Sugarcane Responses to Irrigation and Nitrogen in Semiarid South Texas

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ABSTRACT

Water and N are often limiting factors for sugarcane (*Saccharum* spp.) production. This study was conducted to determine the effect of different levels of water availability on sugarcane growth, yield, and responses to N application, and also to evaluate the effectiveness of alternative N application methods. Three irrigation levels (20% below crop evapotranspiration [ETc], full ETc replacement, and 20% above ETc), four N application rates (0, 60, 120, and 180 kg N ha^{-1}), and three fertilizer application methods (through-the-drip, sidedress, and knifed into the middle of the plant stool or 'stool splitter') were evaluated on sugarcane for four successive crops. Increasing water application in this study resulted in increased growth but no significant differences in cane or sugar yields. Water use efficiency therefore increased as water application declined, averaging 8.4 Mg cane mL^{-1} of water, including both rainfall and irrigation. Nitrogen application through the drip system resulted in linear increases in cane yield every year up to the highest rate applied of 180 kg N ha^{-1}, averaging 74 kg per kg N applied in the plant through second ratoon crops, and 192 kg per kg N applied in the third ratoon crop. Over the 4 yr this study was conducted, N application through the drip system produced yields which were not significantly different from the sidedress application, while the 'stool splitter' application method was consistently the most inefficient N fertilizer application method. This work shows that maximum cane and sugar yields can be obtained, and responses to rate of N application are not reduced at less than optimum soil moisture conditions.

Sugarcane is an important crop for the tropical and subtropical world, and is being used to produce sugar as well as ethanol. Limited water resources restrict increasing the amount of sugarcane grown in many regions throughout the world because sugarcane requires substantial amounts of water (Martin et al., 2007). Therefore it is important to know how much water is necessary to produce maximum yields so that available irrigation water can be used as efficiently as possible.

Crop water use is typically calculated using some estimate of reference evapotranspiration (ETo) which is a function of climatic conditions that can be measured. Subsequently a crop coefficient (Kc) is applied which reflects the effect of crop, stage of growth, and other local variables. Coefficients have been developed for most crops, but it is necessary for the coefficient curve to be calibrated for local conditions (Allen et al., 1998). Sugarcane crop coefficients were developed for use with ETo calculated using the Jensen-Haise formula (Jensen and Haise, 1963) for South Texas conditions by Salinas and Namken (1977), and for use with pan evaporation by Enciso and Wiedenfeld (2005). Crop coefficients for sugarcane using Pennman-Monteith ETo (Walter et al., 2000) have been established from various sources (Allen et al., 1998), and reaffirmed using the Bowen ratio energy balance by Inman-Bamber and McGlinchey (2003). While this approach accurately indicates crop water use under optimum soil water conditions, it does not reveal how crop yields will be affected below or above optimum moisture levels.

Several studies have been conducted to determine the effect of different levels of water application on sugarcane. In a 3 yr flood-irrigated study, when water inputs were reduced by 25 and 43%, yield reductions averaged 30 and 53%, respectively (Wiedenfeld, 1995). Smaller variations in water inputs of <20%, however, have not always produced significant differences in sugarcane yields (Wiedenfeld, 2004). Evaluations of water stress during different stages of plant growth have indicated that while the effect of water stress may be similar during all growth stages (Wiedenfeld, 2000), sugarcane has the capacity to compensate for brief periods or water stress given enough time for growth, therefore the impact of stress later in the growth cycle may be more severe (Inman-Bamber, 2004; Robertson et al., 1999).

Nitrogen is the primary nutrient limiting sugarcane production. Numerous studies have documented the need for N fertilizer application (Thomas et al., 1985). Nitrogen requirements by sugarcane in South Texas have been found to be very low in the plant crop and increase in each successive crop to a maximum of 160 to 180 kg N ha^{-1} in the second and subsequent ratoons (Rozeff and Wiedenfeld, 1998). Soil testing for NO_3–N has not been found to be a useful indicator of sugarcane responses to N fertilization in this subtropical environment. Sugarcane did not respond to N fertilizer, however, when water availability was low enough that it reduced yields (Wiedenfeld, 1995). There is a lack of information, however, about how sugarcane responses to N fertilization are affected

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Published in Agron. J. 100:665–671 (2008).
doi:10.2134/agronj2007.0286

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Abbreviations: Etc, crop evapotranspiration; ETo, evapotranspiration; Kc, crop coefficient; Kc_{mid}, midseason crop coefficient.

by soil moisture conditions in a narrower range above or below optimum moisture levels.

Much of the work on N fertilizer responses by sugarcane has been done using banded fertilizer application particularly in Texas, since this is the most effective method when using furrow irrigation. Very little information is available about how sugarcane responds to N fertilization using different application methods. Subsurface drip irrigation allows placement of the N fertilizer directly in the root zone without damage to the plant and also allows later applications when sidedress applications are no longer possible due to the size of the crop. While late applications theoretically can more closely match the time when demand is greatest, delayed applications also enhance the risk of detrimental effects that occur when late season excess N availability interferes with crop maturity (Thomas et al., 1985). Another alternative is a *stool splitter* application method consisting of a coulter which cuts an opening in the middle of the row slicing the plant stool, followed by a shank which places the fertilizer directly into the soil below the plant. In Australia where this method was developed, burying the fertilizer in the stool has been found to be the easiest and quickest way to apply fertilizer resulting in increased N uptake by the plant (McMahon et al., 1994). On lighter textured soils and in dryer years, lower yields have occasionally resulted, possibly a result of grass competition or the coulter damaging the stool allowing it to dry out. This implement has not been tested in other environments.

The objectives of this study were to determine sugarcane growth and yield responses to water stress, N rate, and N application method.

MATERIALS AND METHODS

A field study was conducted in the Lower Rio Grande Valley of Texas (26°10′ N, 97° 56′ W) beginning in 2000 and continuing for 4 yr. The area has a subtropical, semiarid climate and receives an average annual rainfall of 635 mm. The soil was a Raymondville clay loam (fine, mixed, superactive, hyperthermic Vertic Calciustolls). Sugarcane cultivar TCP87–3388 (Irvine et al., 1997) was planted on 18 Sept. 2000 by placing stalk pieces in the furrow then covering with soil to a depth of 15 to 20 cm. Subsurface drip irrigation was installed before planting by burying drip tubing 10 to15 cm deep in the bottom of the furrow beneath where the sugarcane was to be planted, thus the drip tubing ended up about 30 cm deep. The entire field was initially flood-irrigated following planting to establish the crop and to begin the water balance at field capacity.

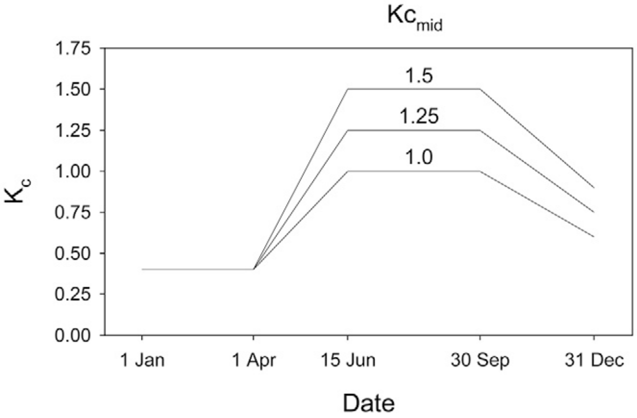

Fig. 1. Crop coefficient (Kc) curves applied to Pennman–Monteith reference evapotranspiration (ET) to calculate water use for the three irrigation treatments based on different midseason coefficients (Kc_{mid}).

The experimental design consisted of a factorial combination of three water application levels (20% below crop ET replacement, full ETc, and 20% above ETc) and four N application levels (0, 60, 120, and 180 kg N ha^{-1}), along with three methods of fertilizer application applied only at the middle water application level but at the 60, 120, and 180 kg N ha^{-1} application levels, giving a total of 18 treatments (Table 1) which were replicated five times in a randomized block design. Plots were 13.7 m in length by six rows wide with 1.5 m between-row spacing.

The different water application levels were achieved by irrigating to replace crop water use calculated using three different crop coefficient curves which had mid-season coefficient values (Kc_{mid}) of 1.0, 1.25, and 1.5 (Fig. 1) with the Pennman–Monteith ET equation (Allen et al., 1998). Crop coefficients are applied to ETo to adjust for the particular crop, stage of growth, and local conditions in determining water use. The standard Kc_{mid} value for sugarcane is 1.25 (Allen et al., 1998). Curves were adjusted to local conditions regarding the duration of the various growth phases based on previous research (Salinas and Namken, 1977) and visual observation of the crop. Rapid growth begins in subtropical South Texas as daily temperatures climb rapidly beginning about 1 April, while maximum leaf area index (LAI) is reached about 15 June.

A balance sheet approach was used for irrigation scheduling. The size of the available soil moisture reservoir varied over time assuming a root zone of 61 cm initially and extending to 76 cm after 1 June annually (Rozeff, 1993), and an available soil moisture holding capacity of 0.16 cm cm^{-1}. Inputs included irrigation added assuming 100% system efficiency, as well as effective rainfall. Effective rainfall was determined as the amount exceeding 2.5 mm within a 24 h period, and was limited to the amount that could be stored in the soil profile based on calculated crop water use. Withdrawals included calculated ETc based on Pennman–Monteith ETo and the crop coefficient curves for each irrigation treatment, adjusted by a stress coefficient based on the depletion level and daily ETc rate (Allen et al., 1998). An automatic weather station (model ET106, Campbell Scientific, Logan, UT) at the site was used to measure rainfall (TE525 tipping bucket rain gauge),

Table 1. Irrigation and N fertilization treatments applied to sugarcane.

No.	Irrigation level	N application Rate	N application Method†
	Kc_{mid}‡	kg ha^{-1}	
1	1.0	0	–
2	1.0	60	1
3	1.0	120	1
4	1.0	180	1
5	1.25	0	–
6	1.25	60	1
7	1.25	60	2
8	1.25	60	3
9	1.25	120	1
10	1.25	120	2
11	1.25	120	3
12	1.25	180	1
13	1.25	180	2
14	1.25	180	3
15	1.5	0	–
16	1.5	60	1
17	1.5	120	1
18	1.5	180	1

† 1, split applications, through the drip system; 2, single applilcation, sidedress incorporated; 3, single application, stollsplitter.

‡ Kc_{mid}, midseason crop coefficient.

maximum and minimum temperature and relative humidity (CS500 temperature and relative humidity sensor), total solar radiation (LI200X pyranometer), and average wind speed (034A wind set) which were recorded hourly using a CR10X data logger. Calculated crop water use and water inputs including irrigation and effective rainfall over time are shown in Fig. 2 for the middle irrigation treatment (Kc = 1.25) for the 4 yr of this study.

Treatments were irrigated up to twice per week in the plant crop and approximately once per week in the first through third ratoon crops. Water application was measured using totalizing flow meters for each irrigation level in each block. Separate supply lines with cutoff valves and fertilizer injection nozzles were set up to provide control of water and N fertilizer injection individually to each plot receiving a different N application level through the drip system. Irrigation water was from the Rio Grande River and had an average electrical conductivity of 0.13 S m^{-1}, and was filtered using sand media filters.

Fertilizer application methods consisted of (i) split applications through the drip system, (ii) a single banded sidedress application, (iii) a single application in the center of the bed using a stool splitter. All fertilizer applications were made using spray grade granular urea (46–0–0) which could be completely dissolved in water. Applications through the drip system were made in three equal split applications in February, in early April when rapid early growth began, and in mid-June at the beginning of the grand growth period each year (Fig. 1). Sidedress and stool splitter applications were made between February and April each year depending on weather conditions. Sidedress applications were made by banding the fertilizer 30 cm to both sides of the center of each row 15 cm deep. Stool splitter applications were made by running a coulter in the middle of the bed splitting the plant stool, and banding the fertilizer 15 cm deep directly behind the coulter.

The drip irrigation system was periodically flushed with dilute solutions of H_2SO_4, HCl, and α,α,α-trifluoro-2,6-dinitro-N,N-dipropyl-p-toluidine (trifluralin) herbicide to dissolve precipitates, prevent algae growth, and discourage root intrusion into the drip emitters. Weed control was applied uniformly to all treatments and was achieved using annual preemerge applications of 2.8 kg ha^{-1} of N-(1-ethylpropyl)-3,4-dimethyl-2,6-dinitrobenzenamine (pendimethalin) and 3.4 kg ha^{-1} of 2-chloro-4 ethylamino-6-isopropylamino-s-triazine (atrazine); spot treatment throughout the season with a 1% solution of isopropylamine salt of N-(phosphonomethyl) glycine (glyphosate), and mechanical cultivation. No pesticide applications were required for insect control in this study.

Soil samples were taken before study initiation within each block, and after the plant, first and second ratoon crops in each plot. Ten to 12 samples were taken within each sample unit to a depth of 15 cm, composited, dried, ground, and analyzed for pH and electrical conductivity in a 1:2 soil to water extractant; for NO_3–N spectrophotometrically in a 1 n*M* KCl extractant using Cd reduction; and for P, K, Ca, Mg, Na, and S in an acidified ammonium acetate +EDTA extractant using ICP (Texas Cooperative Extension, 2005).

In-season growth measurements taken included stalk height and LAI. Stalk height was determined in the plant crop at monthly intervals beginning in April, and in the first ratoon crop at 2 wk intervals beginning in July and continuing through August which is the grand growth period when stalk growth is most rapid. Measurements were made on each date on the same three stalks in each plot from the base to the terminal growing point. Daily stalk growth rates were calculated for each plot by subtracting the early July from the mid August height measurement and dividing by the number of days between measurements. Leaf area index was measured using a plant canopy analyzer (LAI-2000, Li-Cor Biosciences, Lincoln, NE) in the first and second ratoon crops at 1 to 2 wk intervals during May and June, which is the growth period when leaf area is rapidly increasing.

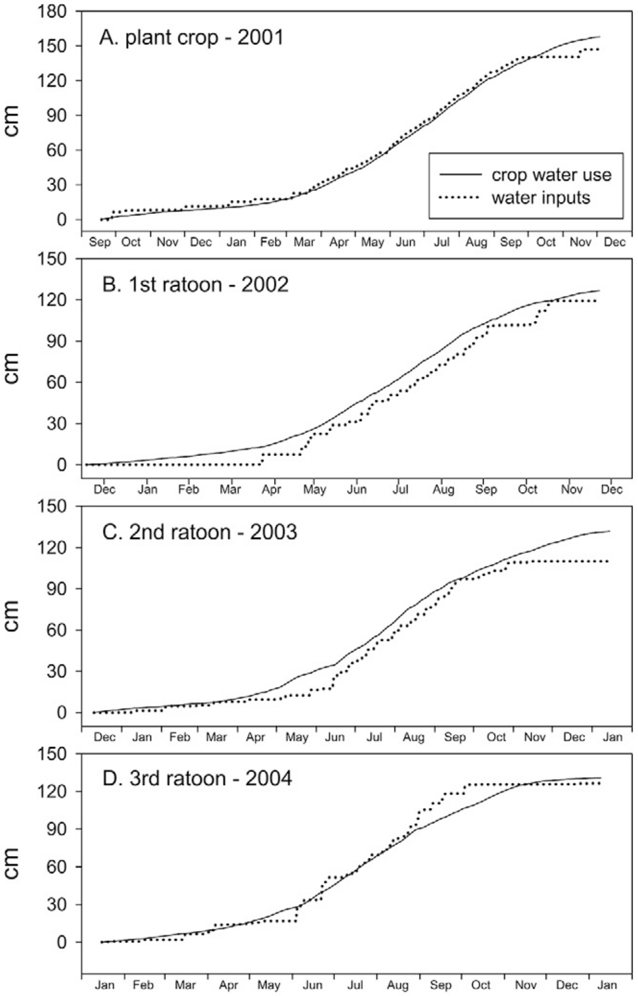

Fig. 2. Calculated crop water use and water inputs over time for the middle irrigation treatment for each of the four sugarcane crops. Inputs occasionally exceeded crop water use doe to changes in storage in the soil profile.

Cane and sugar yields were determined annually on 3 Dec. 2001, 9 Dec. 2002, 10 Jan. 2004 and 10 Jan. 2005 for each plot. The whole study area was burned each year before harvest to remove dried leaf material. In the plant and first ratoon crops 10.7 m of the middle two rows of each six row plot were harvested by hand and weighed, and an 11 stalk subsample was taken. In the second and third ratoon crops the full 13.7 m length of each row of each plot was harvested using a commercial chopper harvester with the weight determined using a 9 Mg weigh wagon equipped with a load cell which could be tared after each plot row. A 20 kg stalk subsample was taken for

Table 2. Crop evapotranspiration (ETc), water inputs, cane yield and water use efficiency defined as cane yield as a function of combined water inputs for the three irrigation treatments based on different crop coefficient curves as indicated by the mid-season crop coefficient (Kc) for four sugarcane crops. Potential crop ET is based on the crop coefficient curve for each treatment, while adjusted crop ET reflects the effect of stress periods which may have occurred.

					ETc‡		Rain§					
Year	**Crop**	**Days**	**ETo†**	**Kc$_{\text{mid}}$**	**Potential**	**Adjusted**	**Total**	**Effective**	**Irrigation**	**Combined water inputs**	**Cane yield¶**	**Water use efficiency**
			mm		mm						Mg ha^{-1}	Mg ML^{-1}
2001	plant	441	1534	1.0	1295	1295	605	279	953	1232	99	8.0
				1.25	1582	1582		305	1168	1471	110	7.5
				1.5	1869	1869		333	1379	1712	102	6.0
2002	first ratoon	371	1389	1.0	1092	1082	587	411	612	1024	96	9.4
				1.25	1323	1267		465	732	1194	97	8.1
				1.5	1565	1361		490	838	1328	102	7.7
2003	second ratoon	401	1491	1.0	1189	1130	752	500	475	973	113	11.6
				1.25	1445	1318		500	602	1100	111	10.1
				1.5	1704	1433		500	699	1196	106	8.9
2004	third ratoon	361	1455	1.0	1166	1133	917	551	427	978	92	9.4
				1.25	1417	1308		747	518	1265	96	7.6
				1.5	1669	1435		747	577	1323	92	7.0

† Penmann–Monteith reference evapotranspiration.

‡ Actual crop evapotranspiration may be less than potential crop evapotranspiration because of water stress occasionally encountered when soil water availability fell below the minimum threshold.

§ Effective rainfall is less than total rainfall due to various losses before the water becomes available to the crop.

¶ No significant differences in cane yield between irrigation levels were found for any crop year.

each plot by taking several grab samples as the harvested cane was being transferred from the harvester to the weigh wagon. Stalk samples were chopped up and mixed, then a 500 g subsample was pressed using a roller mill at 17 MPa to extract the juice. Juice samples were analyzed for Brix using refractometer (PR-101, Atago USA, Bellevue, WA), and sucrose content using a saccharometer (Autopol IIS/589–10, Rudolph Research Analytical, Hackettstown, NJ). Using these data cane sugar content and sugar yields were then calculated using the Winter-Carp formula (Chen and Chou, 1993, p. 580). Water use efficiency was calculated for each irrigation treatment each year by dividing the cane yield by the combined water inputs consisting of effective rainfall and irrigation applied.

Data were analyzed statistically using the GLM and REG procedures of the SAS for Windows software version 9.1 (Copyright, 2002-2003, SAS Institute, Cary, NC) including sample date and crop cycle as random variables. Irrigation, N application level, date and crop cycle effects and their interactions were evaluated using a subset of the treatments (12 of 18) consisting of those which received N application through the drip system, but excluding those which received N sidedressed or using the stool splitter since those treatments were applied at only one irrigation level. Fertilizer application methods and their interaction with N application rates, sample dates and crop cycle were evaluated using only treatments at the middle irrigation level where N was applied at all three rates using one of the three application methods (9 of 18). Nitrogen application rate main effect was analyzed only in the first model. Means were compared using the Tukey's studentized range test for class variables, and multiple linear regression for N application rate.

RESULTS

Irrigation applications in the plant crop were scheduled to replace estimated crop ET twice per week, but this provided very little potential storage capacity in the soil for any rainfall. This is demonstrated by the closeness of the lines for calculated water use and water inputs in Fig. 2A for the plant crop. After the first year, irrigation applications in the first through third ratoon crops were delayed in April or May, and plots were irrigated approximately once per week to keep water deficit levels above 55% but at least 25% of the available soil water holding capacity to provide storage for rainfall while not stressing the sugarcane crop. Brief stress periods occurred in the first through third ratoon crops when we failed to keep calculated water deficit levels above the targeted 55% level.

Potential crop water use based on ETc applying the crop coefficient curves used for the three irrigation treatments, and 'actual' crop water use adjusted for any water stress periods that occurred during the growing season as calculated with the water balance approach are shown in Table 2. The data suggest that actual vs. potential crop growth based on water availability was 100% in the plant crop and ranged between 90 and 94% in the first through third ratoon crops. Calculated combined water inputs were lower than total rainfall plus irrigation because of the adjustments made for 'effective' rainfall (Table 2). Total water inputs on average provided 91% of calculated crop water requirements based on the crop coefficient curves used as the basis for the irrigation treatments.

All growth and yield measurements taken in this study were significantly different between crop cycles (Table 3), which is a result of the different times each year when measurements were made and planting or harvest of the previous crop, as well as annual climatic differences. Treatment effects on the different growth measurements taken on several dates showed no interaction with date (Table 3), therefore measurements were averaged by date within crop. Only LAI and cane yield responses to N application showed a significant interaction with crop and are therefore presented separately by year. Treatment effects on all other growth and yield parameters showed no interaction with crop and were therefore averaged across crops.

Table 3. Statistical significance of differences due to treatment, between dates, crops, or interactions for the various parameters measured. A subset of the treatments was used to analyze irrigation level effects and interactions since different irrigation levels were applied using only one applicaton method. A second subset of the treatments was used to analyze application method effects and interctions since these were applied at only one irrigation level. Nitogen rate main effects were analyzed only in the first analysis.

Effects	Stalk height	Growth rate	LAI†	Cane yield	CRS‡	Sugar yield
Irrigation level (I)	***	*	–§	–	–	–
N rate (N)	*	–	**	***	–	***
N^2	*	–	*	–	**	–
I × N	***	–	–	–	–	–
I × N^2	–	–	–	–	–	–
Date (D)	***		***			
D × I	–		–			
D × N	–		–			
D × N^2	–		–			
D × I × N	–		–			
D × I × N^2	–		–			
crop (C)	*	***	***	***	***	***
C × I	–	–	–	–	–	–
C × N	–	–	*	*	–	–
C × N^2	–	–	*	–	–	–
C × I × N	–	–	–	–	–	–
C × I × N^2	–	–	–	–	–	–
Application (A)	***	–	***	*	–	*
A × N	**	–	–	–	–	–
A × N^2	***	–	–	–	–	–
date (D)	***		***			
D × A	–		–			
D × A × N	–		–			
D × A × N^2	–		–			
crop (C)	–	***	***	–	**	–
C × A	–	–	–	–	–	–
C × A × N	–	–	–	–	–	–
C × A × N^2	–	–	–	–	–	–

* Significant at the 0.05 level.

** Significant at the 0.01 level.

*** Significant at the 0.001 level.

† LAI = leaf area index.

‡ CRS = commercially recoverable sucrose content.

§ A dash (–) designates treatment effects were not significant.

Irrigation Effects

Average stalk heights were greater for the high irrigation treatment ($Kc_{mid} = 1.5$) compared to the middle and low irrigation treatments (Table 4). Stalk growth rates increased with increasing water application during the grand growth period. Others have also found cane elongation and stalk height to be strongly and negatively correlated with drought (Singh and Reddy, 1980; Soares et al., 2004; Wiedenfeld, 1995). Moderate drought applied early in the season between 60 and 150 d after planting, however, may have less of an impact on stalk elongation (da Silva and da Costa, 2004). Leaf area index measurements in this study showed no effect due to differences in water application levels (Table 4). This parameter may be affected by conditions earlier in the growing season when crop water requirements are lower and therefore differences in water availability between treatments is less.

Table 4. Effect of irrigation level and N application method on growth and yield parameters.

Treatment	Stalk height	Growth rate	LAI	Cane yield	Sugar yield
	cm	cm d^{-1}		Mg ha^{-1}	
Irrigation level, Kc_{mid}†					
1.0	198 b‡	1.31 b	2.54	100	13.6
1.25	199 b	1.40 ab	2.57	103	14.0
1.5	208 a	1.50 a	2.53	101	13.5
Application method					
through the drip	202 a	1.41	2.52 a	106 a	14.3 a
sidedress	196 b	1.38	2.52 a	109 a	14.6 a
stool splitter	192 b	1.33	2.39 b	99 b	13.3 b

† Kc_{mid}, midseason crop coefficient.

‡ Means within main effect group within column followed by the same letter are not significantly different according to Tukey's studentized range test. If no letters follow means, differences were not significant.

No statistically significant differences in cane or sugar yield occurred due to irrigation level in any of the 4 yr of this study (Table 4). Cane yields ranged from 92 to 113 Mg ha^{-1} across all irrigation treatments during the 4 yr of this study, while sugar yields ranged from 12.1 to 14.6 Mg ha^{-1}. Water use efficiency varied annually from an average of 7.2 Mg mL^{-1} in the plant crop to 10.2 Mg mL^{-1} in the second ratoon crop, and declined with increasing water application level every year since yields did not increase significantly as water application increased (Table 2).

Nitrogen Rate Effects

Initial soil fertility status in the spring of 2001 indicated very high NO_3–N levels, as well as high or very high levels of all other nutrients and no salinity hazard (Table 5), which are typical results for the young alluvial soils of the Lower Rio Grande Valley. Soil NO_3–N levels following the plant, first and second ratoon crops were much lower, averaging about 4 mg kg^{-1} and showed no significant effects due to N application rate or method.

Rate of N fertilizer application affected stalk height and LAI (Fig. 3), even though LAI was not affected by irrigation level. Stalk height showed a quadratic response to increasing N applied only at the middle irrigation level (Fig. 3A). Leaf area index also increased with increasing N application rate, but the response was quadratic and occurred in the second but not the first ratoon crop (Fig. 3B). Stalk growth rate in the plant and first ratoon crops showed no significant response to rate of N applied.

Sugarcane yields showed good responses to N application in all four crops. Increasing N rate caused a linear increase in cane yield every year including the plant crop (Fig. 4A), which is very unusual in South Texas (Thomas et al., 1985; Rozeff and Wiedenfeld, 1998). The magnitude of the increase was similar in the plant through second ratoon crops, with the slope of the response ranging from 62 to 85 kg of cane per kg of N applied. In the third ratoon crop the slope

Table 5. Initial soil fertility status prior to initiation of the study.

Parameter	Level
pH	8.2
NO_3–N, mg kg^{-1}	41
P, mg kg^{-1}	301
K, mg kg^{-1}	806
Ca, mg kg^{-1}	40,640
Mg, mg kg^{-1}	1,520
Na, mg kg^{-1}	577
S, mg kg^{-1}	245
Salinity, mg kg^{-1}	1,077

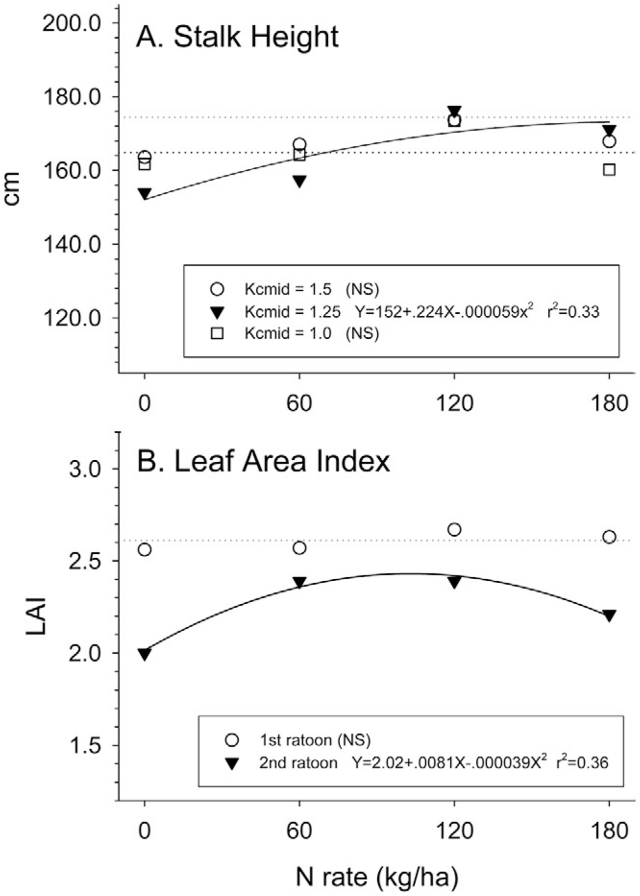

Fig. 3. Effect of N application rate on sugarcane stalk height at the different irrigation levels, and on leaf area index. Stalk height was measured only in the plant and first ratoon crops, and leaf area index (LAI) was measured only in the first and second ratoon crops.

increased dramatically to 191 kg cane per kg of N applied indicating depletion of residual soil N reserves. This result indicates the increasing importance of fertilizer application with successive ratoons as residual nutrient reserves are depleted from the soil. Sugar content showed a small but significant quadratic response to increasing N application rate, decreasing as N rate increased (Fig. 4B). This result is consistent with results from other studies showing that sugar content declines at excess N availability levels (Thomas et al., 1985). Sugar yield showed a linear increase with increasing N application, with a 12.5 kg increase in sugar per kg of N applied (Fig. 4C).

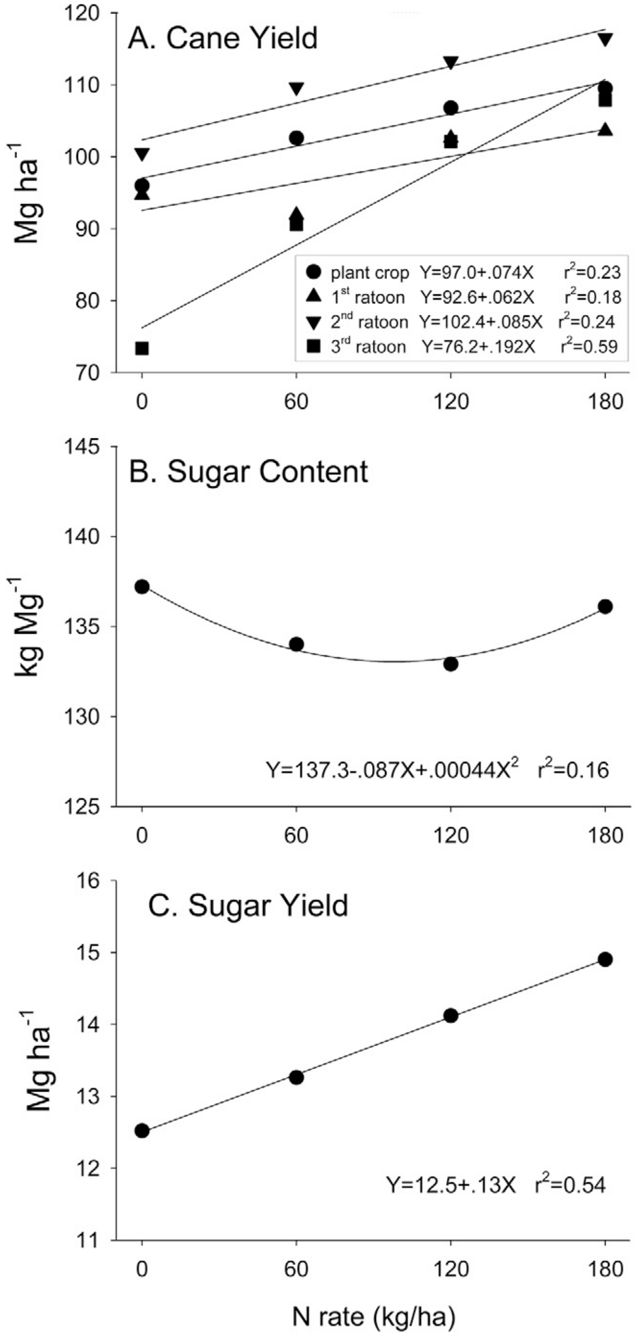

Fig. 4. Effect of N application rate on cane yields over four crops, and on sugar content and yield averaged across the four crops.

Nitrogen Application Methods

Stalk height and LAI both showed an effect due to method of N application. Stalk height was greater when the N was applied through the drip system than when applied sidedress or using the stool splitter while LAI was lower when N was applied using the stool splitter then by the other two methods (Table 4). A significant interaction between application method and N application rate on stalk height occurred, indicating a significant response to increasing N only when applied through the drip system and not by the other application methods. The stalk height response to increasing N applied through the drip system is the same as the N rate response at the middle irrigation level (Fig. 3A). Nitrogen availability to the root system may have been enhanced by drip irrigation.

The stool splitter application method produced lower cane yields than both through the drip and sidedress applications (Table 3). Application methods had no effect on sugarcane sugar content in any year (data not shown).

DISCUSSION

Increased stalk growth rate and stalk height responses at the highest irrigation level suggest an early growth response to the highest water application level. However, the lack of yield responses at different irrigation levels suggest that overall, while sugarcane may use very high levels of water if available, this crop has the capacity to compensate for differences in water levels and is capable of producing maximum yields over a fairly broad range of soil water conditions (32% from lowest to highest water application in this study), including levels 18% below optimum. There is also the possibility that sugarcane water use may be lower than previously documented. It has been suggested that sugarcane growth may decline or cease when air temperatures are very high (>38°C) even if water is not limiting (N.G. Inman-Bamper, personal communication, 2007; N. Rozeff, personal communication, 2002), which occurs frequently in the LRGV. This would result in crop coefficients lower than the published values in certain circumstances. Previous studies have also shown that when water is limiting, sugarcane yields do not respond to N application (Wiedenfeld, 1995). However, in this study responses to N application were not affected by irrigation level indicating that while lower water availability may have had some effect on plant growth it did not limit yields.

Sugarcane fertilization studies over the last 30 yr in Texas have always failed to show any yield response to N application in the plant crop, or occasionally only a yield response to small amounts of N up to about 57 kg N ha^{-1} and nothing thereafter (Rozeff and Wiedenfeld, 1998). In most studies N fertilizer was usually applied as liquid or granular material either broadcast or sidedressed in bands in the shoulder of the bed. Initial inorganic soil NO_3–N levels in this study were very high, which is typical in sugarcane production due to mineralization of crop residues following the extensive soil disturbance resulting from the land preparation requirements for planting. All of this would suggest that we should not expect a cane yield response to N application in the plant crop in South Texas. However, N applied in split applications through the drip system produced a significant linear increase in cane yields in every year including the plant crop. Yields increased linearly for N applications up to 180 kg N ha^{-1}, the highest level applied in this study, and an amount previously considered to be excessive, particularly in plant and first ratoon crops, based on previous research. These results indicate that N injected through the drip system in several smaller applications over time may be more effective at meeting sugarcane crop nutrient requirements than a single banded application, and that plant crop nutrient requirements may be greater than previously thought.

Where method of N application affected plant growth, greater stalk height was found with drip application compared to the two other methods. Cane and sugar yields, however, were lower for the stool splitter than for the through-the-drip or sidedress application methods, which were not significantly different from each other. These results indicate that while drip application may initially be more effective at providing N to the crop than sidedress application, this advantage may later disappear as the sugarcane crop is able to compensate later in the growing season for any early season advantage provided by one application method over the other. The sugarcane plant may not be able to recover later in the growing season, however, from any injury caused by the stool splitter application method early in the year.

ACKNOWLEDGMENTS

This work was supported by the Rio Grande Valley Sugar Growers, Inc., and USDA, CSREES Rio Grande Basin Initiative.

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