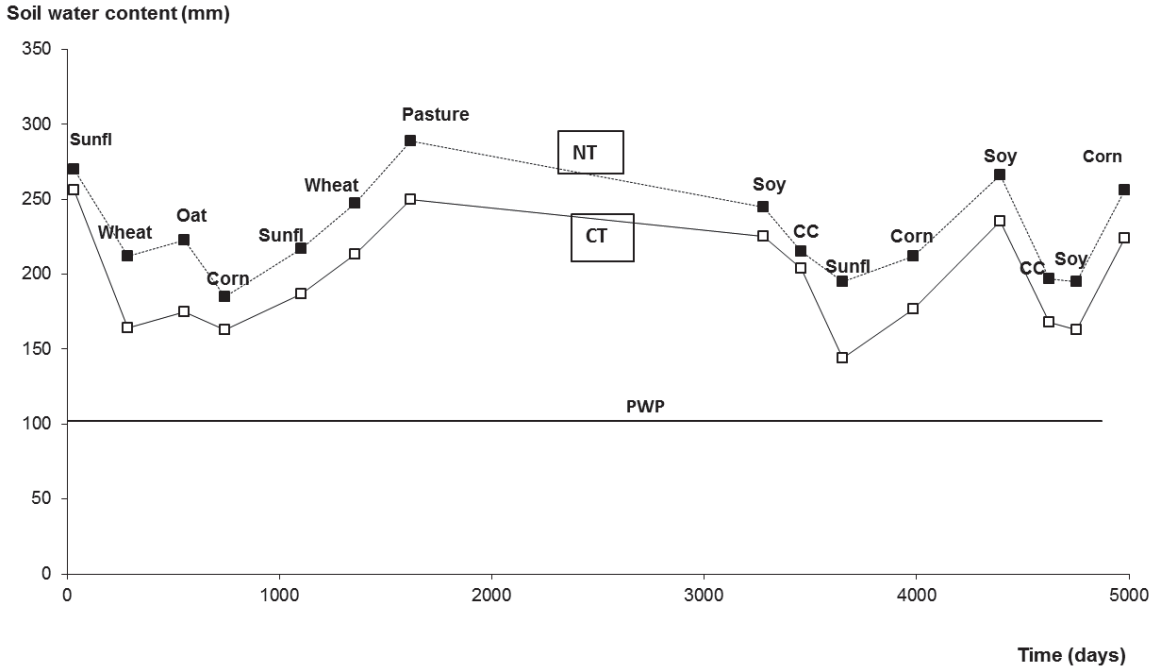
Water contents of soils at seeding were higher in NT for all crops in the 15-year rotation (Figure 2), but an important temporal variability between the same crops in different years was also observed. Since rainfall was the same in NT and CT plots, these differences in water contents indicated that soil infiltration and water storage were affected by tillage system. Several studies reported improved water infiltration and storage in NT due to higher organic matter contents [11,12], crop residue [13], or mulch cover [14]. Significant differences ($p < 0.0001$) between tillage systems were found in the upper 1.4 m of the soil profile. For summer crops under NT, available water contents at seeding were 115 mm, compared with 90 mm in CT; for winter crops these values were 99 mm and 69 mm respectively (Table 2). These results indicate that NT was effective in increasing water availability for crops, coincident with similar studies in Central Chile [15]. On average NT stored 29 mm more water in the soil at seeding than CT. Since in many semiarid regions fallowing for water storage in the soil is very common, NT is recommended for improving the efficiency of fallows. Efficiency of water storage during fallow is reportedly low (6%–20% of rainfall is retained by the soil) [8,9], but residue cover under NT can prevent run-off and evaporation losses [16–18]. Average fallow efficiency of the NT treatments in our experiment was significantly higher and almost twice that of CT (30% and 16%, respectively; $p = 0.0036$).

Table 2. Crop yield, soil available water content (AWC) at seeding, consumptive water use (CWU), and water productivity (WP) in no till (NT) and conventional till (CT) for summer crops (SC) and winter crops (WC).

	Yield (Mg ha^{-1})			AWC (mm)			CWU (mm)			WP (kg grain ha^{-1} mm^{-1})		
	CT	NT	*p*	CT	NT	*p*	CT	NT	*p*	CT	NT	*p*
SC	2.96	3.37	NS	90b	115a	<0.0001	590b	612a	0.005	4.9	5.6	NS
WC	2.43	3.08		69b	99a	0.0034	411	447		5.6	6.9	
Average	2.87b	3.32a	0.05	82b	109a	<0.0001	560b	586a	0.0007	4.9b	5.8a	0.068

Different letters indicate significant differences (paired *t*-test, *p* values show significance) between CT and NT for each variable and crop type.

Figure 2. Gravimetric available water contents (mm) in no-till (NT) and conventional tillage (CT) at seeding of each crop of the rotation. (PWP, permanent wilting point).



3.2. Crop Yields and Water Productivity

Crop yields (Table 2) were higher under NT ($p = 0.05$), and for summer crops compared with winter crops, averaged across tillage systems. Summer crops produced 409 kg ha^{-1} more under NT than under CT, and for winter crops an even higher difference was found (+648 kg ha^{-1}). Water consumption was higher under NT, with a difference compared with CT of +22 mm in summer crops and +36 mm in winter crops, and an overall mean of 560 and 586 mm for CT and NT respectively ($p = 0.0007$). Winter crops had higher water productivity (WP) under both tillage systems (Table 2), and NT was superior for the mean of all crops with a value of 5.8 kg ha^{-1} mm^{-1} *versus* 4.9 kg ha^{-1}mm^{-1} for CT ($p = 0.068$).

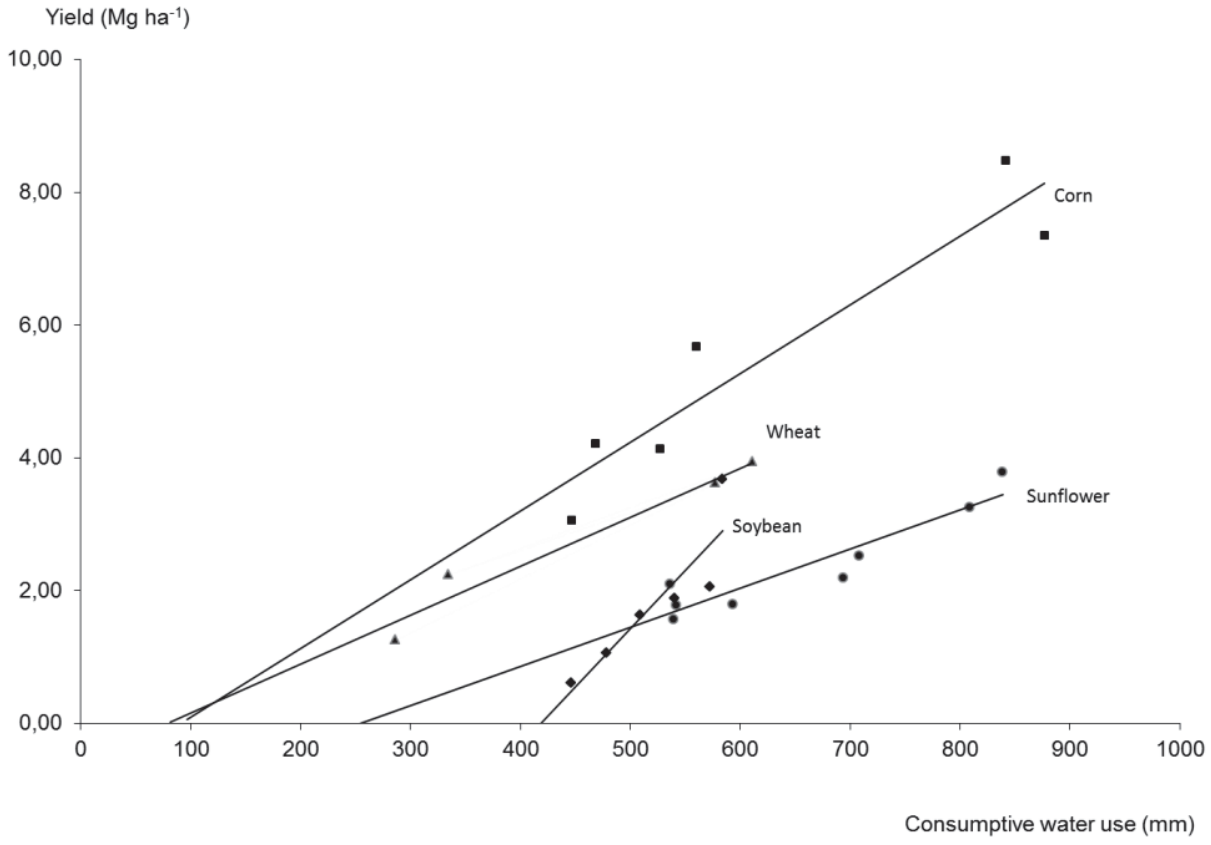
Crop yield is a linear function of available water, within a certain range (Figure 3) [19]. Water productivity is directly related to yield, when water use is equal [20]. Higher yields under NT would explain higher WP if water use remained constant, which was not the case in our experiment. Crops under NT consumed more water, but had proportionally higher yields, resulting in higher WP. Higher crop productivity and WP could be related to less water stress during critical stages of crops [21,22], and more even emergence and crop stand under NT [6].

All crops showed a strong dependence of yields on water availability (Figure 3), but a given level of available water produced very different yields in these crops, and the intercepts of the regression lines were also very different. The reason for this could be the amount of water consumed or lost during vegetative growth of the crops, before yield formation occurs. The pattern coincides with the differences in C pathways, and oil or protein contents, and therefore may not only represent water losses but also be related to the differences in energy required to produce cereal, pulse or oilseed grain. Soybean has the steepest slope which indicates that its yield response to additional available water was higher than that of the other crops. Purcell *et al.* [23] report that at 440 mm cumulative transpiration, as calculated from weather data using the Penman-Monteith equation to estimate ETo, different cultivars of soybean

reached 90% of their maximum yield, while our data indicate that there would be a strong potential for yield increase above this value. This divergence could be explained by the difference in methods used to calculate the crops' cumulative water use.

The paired *t*-test showed significantly higher yields under NT for sunflower and the average yields of all crops (Table 3), but all crops yielded numerically more under NT than in CT, with differences of 352, 354, 523 and 648 kg ha^{-1} for soybean, sunflower, corn and wheat, respectively. Overall average water productivity was significantly higher for NT compared with CT (p = 0.06), whereas for the individual crops no significant differences between tillage treatments could be detected. Corn under NT had the highest value (9.8 kg ha^{-1} mm^{-1}) followed by wheat (6.9 kg ha^{-1} mm^{-1}), while the lowest values were found for soybean and sunflower (2.4 and 3.9 kg ha^{-1} mm^{-1}, respectively). These data are comparable to those reported for the Great Plains of the USA [13].

Figure 3. Crop yields as a function of available water contents at seeding plus rainfall during the season for sunflower, corn, wheat, and soybean. Regression lines were extrapolated to the origin to compare estimated water losses. The regression coefficients were R^2 = 0.98, 0.95, 0.87, and 0.89 for soybean, wheat, sunflower and corn, respectively.



The paired *t*-test showed significant higher yields under NT for sunflower and the average yields of all crops (Table 3), but all crops yielded numerically more under NT than in CT, with differences of 352, 354, 523 and 648 kg ha^{-1} for soybean, sunflower, corn and wheat, respectively. The expected trend of superior response of soybean to higher available water under NT was not confirmed. This might have to do with low water availability during the growing season, which might be under the threshold value for

soybean optimum conditions, which is also confirmed by very low yields compared to "normal" yields in the Argentinean Pampas of around 3 to 5 Mg ha^{-1} [24,25].

Overall average water productivity was significantly higher for NT compared with CT (p = 0.06), whereas for the individual crops no significant differences between tillage treatments could be detected. Corn under NT had the highest value (9.8 kg ha^{-1} mm^{-1}) followed by wheat (6.9 kg ha^{-1} mm^{-1}), while the lowest values were found for soybean and sunflower (2.4 and 3.9 kg ha^{-1} mm^{-1}, respectively). These data are comparable to those reported for the Great Plains of the USA [13].

The improved crop performance in NT, especially in water-limited environments, has been documented by several reviews [26,27]. In fine texture or very hard-setting soils that are susceptible to compaction, yields under NT can be lower after several years of cropping, this also occurs where springs are cool, and residue cover retards germination and residue mineralization [27].

Table 3. Gravimetric water content at seeding, crop yield, and water productivity in CT and NT for the four crops tested in the experiment (n = number of years the crop was grown).

Crops	**Water content (mm)**			**Yield (Mg ha^{-1})**			**Water productivity (kg grain ha^{-1}mm^{-1})**		
	CT	NT	p	CT	NT	p	CT	NT	p
Sunflower (n = 4)	91	114	NS	2.2b	2.6a	0.06	3.5	3.9	NS
Corn (n = 3)	86b	116a	0.01	5.2	5.7	NS	8.8	9.8	NS
Soybean (n = 2)	97	129	-	1.1	1.5	-	1.9	2.4	-
Wheat (n = 2)	86	128	-	2.4	3.1	-	5.6	6.9	-
Average	**90b**	**119a**	**0.0001**	**2.9b**	**3.3a**	**0.05**	**4.9b**	**5.8a**	**0.06**

Different letters indicate significant differences (paired t-test) between CT and NT for each variable and crop.

The observed yield increase in NT compared with CT resulted in improved water productivity of all crops, with an average increase of 0.9 kg ha^{-1} mm^{-1} (mean of all crops). These results indicate that NT could be effective in increasing water productivity in dryland agriculture. Similar improvement of water productivity when changing from CT to NT cropping systems was reported for the Great Plains of the United States [5]. However, our results also showed that the different crops responded in a differential manner to the higher amount of available water under NT, with a similar response of corn, wheat and sunflower (0.0167 to 0.0174 Mg mm^{-1}), superior to that of soybean (0.0125 Mg mm^{-1}) These findings imply that poor performing crops, such as soybean in this case, are less efficient in utilizing the improved water availability under NT.

Molden *et al.* [28] compared different crops in terms of their water productivity and argued that there is much scope for improving the value per unit of water used in agriculture, rather than increasing physical water productivity. The gross revenues at current trade prices [29] were 316, 628, 478 and 680 USD ha^{-1} and the corresponding water productivities were 0.5, 0.9, 1.1, and 1.2 USD ha^{-1} mm^{-1}, for soybean, sunflower, wheat, and corn. Thus, in terms of economic water productivity, corn, wheat, and

sunflower were similar, while soybean had a much lower value. This means that the high market price for this crop could not compensate for its poor agronomic performance.

4. Conclusions

The results of our study indicated that NT improved available water use, yields and water productivity of all studied crops and contributes in reducing the risk of crop water stress in dryland agriculture. Well adapted crops make better use of the advantages of NT to improve water productivity both in physical and economical terms, but for crops with poor agronomic performance even a high market price cannot compensate. Recommendations for crop management in dryland agriculture should take into account the synergistic effect of good agronomic performance of the crops with better water availability in NT to improve overall water efficiency.

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