Lopresti and Bertín, Irrigat Drainage Sys Eng 2018, 7:1
DOI: 10.4172/2168-9768.1000205

Irrigation & Drainage Systems Engineering

ISSN: 2168-9768

Research Article Open Access

Complementary Irrigation in a Maize Silage Double Crop using the BAHICU Software: A Case Study in Northern Buenos Aires, Argentina

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Abstract

Northern Buenos Aires (Argentina) is a rain fed agricultural region. Complementary irrigation, which is mainly used in maize crop, requires the contemplation of strategies that minimize the soil solidification risk. The first alternative to mitigate the limited water quality is to perform an irrigation schedule by using the water balance methodology. The BAHICU software, developed in the study region, is a soil water balance model for agricultural systems under irrigation. The objective of the present study was to evaluate the forage production of irrigated and rain fed double crop of silage maize, using the BAHICU software as a tool to make a more efficient water use and to attenuate the adverse effect of the sodium present in the irrigation water. A field experiment was conducted on a clay soil with a sequence of two maizes during the 2015-2016 growing season: short season maize (maize 1) and late sown maize (maize 2). There were two preceding winter crops: ryegrass and oat. Plant height, dry matter (DM) percentage and DM yield were measured. Crop evapotranspiration (ETc) of irrigated and rain fed treatments was obtained from the BAHICU software. Irrigation was applied using a sprinkler system. Irrigation influenced only the yield of maize 2. Water use efficiency (WUE) did not vary with irrigation incorporation. Maize 2 presented higher forage production and WUE than maize 1. An R^2 value of 0.82 was found after relating DM yield with maize ETc. The preceding winter crops only influenced the yield of the maize 1. The DM yield was linked to plant height. The irrigated maize 2 was the only treatment that presented an optimal DM percentage for silage conservation. Using the BAHICU software allowed comparing the WUE of the maizes analyzed. Irrigation influenced crop yield but not WUE.

Keywords: Forage production; Soil water balance; Water quality; Soil solidification; Harvest time

Introduction

The north of Buenos Aires province, in the Argentine Humid Pampa, is predominantly an agricultural region, where crops are grown mainly under rain fed conditions. However, in recent decades, complementary irrigation has been growing exponentially. The irrigated area in Buenos Aires province increased 124% between 2002 and 2012 [1]. Given the climatic characteristics of the study area, the greatest water deficit occurs in November, December and January, and thus irrigation is mainly used in summer crops. Maize is the most irrigated crop in the region due to hybrid seed production. About 90% of Argentine seed companies are located on a 180-km axis between the cities of Pergamino and Venado Tuerto (north of Buenos Aires province and south of Santa Fe province, respectively) [2]. Maize has a high potential of biomass production, with a lower water use efficiency (WUE) than other C4 summer crops like sorghum [3,4], which makes it highly sensitive to irrigation.

Maize silage is the most common conserved forage used in the north of Buenos Aires province for dairy production, as well as, increasingly, for beef production. It is usually grown as a full season single crop and, in many cases, combined with a winter forage crop to increase production during the annual cycle. Double crop of maize silage had some tests at farmer level, but the practice is not extended because frequent water deficits prevent completing both crop cycles in the same growing season. Bertín et al. [5] have assessed forage production of soybean, maize and double maize crops with two levels of rain in the north of Buenos Aires province and found that, in a year with high rainfall, production of maize as single summer crop does not differ from that of maize as a double crop and that, in a year with normal rainfall, maize double crop has higher productivity. However, maize double crop production in a year with low rainfall could be highly risky due to the deficit of water for both crops. Complementary irrigation technology would allow carrying out maize double crop for silage, increasing forage productivity and decreasing production risk.

In contrast with other irrigated regions, the Argentine Humid Pampa is not so affected by salinity. However, the water of the Pampeano and Puelches aquifers, used for irrigation in the north of Buenos Aires province, is predominantly sodium bicarbonate [6,7]. Thus, the main impact of complementary irrigation in this area is soil sodification [8,9]. Studies by Andriulo et al. [10] showed that, after 11 years of complementary irrigation on a Typic Argiudoll soil, which is characteristic of the study area, the exchangeable sodium percentage of the soil was six-fold greater, the electrical conductivity (EC_s) was two-fold higher and the pH had increased one unit. Increased levels of exchangeable sodium percentage have negative consequences on the soil structure and water dynamics because of the effect of sodium as a soil dispersant. Irrigation with water with a high sodium adsorption ratio causes dispersion of soil aggregates, which partly collapses macro- and mesopores; this decreases infiltration and hydraulic conductivity, reducing water and oxygen circulation and thus favoring soil crusting [8]. In soils with high clay content, like Argiudolls, soil porosity deterioration is exacerbated because of its expansion. Therefore, the adoption of complementary irrigation in the study area requires considering strategies that minimize the soil solidification risk.

Since the amount of groundwater for complementary irrigation in northern Buenos Aires is still not limiting, the irrigation decision is generally based on subjective assessments of crop water needs. Therefore, the first alternative to mitigate the limited water quality is to perform an irrigation schedule by using the water balance methodology.

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Received March 16, 2018; **Accepted** April 07, 2018; **Published** April 15, 2018

Citation: Lopresti MF, Bertín OD (2018) Complementary Irrigation in a Maize Silage Double Crop using the BAHICU Software: A Case Study in Northern Buenos Aires, Argentina. Irrigat Drainage Sys Eng 7: 205. doi: 10.4172/2168-9768.1000205

According to Génova [11], complementary irrigation in the Argentine Humid Pampa requires adequate monitoring and management conditions. Although irrigation increases the exchangeable sodium percentage of the soil, the process is not irreversible because of the leaching of salts due to rainfall during non-irrigated periods and the high cation exchange capacity of soils. The soil water content for crops can be estimated indirectly through a water balance. The BAHICU software, which has been developed in the Argentine Humid Pampa, is a simple water balance model for field crops that requires few input data [12]. The BAHICU, mainly directed to agricultural systems under irrigation, predicts the days to reach water stress. Making a rational use of aquifers not only provides the system with soil and water sustainability but also allows saving money because it allows a more efficient use of the irrigation system.

The objective of this study was to evaluate the forage production of irrigated and rain fed double crop of silage maize, using the BAHICU software as a tool to make a more efficient water use and to attenuate the adverse effect of the sodium present in the irrigation water of northern Buenos Aires.

Materials and Methods

Study area and soil description

The study was carried out at the Pergamino Agricultural and Livestock Experimental Station of the National Institute of Agricultural Technology (INTA-EEA Pergamino) (33° 57.2' S, 60° 34.3' W and 68 m above sea level), in the north of Buenos Aires province. The average annual rainfall, with a monsoon-type pattern, is 1043 mm (data from 1970 to 2016, INTA EEA Pergamino meteorological station). The average rainfall in the irrigation season analyzed (2015-2016) was 104 mm higher than the historical average from September to April (Figure 1). In August, there was a difference of 226 mm in favor of the season analyzed, so the first maize (sown in September) had a high water reserve in the soil. The soil type, Pergamino Series Typic Argiudoll, is class IIe [13]. The soil of the irrigated treatment had five successive irrigation growing seasons before sowing the first maize of the double crop. Therefore, the irrigated and rainfed soil properties were different (Table 1), and, as expected, the irrigated soil presented a high value of exchangeable sodium percentage. The irrigation water characteristics were: pH: 8.3, EC_w: 0.99 dS/m, calcium (Ca): 12.8 mg/L, magnesium (Mg): 9.7 mg/L, sodium (Na): 275.1 mg/L, potassium (K): 12.1 mg/L, carbonate (CO_3): 78 mg/L, bicarbonate (HCO_3): 506.3 mg/L, sulfate (SO_4): 48 mg/L, nitrate (NO_3): 11 mg/L, chloride (Cl): 18.4 mg/L and sodium adsorption ratio: 14. According to Ayers and Westcot [14] guidelines for interpretations of water quality for irrigation, the degree of restriction on the irrigation water of our experiment was “slight to moderate” and the effect to the water infiltration rate into the soil was “severe”. INTA [15] characterized the irrigation water according to the soil and climate conditions at the Argentine Humid Pampa and reported that, in the north of Buenos Aires province, with a sodium adsorption ratio of 10 to 15, the water has “doubtful quality” in relation to the risk of soil solidification.

Experimental design and crop management

The experiment was a field trial with a double crop of silage maize, with a short-season maize (M1) and a late-sown maize (M2). The experimental design was in randomized blocks with three replicates and split plot arrangement, where the main plots were irrigation and rain fed treatments and subplots had two preceding winter crops (ryegrass and oat). The surface of the subplot was 60 m^2 (10 m long and 6 m wide). Measurements in each subplot were: plant density after emergence, plant density and plant height at harvest, dry matter (DM) percentage and DM yield. Crop evapotranspiration (ETc) values of the irrigated and rain fed treatments were obtained from the water balance

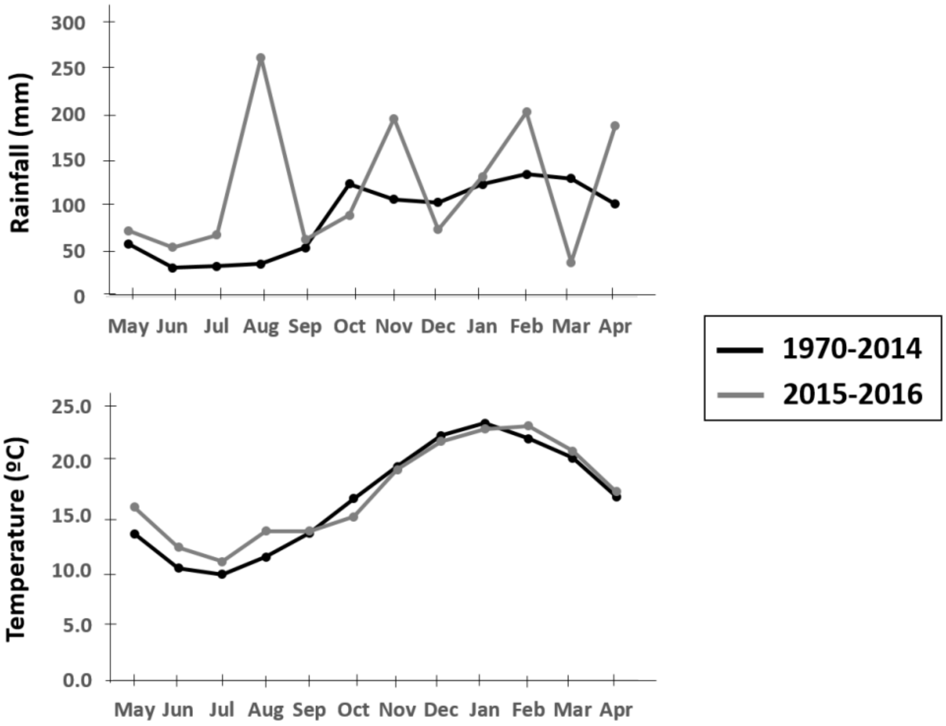

Figure 1: Monthly rainfall and temperature of the treated growing season (May to December 2015 and January to April 2016) and the average from 1970 to 2014 (data from INTA EEA Pergamino meteorological station).

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Treatment	Soil variable							
	pH	EC_s (dS m^{-1})	N (g kg^{-1})	OM (%)	P (mg kg^{-1})	Na (cmol kg^{-1})	ESP (%)	CEC (cmol kg^{-1})
Rainfed	5.7	0.1	1.6	2.9	11.1	0.1	0.7	14.8
Irrigated	6.8	0.14	1.6	2.8	8.6	1.1	6.8	16.7

EC_s: Electrical conductivity; N: Nitrogen; OM: Organic Matter; P: Phosphorus; Na: Sodium; ESP: Exchangeable Sodium Percentage; CEC: Cation Exchange Capacity.

Table 1: Soil properties of complementary irrigation experiment before sowing the first maize.

model. Irrigation was applied using a sprinkler system. Before the beginning of the irrigation season, uniformity and water sheet per hour of the irrigation system were evaluated through seven pluviometers distributed in a plot. Before starting each irrigation, the wind speed and the forecast of a nearby rain were taken into account.

WUE and irrigation water use efficiency (IWUE) were calculated (Eqns. 1 and 2, respectively). WUE and IWUE are common indicators employed to assess the irrigation water productivity at the crop production level [16].

$$\text{WUE (kg m}^{-3}\text{)} = Y/ETc \qquad (1)$$

$$\text{IWUE (kg m}^{-3}\text{)} = (Y_i - Y_0)/I \qquad (2)$$

Where Y -DM yield (kg ha^{-1});

ETc-total crop evapotranspiration (m^3 ha^{-1});

Y_i-irrigated treatment DM yield (kg ha^{-1});

Y_o-rain fed DM yield (kg ha^{-1});

I-irrigation water applied (m^3 ha^{-1}).

Both M1 and M2 were sown with a row distance of 0.52 m with 96,000 and 115,000 seeds per hectare in the rain fed and irrigated treatments, respectively. The M1 hybrid Pioneer 39B77 was sown on September 2, 2015, and fertilized with 103.6 kg ha^{-1} of N, 60 kg ha^{-1} of P, 25 kg ha^{-1} of sulfur (S) and 57 kg ha^{-1} of Ca, distributed in two moments (sowing and V3 stage). Harvest was done on December 28, 2015. The M2 hybrid NK 907 TD/TG (Syngenta) was sown on December 30, 2015, and fertilized with 100 kg ha^{-1} of N, 20 kg ha^{-1} of P, 25 kg ha^{-1} of S and 40 kg ha^{-1} of Ca, distributed in two moments. Harvest was done on April 22, 2016.

Crop water balance (BAHICU)

The water balance is an indirect way of knowing the soil water content available for crops. At field level, the water entering to the system is mainly through the rain and the irrigation, and the exit of the water is through the ETc and the surface runoff. The BAHICU software is a crop water balance model, the version applied to take the decision of irrigation was the 1.02 (http://inta.gob.ar/noticias/nuevo-software-de-balance-hidrico-de-cultivos-extensivos-bahicu-102). The soil water balance equation of FAO 56 [17] was taken as the basis for the development of BAHICU. The software provides a table and a graphical output with the daily evolution of the available water content in the soil for the sown crop. The software database contains its own crop coefficient (Kc) values to obtain the ETc values. The rate of crop root growth and the Argentine Pampa soil types are taken into account to know the available soil moisture for the crop. The program requires the loading of the soil moisture at the beginning of the water balance, so it must be measured a day before sowing. Loading of daily potential evapotranspiration, rainfall and irrigation water sheet are necessary. The software also considers the irrigation system, the soil slope and the rainfall intensity.

Statistical analysis

Results were analyzed by analysis of variance (ANOVA) and the means compared with the Tukey test. Both M1 and M2 showed a non-significant interaction between irrigation and the preceding winter crop (*p*-values of ANOVA were 0.94 and 0.261 for M1 and M2, respectively). Therefore, the irrigated and rain fed treatments were evaluated with six repetitions. The relationship between yield and ETc was observed through a linear regression model. The statistical software used was InfoStat [18] and the statistical significance was determined by a p-value <0.05.

Results and Discussion

Water balance, DM production and WUE

M1 was irrigated only during grain filling. However, the stress line was not reached (Figure 2). Although there was a slight water deficit at the beginning of the critical period for water availability (approximately between October 23 and December 1), the crop had no irrigation during that period. M2 had three irrigations during the critical period (approximately between February 4 and March 14). Although the stress line was not reached either, especially the first 15 days of the critical period, an important difference was observed respect the water balance of the rain fed treatment. In this treatment, the available water line moved away from the stress line so much in a part of the critical period as during grain filling. Therefore, both in M1 and M2, the water requirement in the crop cycle could not be completely covered by irrigation. Table 2 shows values of rainfall, irrigation applied, and ETc of M1 and M2, and for the global double maize.

DM production did not correspond to WUE, i.e., a higher production did not necessarily imply greater WUE (Table 3). In contrast to yield, the WUE did not vary with irrigation incorporation in any of the crops analyzed (M1, M2 and double maize). M2 presented higher forage production and WUE than M1. Evidently, the environmental conditions for the crop growth rate per consumed millimeter were better for M2 (M2 presented lower ETc but higher production than M1). The WUE can obtain variable magnitudes in function of the growth response and water use to specific environmental conditions [19].

The irrigated M2 presented greater DM production than the rain fed M2, due to the larger water consumption. The results for WUE were not the same. Values of M2 WUE were similar to those found by Otegui [20] (4.2 and 3.5 kg m^{-3} for maize under rain fed and irrigation, respectively). The M2 IWUE (2.54 kg m^{-3}) was lower than the WUE, in agreement with that found by Kresović et al. [21], who studied maize grain yield. The DM production of the irrigated and rain fed M1 was similar. The irrigated water sheet (36 mm) had no effect, probably due to the advanced stage when it was applied (outside the critical period). Therefore, the rain fed treatment allowed both preventing Na from entering the soil with irrigation water and lowering irrigation costs. It also allowed reducing the number of seeds needed due to the lower plant density requirement. The double maize required around 800 mm (Table 2), although rain in the growing season analyzed was above that requirement, which occurs very rarely in the study area. This is the reason why irrigation is the key in a double crop of maize, especially in a triple cropping sequence since the soil water reserve is scarce due

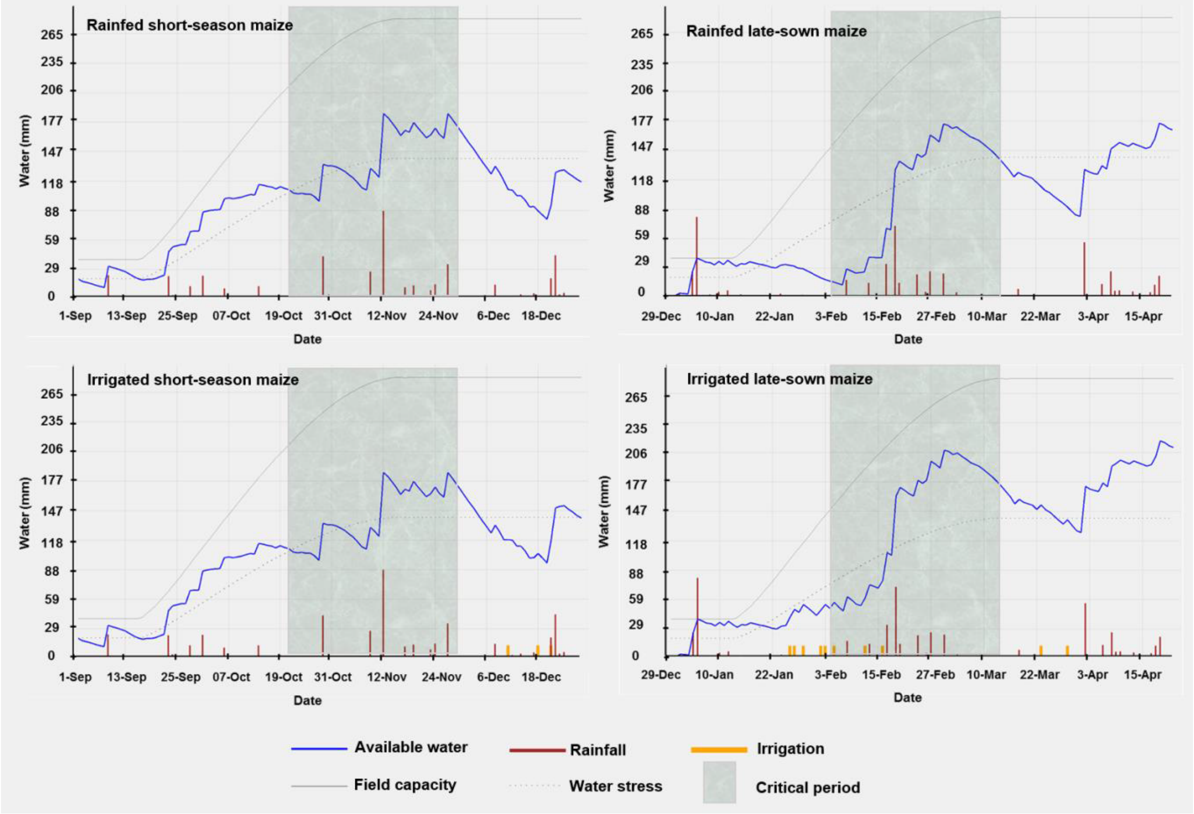

Figure 2: Graphical output of the BAHICU model. Soil water balance of the short-season maize and late-sown maize studied.

Treatment *	Growing cycle (days)	Rainfall-Sowing to harvest (mm)	Irrigation supplies	Irrigation (mm) **	ETc (mm) ***
R_M1	118	443	-	-	424
I_M1			3	36 (8%)	429
R_M2	115	524	-	-	341
I_M2			10	120 (31%)	387
R_MM	233	967	-	-	765
I_MM			13	156 (19%)	816

*R: Rainfed treatment; I: Irrigated treatment.

** Value in parentheses indicates the irrigated percentage of ETc.

***Output of the BAHICU model.

Table 2: Growing season of short-season, late-sown and double crop maizes (M1, M2 and MM).

Treatment*	DM yield (t ha^{-1})	WUE (kg m^{-3})**
R_M1	10.3^{a}	2.43^{a}
I_M1	10.66^{a}	2.48^{a,b}
R_M2	13.52^{b}	3.97^{d,e}
I_M2	16.57^{c}	4.28^{e}
R_MM	23.82	3.11^{b,c}
I_MM	27.23	3.34^{c,d}

^{a,b,c,d,e} Data with different letters indicate significant differences (Tukey, $p < 0.05$).

DM: Dry matter; WUE: Water use efficiency.

*R: Rainfed treatment; I: Irrigated treatment. The number of treatment repetitions (*n*) was six.

**Standard error of the mean: 0.16.

Table 3: DM yield and WUE of short-season, late-sown and double crop maizes (M1, M2 and MM).

to winter crop consumption. The highest forage production obtained in this study (27.23 t ha^{-1}) was lower than that obtained by Camarasa et al. [22] in a double crop of irrigated maize silage in Pergamino (34.2 t ha^{-1}), which could be the productive potential of the zone.

Relationship between yield and ETc

Water stress due to the absence of rain or irrigation reduces the growth of maize leaves and increases the senescence of the older leaves, thus decreasing the biomass production rate. Maize is considered more sensitive to water stress than sorghum or wheat; its highly determinate nature makes it difficult to compensate the lost productivity after the stress period has passed [23]. Although the number of data analyzed in this study was limited, the range of data was wide, so it was possible to determine the relationship between DM yield and maize ETc (Figure 3). However, the degree of fit found (R^2: 0.82) was higher than that found by Amaducci et al. [4], who obtained a significant linear regression between maize aboveground biomass and ETc with a R^2 value of 0.5. In wheat, Dardanelli et al. [19] found relationships between aboveground

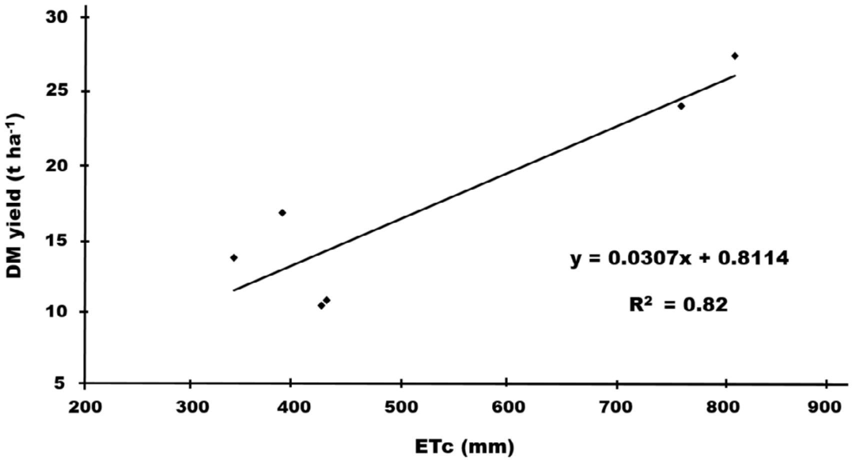

Figure 3: Relationship between forage yield and evapotranspiration of the crop (ETc) of the irrigated and rain fed short-season, late-sown and double crop maizes.

Preceding crop (*n*)	Pl ha^{-1}_5/10	Pl ha^{-1}_28/12	Plant height (m)	DM percentage (%)	DM yield (t ha^{-1})
Ryegrass (6)	87927^a	81731^a	2.31^a	25.95^a	9.62^a
Oat (6)	101353^a	99359^a	2.51^b	26.37^a	11.34^b
SEM	5229	6538	0.03	0.54	0.36

^{a,b}Data with different letters indicate significant differences (Tukey, $p < 0.05$).

Pl ha^{-1}_5/10: Plants per hectare on October 5;

Pl ha^{-1}_28/12: Plants per hectare on December 28.

SEM: Standard error of the mean.

Table 4: Results of short-season maize according to the preceding winter forage crop.

biomass and ETc, with R^2 values of 0.98 and 0.92 in different localities of Argentine Pampa.

As the maize is a crop with determinate growth, it is feasible to expect greater efficiency when irrigating only during the most sensitive phenological stages of the crop. Farré and Faci [24] reported that it is possible to maintain relatively high yields of maize if the water deficit is limited to periods other than around flowering stage. In the present study, biomass production of rain fed M2 had a good recovery after rainfall in the second half of the critical period (Figure 2). Although there was a significant difference in yield between the irrigated and rain fed M2 treatments, the difference would have been greater if it had not rained in the critical period. This suggests the possibility of applying the deficit irrigation strategy, limiting the use of irrigation only to the crop critical period, which would allow reducing the irrigated water that degrades the soil. Irrigation water supply mainly at the time of greatest crop sensitivity to water deficit could result in a higher IWUE. In a study carried out in the south of Santa Fe province (Argentina), maize presented the highest IWUE after measuring yields in rain fed and irrigated wheat, maize and soybean during four growing seasons [25]. An optimized regulated deficit irrigation may increase maize yield up to 20% compared with a constant deficit irrigation through growth stages in a semi-arid environment [26]. Therefore, the use of maize critical period and deficit irrigation strategy could be a better alternative than the single use of the water balance methodology to reduce the risk of soil solidification in the study area.

Short-season maize

Maize forage production was higher when the preceding winter crop was oat than when it was ryegrass (Table 4). Only the plant height showed a significant difference in relation to the different maize production. However, on October 5 and December 28, a higher plant density was observed after oat. Therefore, the higher maize yield over oat was due to a higher plant height (0.2 m) and a possible higher plant density. The forage DM percentage was low for its conservation (approximately 26%), which shows that the harvest was done early. It is widely accepted that the optimal harvest time for silage maize is when the plant DM content is around 35% [27,28]. At that time, an adequate compaction and enough water soluble carbohydrates are obtained to assure good forage conservation. If the maize harvest is made with a DM content lower than 30%, the concentration of water soluble carbohydrates will be high and nutrients may leach due to the high water content [29].

Treatment	Plant height (m)	DM percentage (%)
R_M2* (*n* : 6)	2.23^a	42^a
I_M2* (*n* : 6)	2.48^b	34^b
SEM	0.03	0.81

Data with different letters indicate significant differences (Tukey, $p < 0.05$).

*R: Rainfed treatment; I: Irrigated treatment.

SEM: Standard error of the mean.

Table 5: Plant height and dry matter (DM) percentage of late-sown maize (M2).

Late-sown maize

M2 yield did not differ according to the preceding winter crop (data not shown). Therefore, the influence of the winter forage was lost in the second maize. Plant height was different between the irrigated and rainfed M2 treatments (approximately 0.25 m) (Table 5). Consequently, as in M1, a higher forage yield was related to a higher plant height. After comparing three silage maize hybrids of different growth cycles, Scheneiter et al. [30] observed a greater DM production when the vegetative cycle was longer and the plant height was higher. In the present study, the DM percentage was different between the irrigated and rain fed M2 treatments. Irrigated M2 presented an optimal DM percentage for silage conservation (34%). However, DM percentage was high under rain fed M2 (42%), compromising the silage quality because of possible difficulties in compaction. A maize silage made with 45% of DM worsens its aerobic stability and leads to a greater loss of DM respect to silages made with 25 and 35% of DM [31]. Therefore, considering the same harvest time for irrigated and rain fed M2, irrigation influenced yield but also determined a different silage quality. Possibly, when irrigation influences the silage maize yield, the harvest time should be changed, accelerating the harvest under rain fed conditions and delaying it under irrigation conditions.

Conclusion

The use of the BAHICU software allowed comparing the WUE of the maizes analyzed and knowing that the line of crop water stress was not reached by the irrigated treatments. Irrigation incorporation influenced the yield but not the WUE. Since irrigated water had no effect on the crop cycle of the first maize, the rain fed treatment prevented the entry of Na to the soil and allowed saving costs due to the lower seed requirement and the non-use of the irrigation system. However, the production of a double crop of maize without irrigation in the study area can be very risky, a risk enhanced when preceded by a winter crop. Since the results of this study come from only one season, more validation is necessary. Further studies should assess the maximization of IWUE under the deficit irrigation strategy, applying irrigation water mainly in the critical period of the crop. Although maximum maize yields are generally obtained only with high irrigation sheets, perhaps irrigation in the study area should be used only to obtain stability in yields due to the water quality and soil degradation risk.

Acknowledgments

We thank Pacente E, Mattera J, Camarsa J, Barletta P Codaro A for their help in the field work. We are grateful to Andriani J for his valuable collaboration and training in the use of the BAHICU software. We also thank Mattera J for his suggestions to improve the manuscript and Ferreyra A, Cirilo A, Llorente R, Severini A and Beribe MJ for their contributions. The research was performed in the frame of PNAGUA 1133042 and PNPA 1126073 INTA projects.

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