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Irrigation and nitrogen effects on seed cotton yield, water productivity and yield response factor in semi-arid environment

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Abstract

The study of irrigation technologies for growing cotton in the Brazilian northeastern semi-arid region is very important to better understand the water-soil-plant-atmosphere interactions. Modern varieties are adapted to these conditions, reaching their maximum yield potential. In irrigated areas, application of nitrogen fertilizer is also necessary to keep up cotton to its maximum productive potential. The ideal conditions should be offered to the crop, where this knowledge is still scarce in this region. The objective of this work was to evaluate the effects of water levels and N rates on growth and yield of cotton ('BRS 286') in semi-arid condition. The experiment consisted of a factorial combination of four irrigation levels [40, 70, 100, and 130% ET_c (crop evapotranspiration)] and four N rates (0, 70, 140, and 210 kg N ha^{-1}), in a randomized complete block design with four replicates. Seed cotton yield and growth parameters were determined at harvest. Irrigation and N fertilization influenced growth parameters and cotton yield. The highest seed cotton yield (5707 kg ha^{-1}) was reached with 130% ET_c and 210 kg N ha^{-1}. The maximum N agronomic efficiency was achieved at 140 kg N ha^{-1}. The treatment 70% ET_c showed significant benefits in terms of irrigation water savings, with WUE 0.587, indicating the possibility of use to deficit irrigation under water scarcity conditions. The seasonal yield response factor (K_y) was 0.70, demonstrating that the 'BRS 286' was water stress-tolerant crop.

Keywords: Evapotranspiration; *Gossypium hirsutum*; plant nutrient; water deficit; yield response factor.
Abbreviations: WUE_water use efficiency; ET_c_crop evapotranspiration; N_nitrogen; K_y_yield response factor.

Introduction

In the semi-arid region of Northern Brazil, drought stress is caused by low rainfall or poor distribution of rain during the crop growing cycle, affecting3 crop yields. Therefore, irrigation is the most important factor in crop production for semi-arid regions throughout dry season (Dagdelen et al., 2006). It is one of the techniques used to ensure high yield (Aujla et al., 2005; Dagdelen et al., 2009). Besides, different products are provided for different purposes with cotton cultivation, generating income by many goods as fiber (textile industry), seed (for biodiesel, cooking oil, etc.) and bran (for animal feed), moving activities from different sectors of the economy.

In many regions, the water resources are scarce and have declined because of their use in areas like urbanization and industrialization. According to Payero et al. (2006), this situation may force farmers from many regions of the world to consider other options to keep the optimization of crop yield and water use efficiency through irrigation water deficit, which is based on performing the irrigation with less water than required throughout the whole growing season or during the phases, in which the culture is less sensitive to water stress, allowing great economic return (Zegbe-Domingues et al., 2003).

Crop productivity under irrigated agriculture is usually higher than rainfed farming. Like most major field crops, cotton (*Gossypium hirsutum* L.) production is adversely affected by water stress (Pettigrew, 2004; Dagdelen et al., 2006; Basal et al., 2009). Insufficient soil water content is caused by water stress during the sensitive growth stages, such as the peak flowering and fruit-setting stages, which can lead to a reduced number of fruiting positions, boll shedding, and poorly developed bolls (Aujla et al., 2005). On the other hand, over-irrigation of cotton can cause undesired excessive vegetative growth, which may reduce cotton yields (Karam et al., 2006). Knowing the optimum water requirement of irrigated cotton is essential to achieving a balance between vegetative and reproductive growth in cotton. Basal et al. (2009) reported that deficit drip irrigation of cotton at 75% of full irrigation requirements did not decrease seed cotton yield or yield components for two growing seasons. The deficit drip irrigation was designated to receive 100% replenishment of soil water depletion, which was defined as the difference between the depth of water held in the root zone at field capacity and the depth of water actually held in the root zone at the time of irrigation. However, Dagdelen et al. (2006) reported that, after irrigating cotton at five different rates (full irrigation and four deficit rates) for two seasons, the total irrigation depth ranged from 257 to 867 mm and the highest yield was obtained with the highest irrigation level.

A properly managed irrigation improves the water use efficiency (WUE) and nutrient uptake. Although the high costs to initial investments are a disadvantage, the profits can be quickly recovered with appropriated crop fertilization. So, fertilization should be done only with the quantities required by crop, avoiding deficits or waste. To reach this goal, high yields must be achieved in order to obtain the maximum economic yield of the crop.

Despite the fact that responses to fertilization under irrigation are differentiated from rainfed conditions, even considering the importance of cotton for semi-arid, there is a lack of research based on irrigation and fertilization management in Brazilian semi-arid. This region has shallow soils with low organic matter content. Like most crops, cotton requires N for normal growth and development, then farmers greatly rely on N fertilizers. Several studies have been done to determine the effect of N on cotton (Ali et al., 2003). Seilsepour and Rashidi, (2011) found that seed cotton yield significantly enhanced by increasing N application rate. The highest seed cotton yield (4363 kg ha^{-1}) was recorded in a case of 200 kg N ha^{-1} treatment and there was no significant difference between 200 and 300 kg N ha^{-1} treatments.

Therefore, this study evaluates different levels of water supply and rates of N to semi-arid climate and local soil type conditions, helping to reach highest cotton yield with more efficient nutrient utilization and reducing N environmental impacts and water waste. The objective of this study was to evaluate the effect of N rates applied on different water levels on cotton yield, plant growth, and yield components for 'BRS-286' cotton in Brazilian semi-arid region.

Results and Discussion

Irrigation pattern

The total water applied to each treatment was 414, 659, 904, and 1150 mm at 2010 and 408, 724, 1034, and 1342 mm at 2011, considering treatments 40%, 70%, 100%, and 130% ET_c, respectively.

Agronomic characteristics

Relationship between the mean squares of the residue of 2 yr was less than 7. So, it was decided for the conjoint analysis of data (Cruz and Carneiro, 2013). The results indicated that the interaction between irrigation levels and N rates was significant only at the 5% probability only for cotton yield (Table 3). For other characteristics such as plant height and average weight of bolls, the effect of irrigation levels and N rates was not significant. However, isolated effects of irrigation levels and N rates were significant ($p \leq 0.01$) (Table 3).

Seed cotton yield

A significant interaction for seed cotton yield and N rates with differentiated effects as a function of water levels was observed (Fig. 2 and Table 4). There was significant effect of N rates just to 70% and 100% ET_c of treatments, with linear and quadratic models, respectively. Extreme irrigation levels (40% and 130% ET_c) did not show significant effect to N rates. These results can be explained by the fact of underwater deficit (40% ET_c), in which the N was not absorbed in the sufficient amount required for ideal growth. Thus, despite being applied, it was speculated that N was lost by volatilization. In contrast, for 130% ET_c treatment, N was supposedly lost by leaching, which may have occurred due to high volume of water applied.

Considering 70% ET_c irrigation level, the higher cotton yield (4584 kg ha^{-1}) was achieved at a dose of 210 kg N ha^{-1} (Fig. 2 and Table 4), whereas for the 100% ET_c, the higher yield (5251 kg ha^{-1}) was achieved at a dose of 103 kg N ha^{-1} (Fig. 2). Thus, we noted that the application of N modified the efficiency of water use for 70 and 100% ET_c, and not changed for the irrigation levels of 40% and 130% ET_c, (Fig. 2). The Fig 2. shows the statistically significant regression adjustment, which relates the yield and N rates just for treatments of 70 and 100% of ET_c. For extreme water levels (40% and 130% ET_c), the greatest cotton yields were 2311 and 5707 kg ha^{-1}, respectively, with the best N dose (210 kg N ha^{-1}) (Table 4). Singh et al. (2010) assessing different N doses and irrigation, concluded that N fertilization changed the efficiency of water use in cotton at all irrigation levels, which agrees in part with the results presented here. Vyas et al. (1995) reported that the increased rate of nitrogen fertilization enhanced the soil moisture extraction and improved the water use in mustard.

Seilsepour and Rashidi (2011) found that cotton yield increases as the applied N doses are higher, obtaining the highest yield (4363 kg ha^{-1}) at the dose of 200 kg N ha^{-1}. Singh et al. (2010) studied different N levels on irrigated cotton, and found an increase of 27% in yield when compared to similar doses of 200 and 80 kg N ha^{-1}. Aujla et al. (2005) remarked that lower N doses, applied in coverage, result in lower productivity regardless of the level of irrigation. The soil water content under ideal condition is important to promote N uptake by plants. So, the correct water management is essential to avoid waste of inputs. Regarding the water treatments, cotton yield response was linear to the increase in irrigation levels for all N rates applied (Fig. 3). The highest yield was obtained with application of highest nitrogen doses (140 and 210 kg ha^{-1}).

Considering the fully water supplied plants (water replacement ≥ 100% ETc), cotton yield raised with increasing amount of applied N. So, yield in the treatment of 210 kg ha^{-1} N was greater than that obtained with the N dose of 140 kg ha^{-1} (Fig. 3). Instead, plants were not able to absorb all the applied N under minor irrigation levels. Therefore, the highest productivity was observed at the 140 kg ha^{-1} N rate, and probably the nitrogen surplus application was not absorbed. The lowest yield increment resulted from the treatment without N application.

Other authors such as Cetin and Bilgel (2002), Jalota et al. (2006) and Onder et al. (2009) also reported cotton yield increment when water depth is enlarged. When a bigger deficit enforced, e.g. equivalent to 40% ET_c irrigation level, seed cotton yield decreased drastically to 2294 kg ha^{-1}, which corresponds to 57% of reduction compared to maximum yield (5342 kg ha^{-1}). These results agreed with those obtained by Dagdelen et al. (2006), using irrigation levels in a range of 867 to 257 mm per cycle and verified a decrease in cotton yield from 5490 to 1780 kg ha^{-1}. Similar effects were observed by Bezerra et al. (2008), who achieved the best cotton yield at 120% ET_c. The water supply through vegetative growth and fructification stages is strongly related with cotton yield. Proper applications of deficit irrigation can guarantee significant savings in irrigation water but, the plant's behavior must be observed throughout the growing season to ensure the best economic return and yield. Sometimes, the choice of irrigation method can save water, even keeping the full replacement of crop evapotranspiration (Aujla et al., 2005).

Under semi-arid climate conditions, Brazilian cotton cultivars responded to irrigation above 100% ET_c for yield. The maximum cotton yield was obtained when water was applied at 130% ET_c (Fig. 2 and 3). Deficit irrigation causes considerable decrease in cotton yield. Singh et al. (2010) reported water deficit from 100% ET_c to 50% ET_c decreasing cotton yield from approximately 50%. Cetin and Bilgel (2002), presumed that conditions such as more sunshine and nutrients, relatively constant soil water content would produce more assimilation products. This means more boll number per plant and total yield.

Table 1. Chemical characteristics of the soil, collected at three depths in the experimental field, located in Apodi, Brazil, 2010.

Depth	pH (water)	OM	P	Na^+	K^+	Ca^{2+}	Mg^{2+}	H + Al	CEC	BS
cm		g kg^{-1}	mg kg^{-1}	——— cmol$_c$ dm^{-3} ———						
0-20	6.20	3.92	23.69	0.83	0.69	5.00	2.40	2.47	11.40	8.92
20-40	6.10	2.40	20.92	0.63	0.54	5.80	2.90	2.14	12.01	9.87
40-60	6.20	2.40	20.92	0.53	0.40	6.50	2.50	1.82	11.74	9.93

(MO) - organic matter; CEC - cation exchange capacity, BS – Base Sum.

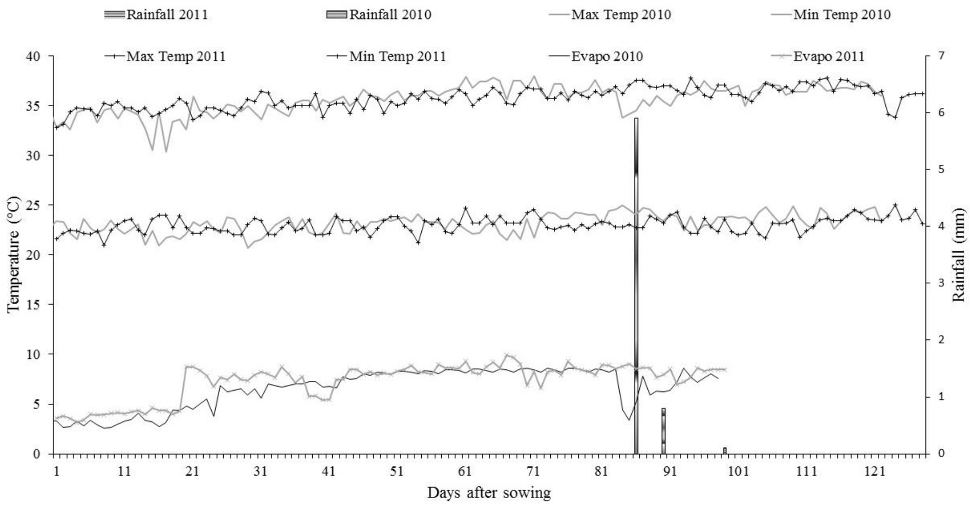

Fig 1. Weather parameters recorded during the crop cycle, Apodi, Brazil.

Table 2. Data and agronomic parameters of irrigation throughout the 2010 and 2011 cotton ('BRS 286') growth seasons, Apodi, Brazil.

Variable	2010	2011
Sowing date	23 July	24 July
First irrigation	24 July	24 July
Start irrigation treatments	17 August	12 August
Last irrigation	6 November (100 DAE)	7 November (97 DAE)
Harvest	29 November (123 DAE)	4 December (129 DAE)
Crop cycle, d	129	135
Total rainfall, mm	7.9	0.0
Cumulative growing degree days (base temperature 15.6 °C), °C	1698	1712

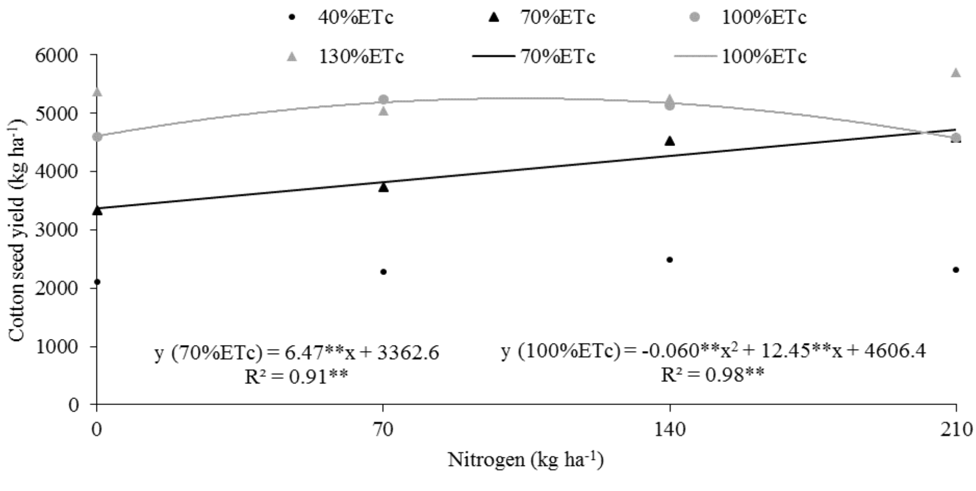

Fig 2. Effect of N fertilization levels on seed cotton yield in function of irrigation levels (2 yr pooled data).

Table 3. Effect of deficit irrigation and N on seed cotton yield and growing data (pooled data), Apodi, Brazil.

ANOVA	Pr > Fc Seed cotton yield	Plant height	weight of bolls
	kg ha^{-1}	cm	g
Irrigation (I)	< 0.01**	< 0.01**	< 0.01**
Nitrogen (N)	< 0.01**	< 0.01**	< 0.01**
I × N	< 0.05*	0.13ns	0.18ns
Averages			
Irrigation			
40% ET$_c$	2294	54.5	4.95
70% ET$_c$	4042	74.1	5.49
100% ET$_c$	4882	82.4	5.25
130% ET$_c$	5342	97.8	5.62
LSD	321,06*	5,37*	0,21*
Nitrogen			
0 kg ha^{-1}	3850	69.6	5.04
70 kg ha^{-1}	4066	80.2	5.21
140 kg ha^{-1}	4347	79.2	5.51
210 kg ha^{-1}	4297	79.8	5.50
LSD	383,52*	5,52*	0,13*

Pr>Fc – Indicate the minimum significance level for the variables to become significant. *****, ****** Significant at the 0.01 and 0.05 probability levels, respectively, according to F test; ns: nonsignificant according to F test (p ≤ 0.05).

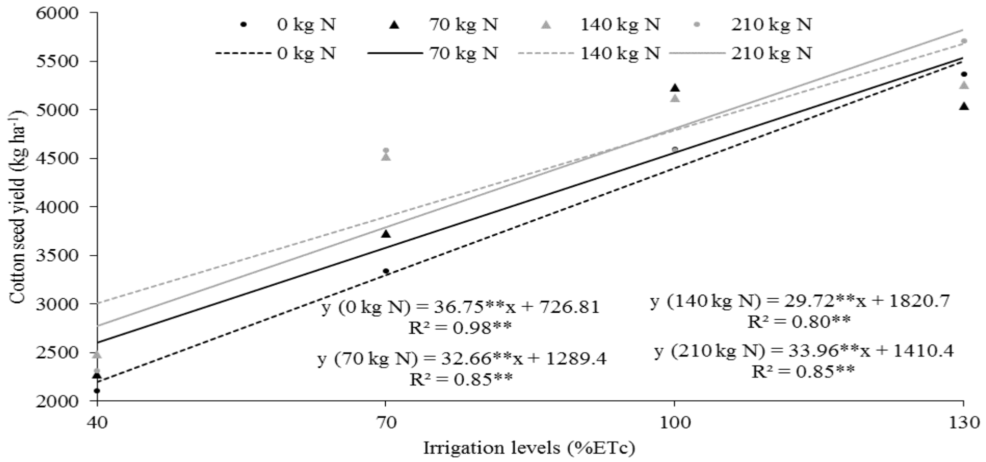

Fig 3. Effect of irrigation levels on seed cotton yield in function of N fertilization levels (2 yr pooled data).

In addition, Morais et al. (2008) reported that water is one of the most essential factors for agricultural production, since its lack or excess considerably affects crop yields, making it necessary to manage water rationally to improve the production.

Yield attributes

The effect of N rates and irrigation on plant height and bolls average weight was significant, with no interaction between the variables (Table 3). Considering the bolls average weight, the effect was linear for both N rate and irrigation levels (Fig. 4A and B). Comparing doses 0 and 210 kg N ha^{-1}, an 8% decrease was observed in the average weight, while comparing 40% ET$_c$ with 130% ET$_c$, there was a decrease of 12% in boll average weight (Table 3). The increased N supply might have helped in fulfilling the optimum nitrogen requirement of the crop *vis-à-vis* in creating proper environment in crop root zone for better growth and nutrient uptake. Singh et al. (2010), studied four different N rates for cotton, found that nitrogen fertilization caused a significant increase in the bolls weight. In this study, boll weight in the highest treatment was found 16.6% higher than the lowest N rate, which were 200 kg N ha^{-1} and 80 kg ha^{-1}, respectively. In another study, Seilsepour and Rashidi (2011) also observed that boll weight was improved by increasing N doses up to 200 kg N ha^{-1}. Regarding irrigation, Singh et al. (2010) found significant differences in bolls weight when irrigation was lower than 80% ET$_c$, compared to full irrigation, corroborating our results.

Nitrogen fertilization increases height of cotton plants in the linear rates to N and irrigations levels (Fig. 5A and B). Plant height was 24% lower, if compared to the lower and higher levels of nitrogen and irrigation factors, respectively (Table 3). Fritschi et al. (2003) obtained significant differences in plant height with N rates of 0, 56, and 168 kg ha^{-1}, finding that cotton height was directly related to application of N dose. So, the higher dose provided the higher plant height. Some researches fulfilled in the Brazilian savanna, indicated similar responses for cotton with lower doses of N reaching from 130 up to 150 kg N ha^{-1}, considering similar climate and temperatures (Lamas and Staut, 2005; Teixeira et al., 2008). Hussein et al. (2011) observed significant differences among irrigation level treatments on cotton height, with plant height in a range from 56.8 to 105.5 cm.

Table 4. Interaction effect of irrigation levels and N on seed cotton yield, Apodi, Brazil (2 yr pooled data).

Irrigation levels	Seed cotton yield				
	Nitrogen doses (kg ha^{-1})				
	0	70	140	210	LSD
40% ET_c	2107	2273	2486	2311	659,02*
70% ET_c	3339	3724	4520	4584	659,02*
100% ET_c	4591	5229	5125	4585	659,02*
130% ET_c	5365	5038	5257	5707	659,02*
LSD	642,03*	642,03*	642,03*	642,03*	

*Significant at the 0.05 probability level.

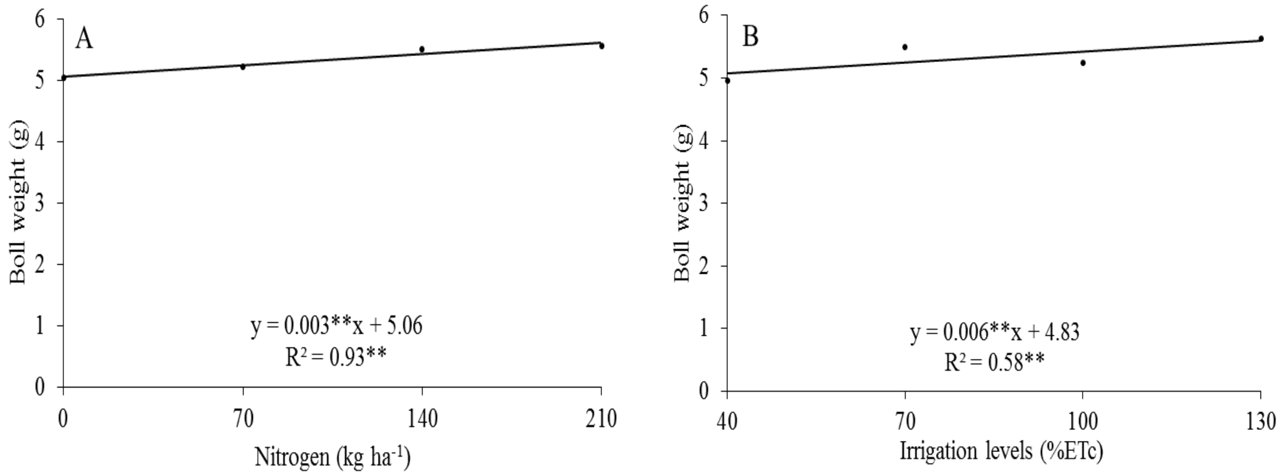

Fig 4. Effect of N fertilization (A) and irrigation levels (B) on weight of boll, in irrigated semi-arid Brazilian cotton (2 yr pooled data).

Table 5. Agronomic efficiency of N affected by different doses of N applied in coverage and water use efficiency (WUE) affected by irrigation depths (2 yr pooled data).

Agronomic efficiency of N (kg cotton/kg N)		
70 kg N ha^{-1}	140 kg N ha^{-1}	210 kg N ha^{-1}
5.2a	5.6a	2.6b

Water use efficiency (WUE) (kg m^{-3})			
40% ET_c	70% ET_c	100% ET_c	130% ET_c
0.56ab	0.59a	0.51bc	0.43c

Mean followed by the same letter does not differ significantly according to Tukey's test ($p \leq 0.05$).

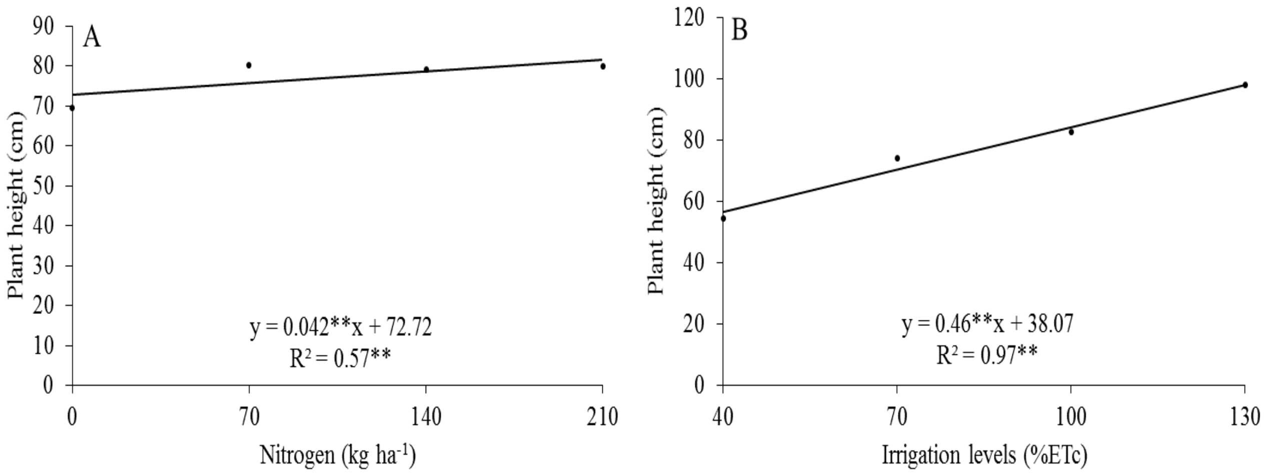

Fig 5. Effect of N fertilization (A) and irrigation levels (B) on plant height in irrigated semi-arid Brazilian cotton (2 yr pooled data).

Table 6. Relation between the decrease in relative water depth (*1 - (La/Lm)*) and decrease in relative yield (*1 - (Ya/Ym)*) and yield response factor (K_y) for the cotton 'BRS 286' irrigated by sprinkler in Brazilian semi-arid conditions (2 yr pooled data).

Irrigation levels	Yield	Depth	*Ya/Ym*	*La/Lm*	1 - (*Ya/Ym*)	1-(*La/Lm*)	K_y
	kg ha^{-1}	mm					
40% ET_c	2294	411	0.57	0.33	0.57	0.69	0.82
70% ET_c	4042	691	0.61	0.55	0.24	0.46	0.53
100% ET_c	4882	969	0.91	0.78	0.09	0.23	0.37
130% ET_c	5342	1247	1.00	1.00	0.00	0.00	0.00

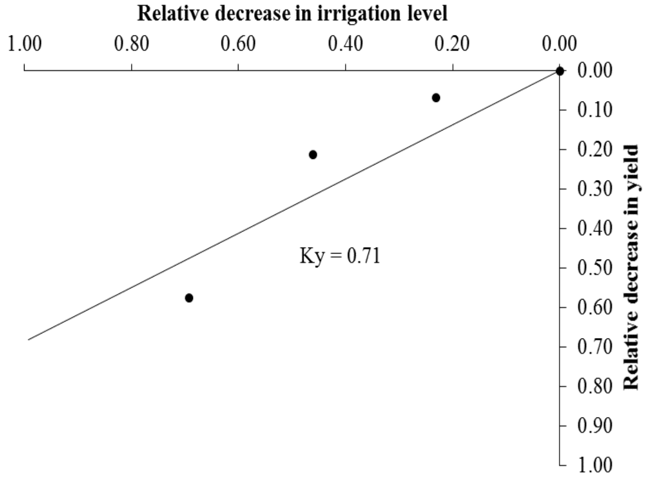

Fig 6. Relative decrease of seed cotton yield in Brazilian semi-arid region in response to relative decrease in irrigation level (2 yr pooled data).

Looking at the results of seed cotton yield and plant height, we noted that there was a strong positive correlation between seed cotton yield and plant height.

Agronomic N use efficiency

The values of the N use efficiency showed that among different N doses, the highest efficiency was found at 70 and 140 kg N ha^{-1} doses. It demonstrates that, although the cotton yield can respond until the maximal dose applied (210 kg N ha^{-1}); this dose has lower use efficiency (Table 5). Devkota-Wasti (2011), in a study with irrigated cotton in the arid region of Uzbekistan, found that the N agronomic efficiency of 11.8 and 7.85 kg cotton kg^{-1} N was achieved upon application of of 125 and 250 kg N ha^{-1} doses respectively. In their study, the highest efficiency was obtained at the dose of 125 kg N ha^{-1}, agreeing with the results of this work. Highest N agronomic efficiency at 140 kg N ha^{-1} level indicated that there was balanced increase in vegetative and reproductive fractions in this level, resulting in higher seed cotton yield (Fritschi et al., 2003). On the other hand, excessive N application (210 kg N ha^{-1}) may shift the balance between vegetative and reproductive growth towards excessive vegetative development; thus, delaying crop maturity and reducing cotton yield. Considering an economic evaluation, these results should be taken into account due to high price of N fertilizer. Furthermore, the waste of N with high doses leads to environmental injuries especially in irrigated conditions.

Water productivity

Considering that rainfall (7.9 and 0.0 mm in 2010 and 2011 years, respectively) (Table 2) was not significant during the cotton growing seasons, the crop water consumption predominantly depended on the amount of water supplied by irrigation on the treatment plots. The WUE was significantly influenced by irrigation level (Table 5). The excess irrigation (130% ET_c) provided the highest yield; however, it was not efficient, since it presented the lowest WUE (0.43 kg m^{-3}) (Table 5).

Although, water stress in deficit irrigation treatments resulted in lower yields as compared to the full and excess irrigation treatments, the better efficiency of water was achieved by deficit irrigation at 70% ET_c, where WUE was 0.59 kg m^{-3} and cotton yield was 4042 kg ha^{-1}. Without significant difference to deficit irrigation (40% ET_c), the WUE was registered as 0.56 kg m^{-3}. Despite the difference of yield recorded at 20.8%, the full irrigation (100% ET_c), in which cotton yield reached 4882 kg ha^{-1}, did not show the better WUE, being just 0.51 kg m^{-3} and less than the deficit irrigation at 40% ET_c (Table 5). It is clear that under these experimental conditions, WUE is affected with change in water quantity applied through. Analogous results were related by other authors. Nalayini et al. (2006) found that cotton yield irrigated with 80% ET_c was equivalent to 100% ET_c; therefore, the WUE for treatment with 80% ET_c was higher. Onder et al. (2009), working on drip-irrigated of cotton in Turkey, obtained WUE of 0.81 and 0.77 for the irrigations, considering 50% and 75% of the evaporation of class A. These great results were obtained probably due to greater efficiency of drip irrigation system over sprinkler system.

Bronson et al. (2001) reported that, for the southern USA, agricultural production is often optimized with irrigation around 70% ET_c, since irrigation at 100% ET_c can result in excessive vegetative growth and delayed crop maturation. Singh et al. (2010), working with deficit irrigation, found significant differences in WUE for different irrigation levels, varying from 0.54 to 0.65 kg m^{-3} for levels of 100% ET_c and 50% ET_c, respectively. Other study carried out by Dagdelen et al. (2009) also observed a greater WUE (1.46 kg m^{-3}) when using 25% ET_c, while for 100% ET_c the WUE was 0.81 kg m^{-3}. Basal et al. (2009) found that deficit irrigation maintained high cotton yields with a 25% reduction in irrigation water applied, which resulted in a substantial increase in WUE. According to our results and those reported in the literature, it is observed that under low water availability in semi-arid regions, economic studies must be carried out to determine the irrigation management feasibility in water deficit, since it leads to great savings in water, which can aid in the sustainability of the production system.

Yield water relationship

The crop yield response factor gives an indication of whether the crop is tolerant to water stress or not. A response factor greater than unity indicates that expected relative yield decrease for a given evapotranspiration deficit is proportionately greater than the relative decrease in evapotranspiration (Kirda et al., 1999). When observing irrigations with higher deficits, the factor K_y was 0.53 and 0.82, for the irrigation of 70 and 40% ET_c (Table 6), respectively. Similar to these results, Singh et al. (2010) found K_y as 0.98 and 1.02 for cotton yields in Indian semi-arid regions with irrigation levels of 60% ET_c and 50% ET_c, respectively, and K_y as 0.28 to 90% ET_c irrigation level.

The relationship between decrease in seed cotton yield and reduction in amount of water applied is presented in Fig. 6, which offers a K_y of 0.71 to 'BRS 286' cotton, cultivated in Brazilian semi-arid region. Thus, under these conditions, for each unit decreasing in irrigation level, there is a reduction of 0.71 unit in seed cotton yield for this cultivar. In semi-arid region of Turkey, Dagdelen et al. (2006; 2009) found values of K_y ranging from 0.78 to 0.98. These results demonstrate that cotton is a good choice for cultivation in semi-arid region, for irrigated areas without water limitation using the total recommended water level, or for areas with water scarcity, in which it can pick up the irrigation deficit, e.g., using levels for 70% ET_c as recommended.

For the variety used in this study, the lowest K_y factor value (compared to results obtained by Dagdelen et al. 2009) may be related to greater precocity of cotton BRS 286, since the completed cycle was just 129 and 135 d (Table 2), while the cultivar used by the authors has next cycle lasting 180 d. According to Steduto et al. (2012), the K_y value to cotton can range from 0.46 to 0.99 depending on the time, at which the plant was subjected to drought stress as well as the irrigation system. These results demonstrate that cotton is a good choice for cultivation in semi-arid region. Both for cotton under full irrigation system and deficit irrigation for areas with restricted water availability, cotton can be cultivated with good yield, even saving 30% of water applied, when using irrigation level of 70% ET_c. Some authors like Hussein et al. (2011) claimed that deficit irrigation at around 80% full irrigation had the potential to save water and could be a proper irrigation level for producing cotton in arid areas.

Materials and Methods

Location, soil, and climate

The field experiment was carried out during 2010 and 2011 at the Research Farm and Extension Center of Empresa de Pesquisa Agropecuária do Rio Grande do Norte (EMPARN), located in the Apodi Plateau (5º37'24" S, 37º48'58" W; 130 m), Rio Grande do Norte, Brazil. The mean annual rainfall is 772 mm with very uneven distribution of rain from January to May. Soil of experimental area was classified as eutrophic Cambisol (SiBCS, 2006) or Inceptisol (USDA, 1999), with sandy-clay texture. The average content of sand, clay, and silt were 49%, 45%, and 6%, respectively. Water content at field capacity varied from 11.3 to 27.1% by volume, and wilting point from 6.6 to 17.5%. Soil bulk densities ranged from 1.10 to 1.28 g cm^{-3} and total available soil water of 40 mm for 0-0.6 m soil profile. The soil chemical characteristics are presented in Table 1. Climate is semi-arid tropical and hot with temperature between 23 and 35ºC, and predominance of type BSw'h', according to Köppen's climate classification (Thornthwaite, 1948). The amount of scattered radiation in this region is high, usually more than 3030 h of sunshine annually, while the mean annual evaporation reaches 3215 mm. Additionally, some climatic parameters (rainfall, temperature, humidity, net radiation and wind speed) for the growing seasons of experimental years were recorded in the meteorological observatory located at 400 m from the experimental field (Fig. 1).

Experimental design

The experiments were conducted in a sprinkle irrigation system during the 2010 and 2011 growing seasons at four different levels of irrigation water (40, 70, 100, and 130% of crop evapotranspiration, ET_c), and four N doses (0, 70, 140, and 210 kg N ha^{-1}). We used a factorial design laid out in a randomized complete block design with four replicates. Each plot consisted of six rows with 15 m long, with a total area of 75.6 m^2.

Planting and management practices

Cotton seed BRS-286 cultivar was sowed at 23 July and 24 July in the 2010 and 2011 seasons, respectively. Seeds were distributed to achieve a population density of 10 plants m^{-1} and 0.84 m between rows. Recommended practices were followed to control weeds and pests. Fertilization, except for N, and liming were performed according to the recommendations for the crop based on soil analysis (Table 1).

Nitrogen fertilization

For N rate treatments, half the dose for each treatment was applied at sowing and the remaining fertilizer was applied 30 d after sowing (DAS). Urea was used as N source.

Irrigation

The sprinkler irrigation system with 12 × 15 m of space between nozzles had application intensity of 11 mm h^{-1} and the Christiansen Uniformity Coefficient (CUC) was 85%.
Regarding water levels treatments, they started 19 and 10 days after emergence (DAE) for 2010 and 2011, respectively. The irrigation intervals were determined using the maximum evapotranspiration. Irrigation was performed every 3 days to ensure the moisture replacement when the decreasing of available water in soil reached 60%. Agronomic and irrigation data are shown in Table 2.
The water replacement was calculated according to:

$$L_{irrig} = ET_c / f \quad (1)$$

Where; L_{irrig} (mm) is the amount of irrigation water applied; ET_c (mm) is the cotton evapotranspiration, and f is the application's efficiency.

The crop evapotranspiration was calculated by multiplying the reference evapotranspiration, ET_0 (mm d^{-1}), by a crop coefficient Kc (dimensionless) according to the equation proposed by Allen et al. (1998):

$$ET_c = ET_0 \times K_c \quad (2)$$

The reference evapotranspiration ET_0 was calculated by FAO Penman-Monteith method (Allen et al., 1998); and K_c coefficient was obtained for four crop phenological stages by Bezerra et al. (2010), which estimated the K_c for cotton:

$$K_c = -0.00006 \times DAE^2 + 0.011 \times DAE + 0.5703 \quad (3)$$

Where; DAE are the number of days after the emergence of plants.

Traits measured

In order to evaluate the sensitivity of cotton yield to water deficit, the yield response factor K_y was calculated. The K_y is defined as the ratio of relative yield decrease to relative evapotranspiration (ET_c) decrease. The yield response factor was computed by using the Doorenbos and Kassam (1979) equation rearranged as:

$$1-(Y_a/Y_m) = K_y(1-L_a/L_m) \quad (4)$$

Where; Y_a (kg ha^{-1}) is the actual yield of specific irrigation treatment; Y_m (kg ha^{-1}) is the maximum crop yield; 1 - (Y_a/Y_m) (dimensionless) is the relative decrease of yield; L_a (mm) is the actual amount of water to obtain Y_a; L_m (mm) is the maximum amount of water applied; and 1 – (L_a/L_m) (dimensionless) is the relative water decrease. The K_y is an yield decrease to relative reduction of water applied, and is dimensionless.

To evaluate how each kilogram of N applied influences on yield, it was determined the agronomic efficiency of N, which is calculated from:

$$EA_N = Y_{ap} - Y_0 / N_{ap} \quad (5)$$

Where; EA_N is agronomic efficiency of N (kg cotton kg^{-1} N); Y_{ap} is yield by the dose of N applied for treatment, N_{ap} (kg ha^{-1}), Y_0 is yield for treatment without N (dose 0), and N_{ap} is the N rate applied (kg ha^{-1}) to reach Y_{ap} yield. Seed cotton yield and some growth parameters as plant height and boll weight were evaluated at harvest time.

Statistical analysis

All parameters were subjected to ANOVA, average test and regression using the statistical software Sisvar 5.3 (Ferreira, 2011). Mean were compared using least significant differences (LSD) at 5% probability levels. Linear regression analysis was performed to determine the relationship of seed cotton yield, plant height, and boll weight with N and irrigation levels.

Conclusions

The highest agronomic efficiency for N was achieved with application of 70 and 140 kg N ha^{-1}. The water use efficiency was highest with the irrigation treatments equivalents to 40% ET_c and 70% ET_c. However, the highest seed cotton yield (5707 kg ha^{-1}) was achieved when irrigated at 130% ETc, and 210 kg N ha^{-1} treatment. According to the K_y value of 0.71, 'BRS 286' cotton has proved to be a water stress tolerant crop. Also, a full irrigation treatment could be used for semi-arid climatic conditions with no water shortage conditions. Results of this experiment indicate that only marginal yield reductions were recorded by watering at 70% deficit irrigation, saving 30% of irrigation water. Consequently, the WUE was improved, indicating a definitive advantage in adopting deficit irrigation for cotton production for semi-arid climatic conditions with water shortage conditions.

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