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Crop Nutrition and Yield Response of Bagasse Application on Sugarcane Grown on a Mineral Soil

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Abstract: The addition of agricultural by-products to mineral soils has the potential to improve crop production. This study aimed to determine the effects of the readily available sugarcane (*Saccharum officinarum*) milling by-product bagasse as a soil amendment on yields of sugarcane grown on a sandy Entisol of South Florida. The field trial was conducted on a commercial sugarcane farm for three annual crop cycles (plant cane and two ratoons). Four treatments including 5 cm bagasse (85 ton ha^{-1}); 10 cm bagasse (170 ton ha^{-1}); 10 cm bagasse (170 ton ha^{-1}) plus 336 kg ha^{-1} ammonium nitrate; and a control (without bagasse and ammonium nitrate) were evaluated. Results indicate that one single application of bagasse increased sugarcane biomass and sugar yield by approximately 23% in the plant cane year. A higher application rate of bagasse (10 cm of bagasse) was recommended since it had a longer effect on increasing sugarcane biomass and sugar yield. Bagasse application enhanced silicon (Si) supply and increased Si plant nutrition. However, the effects of bagasse on the other leaf nutrients were not significant.

Keywords: bagasse; leaf nutrient analysis; mineral soils; sugarcane production

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1. Introduction

The sugarcane (*Saccharum officinarum*) industry is a major economic driver in Florida, with a total value of over $4.5 billion annually [1]. With approximately 1600 km^2 in South Florida, sugarcane is one of the major agricultural commodities produced in this region [2]. Mineral soils used for sugarcane production in South Florida are low in soil organic matter (OM) (10–40 g kg^{-1}) and clay contents (0–30 g kg^{-1}), thus resulting in low water and nutrient holding capacities [3]. These mineral soils account for approximately 28% of the total sugarcane acreage in South Florida [4]. Recently, the proportion of sugarcane grown on mineral soils has increased and there is a need for sugarcane expansion on these soils if production is to be increased. Typically, sugarcane growers relied on inorganic fertilizers to improve yield, which ultimately increases production costs and the risk of water pollution [5]. Therefore, sugarcane producers and environmental researchers in Florida and elsewhere are interested in examining innovative nutrient management practices involving organic sources to reduce fertilizer costs and environmental risks.

Organic materials such as crop residues and by-products from industries are a valuable source of OM and plant nutrients, which bring many benefits when they are applied to mineral soils, such as decreasing soil bulk density (BD), increasing water holding capacity

(WHC) and enhancing soil structure, increasing cation exchange capacity (CEC) and nutrient cycling, increasing macronutrients and micronutrients in soils, and controlling erosion [5–7]. The improved soil physical, chemical, and biological properties assist in increasing crop quality and yield. The enhanced soil structure and lower BD provide a better soil environment for root growth. The improved CEC helps to retain more essential nutrients in soils for crop uptake and limit leaching. Moreover, organic amendments help to improve crop physiological responses to stress, stimulate crop growth, and protect against plant disease [8].

In South Florida, locally derived organic wastes from the sugarcane industry are available, with the potential to be used as soil amendments for sugarcane grown on mineral soils. Bagasse, one of the industry by-products generated and accumulated in the mills, is a fibrous material left after the extraction of sugar juice from sugarcane. Although it is currently used as a fuel for sugar mills in this region, there is still large amount of bagasse left in need of disposal. Bagasse contains approximately 56.17% moisture, 33.91% carbon (C), 0.51% nitrogen (N), 0.26 g kg^{-1} phosphorous (P), 1 g kg^{-1} potassium (K), and 0.4 g kg^{-1} silicon (Si) and has a C/N ratio of 65.88. The composition, nutrient levels, and benefits of bagasse vary depending on sugarcane variety, locality, mill efficiency, soil type, and climate factors. The use of bagasse has shown positive effects in terms of crop growth and yield [9–13]. In Sudan, it has been reported that bagasse applied at 45 ton ha^{-1} increased sunflower yield by 21.6% and 29.3% in the winter of 2004 and autumn of 2005, respectively [12]. This study also showed that the depth of roots, plant height, and head diameter of sunflower were significantly increased by adding bagasse to the cracking clay soil. Sugarcane yield was increased by 1.83 ton ha^{-1} over the control when bagasse was mixed into a vertisol in Colombia at 60 ton ha^{-1} [9].

While several studies have examined the effects of bagasse on crop growth and yields, no studies have been done in South Florida using bagasse as a soil organic amendment for sugarcane production on mineral soils. Some of the previous work in this region included studying the effects of other sugarcane industry by-products such as mill mud and mill ash on sugarcane nutrition and yield [2,5,14]. These studies indicated that the sugarcane yields were significantly improved due to mill mud application on mineral soils in South Florida.

The objective of this study was to investigate how sugarcane grown on mineral soils responded when treated with different rates of bagasse (5 cm bagasse, 10 cm bagasse, and 10 cm bagasse plus N) compared with the control (no bagasse application). The specific objectives of this farm trial were to: (1) compare the commercial sugarcane, sucrose, and sugar yield in the soils amended with bagasse applied at various rates with the control; (2) determine the nutritional effects of bagasse on sugarcane leaf tissue contents.

2. Materials and Methods

2.1. Study Area and Experimental Design

The field trial was conducted in Clewiston, South Florida (26°41′18.3′′ N 80°57′01.6′′ W), on mineral soils, predominantly comprised of Margate sand (Siliceous, hyperthermic Mollic Psammaquents). Mean annual precipitation in this region is 1154 mm, and average maximum and minimum temperatures are 28.7 °C and 18.5 °C, respectively (U.S. Climate Data).

Basic physiochemical properties of the mineral soil at this experiment site are shown in Table 1. The soil pH was determined using a 1:1 water to soil (v/v) mixture, and BD was calculated by dividing the mass of soil by a fixed volume. Organic matter (OM) was measured by loss on ignition (LOI) method. Water holding capacity (WHC) was determined by a modified method described by measuring the amount of water retained in soil after saturation [15]. Cation exchange capacity (CEC) was determined by the ammonium acetate method [16], and ammonium concentration was analyzed by flow injection analysis on Lachat analyzer (Hach Company, Loveland, CO, USA). Total Kjeldahl Nitrogen (TKN) was analyzed by digesting soil samples followed by colorimetric determination (EPA method 351.2). Total phosphorus (P) was measured by ashing soil samples and extracting using 6 M hydrochloric acid (HCl) and analyzed with an Agilent 5110 inductively coupled plasmaoptical emission spectrometer (ICP-OES) (Santa Clara, CA, USA). Plant available nutrient concentrations including P, potassium (K), calcium (Ca), iron (Fe), and magnesium (Mg) of the mineral soil were determined using Mehlich-3 (M3) extraction method.

Table 1. Basic physiochemical properties of Margate mineral soils (0–30 cm depth) in the experiment site (n = 10) (mean and standard deviation).

Property	Unit	Value
pH		7.35 ± 0.53
BD	g cm^{-3}	1.28 ± 0.06
OM	%	4.32 ± 0.85
WHC	%	49.71 ± 4.67
CEC	cmol$_c$ kg^{-1}	14.9 ± 7.13
TKN	mg kg^{-1}	1328.32 ± 450.87
Total P	mg kg^{-1}	282.69 ± 83.7
M3 P	mg kg^{-1}	42.39 ± 13
M3 K	mg kg^{-1}	71.17 ± 19.07
M3 Ca	mg kg^{-1}	1899.17 ± 708.46
M3 Fe	mg kg^{-1}	208.06 ± 35.87
M3 Mg	mg kg^{-1}	134.24 ± 43.5

BD, bulk density; OM, organic matter; WHC, water holding capacity; CEC, cation exchange capacity; TKN, total Kjeldahl nitrogen; Total P, total phosphorous.; M3, Mehlich-3.

The experiment was conducted in a completely randomized design with three treatments plus a control. The three treatments included 5 cm bagasse (85 ton ha^{-1}, wet weight), 10 cm bagasse (170 ton ha^{-1}, wet weight), and 10 cm bagasse plus N (336 kg ha^{-1} ammonium nitrate). The control was no bagasse and no extra N added. The rates of bagasse were selected in conjunction with discussions with farm mangers and bagasse applicators, taking into account the feasibility and logistics of field-scale bagasse application in a commercial setting. The 5 cm of bagasse is the minimum amount that can be applied uniformly in the fields. Each treatment and the control were replicated three times. The ammonium nitrate fertilizer was applied in two evenly divided split applications: the first was right after bagasse application and the second application was approximately one month before planting sugarcane. The C/N ratio of the 10 cm bagasse plus N treatment would be decreased to approximately 58.75 after N application.

Bagasse was applied only once to the soil surface and incorporated into top 15 cm soil with a disk on June 2017, with no posterior application over the entire experimental period. Calcium silicate was applied uniformly to the experimental plots on August 2017 based on soil-test silicon (Si). Sugarcane was planted in November 2017 and grown for approximately 4 years, including plant cane (approximately 13 months) and two ratoons (16 months and 13 months, respectively). Bagasse was obtained from the U. S. Sugar Corporation sugarcane mill in Clewiston, Florida. Basic physiochemical properties of bagasse in this experiment site are shown in Table 2. The pH of bagasse was determined by a 1:1 water to bagasse (v/v) mixture; total carbon (C) of bagasse and total N were determined by a Costech ECS 4010 elemental analyzer, and then the C:N ratio was calculated from these analyses. All total nutrient contents were measured by ashing bagasse samples and then extracting using 6 M HCl and analyzing with ICP. More information about physicochemical properties of bagasse can be found in [17].

Table 2. Basic physiochemical properties of bagasse in the experiment site (n = 6) (mean and standard deviation) (reported as dry basis).

Property	Unit	Value
pH		3.79 ± 0.01
MC	%	56.17 ± 4.14
OM	%	95.77 ± 0.44
BD	g cm^{-3}	0.11 ± 0.00
CEC	cmol$_c$ kg^{-1}	70.12 ± 12.62
Total C	%	33.91
Total N	%	0.51
C:N Ratio		65.88
P	g kg^{-1}	0.26 ± 0.01
K	g kg^{-1}	1 ± 0.04
Ca	g kg^{-1}	2.1 ± 0.01
Fe	g kg^{-1}	0.33 ± 0.01
Si	g kg^{-1}	0.4 ± 0.01
Mg	mg kg^{-1}	14.78 ± 6.87
Mn	mg kg^{-1}	32.67 ± 1.04
Zn	mg kg^{-1}	13 ± 0.87
Cu	mg kg^{-1}	6.67 ± 0.29
B	mg kg^{-1}	10.67 ± 1.53

MC, moisture content; OM, organic matter; BD, bulk density; CEC, cation exchange capacity; Total C, total carbon; Total N, total nitrogen.

All 12 experimental plots received standard fertilizer, pesticide and herbicide applications over the entire cane production cycle (plant cane and two ratoons) based on recommendations for commercial sugarcane production on mineral soils in South Florida. Nutrient applications include N, P, K, Fe, Mg, boron (B), copper (Cu), manganese (Mn), and zinc (Zn). N and K fertilizers were split into three applications in the plant cane year and two applications in ratoon year 1 and 2.

2.2. Leaf Tissue Analyses

Sugarcane leaf samples were collected during the grand-growth period in June or July of each crop year. Top visible dewlap (TVD) leaves were collected randomly from all 12 field plots. Sugarcane leaf blades were separated from leaf midribs, rinsed with DI water, dried in the oven at 60 °C until up to a constant weight, ground to pass through 1 mm sieve, and analyzed for different nutrient concentrations. Leaf K, P, Ca, Mg, Cu, Fe, Mn, and Zn were determined by the nitric acid and hydrogen peroxide digestion method, and tissue N and Si were analyzed by the autoclave digestion method.

Leaf tissue analysis is a diagnostic tool for detecting nutritional problems and achieving a high degree of precision in nutrient management in sugarcane production system in Florida [18,19]. The critical nutrient level (CNL) approach was used in leaf tissue analysis, which determines whether nutrient concentrations in sugarcane leaves are adequate for optimal growth. The leaf nutrient concentrations were grouped into six categories as described in [19]: very deficient (VD), deficient (D), marginal (M), sufficient (S), sufficient plus (SP), and high (H) (refer Appendix A).

2.3. Yield Measurements

Stalk heights and diameters were measured in August–September of each crop year. Five random millable stalks were measured at four different locations in each experimental plot for a total of 20 millable stalks. These locations were near the four corners of each plot. The selected locations were 15 rows away from plot sides (ditch). Sugarcane height was measured from the bottom of cane to the first clearly visible dewlap, and the diameter was measured in the middle of the stalk.

Sugarcane plant cane was harvested in December 2018, the first ratoon crop was harvested on April 2020, and the second ratoon crop was harvested on May 2021. The sugarcane was harvested commercially from each experimental plot and the sugarcane yield was recorded.

After the cane was harvested, stalks were milled and the crusher juice was immediately analyzed for brix and pol. Brix is a measurement of percent soluble solids, while pol is a unitless measurement of the polarization of the sugar solution. Brix and pol measurements were calculated by the theoretical recoverable sugar method calculator [20], which determined percentage sucrose, and was expressed as normal juice sucrose (NJS%). The sugar yield was also calculated.

2.4. Statistical Analyses

Analyses of variance for stalk heights and diameters, sugarcane yield, percentage normal juice sucrose (NJS%), sugar yield, and leaf nutrient concentrations were performed using SAS/GLIMMIX in SAS 9.4 (SAS Institute, 2011) to determine statistically significant differences among treatments. Treatment (bagasse applied at different rates) and crop cycle were analyzed as the fixed effects, and plots were considered as random effects. Least significant mean differences ($p < 0.05$) were used to determine the significant treatment effects. Sugarcane yield parameters data were normally distributed, while leaf nutrient concentrations were not normally distributed. Thus, Spearman correlation analyses were used to determine the relations between sugarcane yield parameters and leaf nutrient concentrations.

3. Results

3.1. Leaf Nutrient Concentrations

Leaf nutrient analyses of variance were conducted (Table 3). All nutrients except P, Fe, and Zn had a significant crop year effect. Only Si showed a significant treatment effect. Crop year × treatment interactions were significant for leaf N and Zn.

Sugarcane leaf macronutrient concentrations for all treatments and the control during the grand-growth season of the plant cane year and two ratoons are presented in Table 4. Nitrogen leaf concentrations were considered marginal for all treatments and sufficient for the control in the plant cane year. However, there were no significant differences in N leaf concentrations between all treatments and the control in the plant cane year. N leaf concentrations were marginal for all treatments and the control in the first ratoon, while they were sufficient in the second ratoon. Phosphorus concentrations were in the sufficient category for all treatments and the control in the plant cane year and the second ratoon but were marginal for all treatments in the first ratoon crops. However, there were no significant differences in P leaf concentrations between all treatments and the control in the first ratoon crops. Potassium leaf concentrations were in the sufficient or sufficient plus category for all treatments and the control in plant cane and the two ratoon crops. A general decrease in K was observed from plant cane to the first ratoon crops, but K increased for the second ratoon crop. Calcium leaf concentrations were significantly higher in the first ratoon than in plant cane and the second ratoon. Magnesium leaf concentrations were deficient for all treatments and the control in plant cane crops, except for Mg for the 5 cm bagasse for which Mg was in the marginal range. Sufficient levels of Mg were determined for 5 cm bagasse and 10 cm bagasse in the first ratoon crop, and levels were marginal for the 10 cm bagasse + N and the control in the first ratoon crop. However, Mg leaf concentrations decreased generally from the first ratoon to the second ratoon.

Table 3. Analysis of variance F ratios and level significance for yield parameters and leaf nutrients for crop, treatment, and interaction effects.

Parameters	Crop (CR)	Treatment (TMT)	CR × TMT
	F Value		
Yield			
Stalk diameter	7.88 **	0.78	0.37
Stalk height	19.76 ***	0.47	0.49
Commercial cane yield	50.16 ***	6.93 **	0.45
Sucrose content	24.55 ***	0.48	0.46
Commercial sugar yield	71.54 ***	7.23 **	0.63
Leaf nutrients			
N	48.47 ***	0.4	2.69 *
P	3.4	0.09	0.32
K	49.42 ***	1.66	1.87
Ca	64.04 ***	2.94	2.27
Mg	10.15 ***	0.93	0.54
Fe	1.91	0.27	0.45
Cu	75.3 ***	0.33	0.38
Mn	14.38 ***	0.6	1.07
Zn	1.35	2.54	3.34 *
Si	23.75 ***	5.1 **	2.23

* Significant at the 0.05 probability level; ** Significant at the 0.01 probability level; *** Significant at the 0.001 probability level.

Table 4. Leaf macronutrient concentrations for plant cane and two ratoon crops.

Treatment *	N			P			K		
	Plant Cane	1st ratoon	2nd ratoon	Plant Cane	1st ratoon	2nd ratoon	Plant Cane	1st ratoon	2nd ratoon
	%								
0 cm B	2.04a B (S)	1.88a C (M)	2.16a A (S)	0.22a A (S)	0.22a A (S)	0.23a A (S)	1.38a A (SP)	1.03ab B (S)	1.44a A (SP)
5 cm B	1.97a B (M)	1.93a B (M)	2.14a A (S)	0.23a A (S)	0.21a A (M)	0.23a A (S)	1.29a A (S)	1b B (S)	1.35ab A (SP)
10 cm B	1.92a A (M)	1.94a A (M)	2.09a A (S)	0.24a A (S)	0.21a A (M)	0.23a A (S)	1.3a B (S)	1.1a C (S)	1.48a A (SP)
10 cm B + N	1.93a B (M)	1.89a B (M)	2.21a A (S)	0.24a A (S)	0.21a A (M)	0.23a A (S)	1.43a A (SP)	1.01ab B (S)	1.26b A (S)

Treatment	Ca			Mg		
	Plant Cane	1st ratoon	2nd ratoon	Plant Cane	1st ratoon	2nd ratoon
	%					
0 cm B	0.4ab B (n/a)	0.59a A (n/a)	0.45ab B (n/a)	0.12a AB (D)	0.13a A (M)	0.1a B (VD)
5 cm B	0.44a B (n/a)	0.65a A (n/a)	0.46ab B (n/a)	0.13a A (M)	0.15a A (S)	0.11a A (D)
10 cm B	0.4ab B (n/a)	0.62a A (n/a)	0.36b B (n/a)	0.11a A (D)	0.15a A (S)	0.1a A (VD)
10 cm B + N	0.37b C (n/a)	0.66a A (n/a)	0.53a B (n/a)	0.11a B (D)	0.14a A (M)	0.11a B (D)

* 0 cm B = 0 cm Bagasse, 5 cm B = 5 cm Bagasse, 10 cm B = 10 cm Bagasse, 10 cm B + N = 10 cm Bagasse plus N. Means followed by different lower case letters within same column are significantly different ($p < 0.05$). Means for the same treatment with different upper case letters for plant cane and two ratoons are significantly different ($p < 0.05$). H, high; SP, sufficient plus; S, sufficient; M, marginal; D, deficient; and VD, very deficient from [18].

Sugarcane leaf micronutrient concentrations for all treatments and the control during the grand-growth season of the plant cane year and two ratoons are presented in Table 5. Concentrations of Fe in leaf tissue were in the sufficient level for all treatments and the control in the plant cane year and the two ratoons. No treatment effect was observed for Fe. Copper leaf concentrations increased significantly from the sufficient level for plant cane to the sufficient plus level for the two ratoon crops for all treatments and the control. Concentrations of Cu in the two ratoon crops for all treatments and the control were significantly higher than plant cane crop. Manganese leaf concentrations were significantly higher for all treatments compared to the control in plant cane crops. Zinc leaf concentration was only in the sufficient level for the control in plant cane crops. A significantly higher level of Zn was verified for the control in plant cane crops compared to 10 cm bagasse and 10 cm bagasse + N. Concentrations of Zn ranged between marginal to very deficient values for all treatments and the control in the two ratoon crops. There was a general decrease in Si from plant cane to the two ratoon crops for all treatments and the control. The 10 cm bagasse and 10 cm bagasse + N showed a significantly higher level of Si in plant tissue than the control in plant cane crops.

Table 5. Leaf micronutrient concentrations for plant cane and two ratoon crops.

Treatment *	**Fe**			**Cu**			**Mn**		
	Plant Cane	1st ratoon	2nd ratoon	Plant Cane	1st ratoon	2nd ratoon	Plant Cane	1st ratoon	2nd ratoon
	mg kg^{-1}								
0 cm B	70.2a A (S)	70.4a A (S)	68.37a A (S)	4.8a B (S)	6.12a A (SP)	6.33a A (SP)	28.27b A (S)	24.04a A (S)	28.97a A (S)
5 cm B	66.77a A (S)	71.25a A (S)	69.76a A (S)	4.83a B (S)	6.44a A (SP)	6.28a A (SP)	37.98a A (S)	22.85a B (S)	27.22a B (S)
10 cm B	64.2a A (S)	71.46a A (S)	69.76a A (S)	4.66a B (S)	6.42a A (SP)	6.17a A (SP)	34.34a A (S)	22.55a B (S)	24.13a B (S)
10 cm B + N	64.44a A (S)	74.64a A (S)	75.37a A (S)	4.96a B (S)	6.41a A (SP)	6.27a A (SP)	35.43a A (S)	23.56a A (S)	25.46a A (S)

Treatment	**Zn**			**Si**		
	Plant Cane	1st ratoon	2nd ratoon	Plant Cane	1st ratoon	2nd ratoon
	mg kg^{-1}			%		
0 cm B	16.2a A (S)	13.27a B (D)	12.8a B (VD)	0.75b A (S)	0.59a A (M)	0.59a A (M)
5 cm B	14.75ab A (M)	13.51a A (D)	14.65a A (M)	1.13ab A (H)	0.64a B (S)	0.64a B (S)
10 cm B	13.13b A (D)	13.27a A (D)	13.35a A (D)	1.25a A (H)	0.78a AB (S)	0.6a B (S)
10 cm B + N	12.39b A (VD)	13.69a A (D)	13.5a A (D)	1.69a A (H)	0.78a B (S)	0.7a B (S)

* 0 cm B = 0 cm Bagasse, 5 cm B = 5 cm Bagasse, 10 cm B = 10 cm Bagasse, 10 cm B + N = 10 cm Bagasse plus N. Means followed by different lower case letters within same column are significantly different ($p < 0.05$). Means for the same treatment with different upper case letters for plant cane and two ratoons are significantly different ($p < 0.05$). H, high; SP, sufficient plus; S, sufficient; M, marginal; D, deficient; and VD, very deficient from [18].

3.2. Sugarcane Yield Parameters

All yield parameters presented a significant crop year effect (Table 3). Commercial sugarcane and sugar yield had a significant treatment effect. No significant crop year × treatment interaction effects were observed.

No significant differences were observed in sugarcane stalk diameters and heights between all treatments and the control over the plant cane year and two ratoons (Figures 1 and 2). All treatments showed a significantly higher commercial sugarcane and sugar yield than the control in the plant cane year (Figures 3 and 4). The commercial sugarcane yield was significantly higher with the higher bagasse rate applied (10 cm bagasse) compared with the control in the first ratoon (Figure 3). A significantly higher commercial sugar yield was also observed for the 10 cm bagasse compared with the control in the second ratoon (Figure 4). There were no significant differences in sucrose content between all the treatments and the control over the entire three crop years (Figure 5).

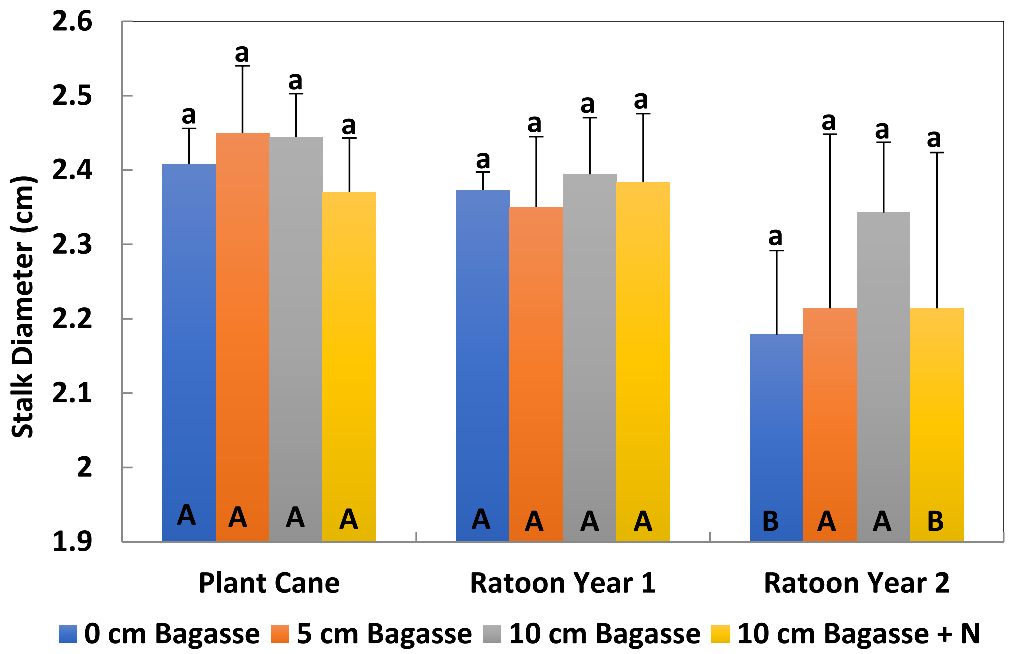

Figure 1. Stalk diameter for plant cane and two ratoons (mean and standard deviation). Different lower case letters within the same crop year are significantly different ($p < 0.05$). The same treatment with different upper case letters for plant cane and two ratoons are significantly different ($p < 0.05$).

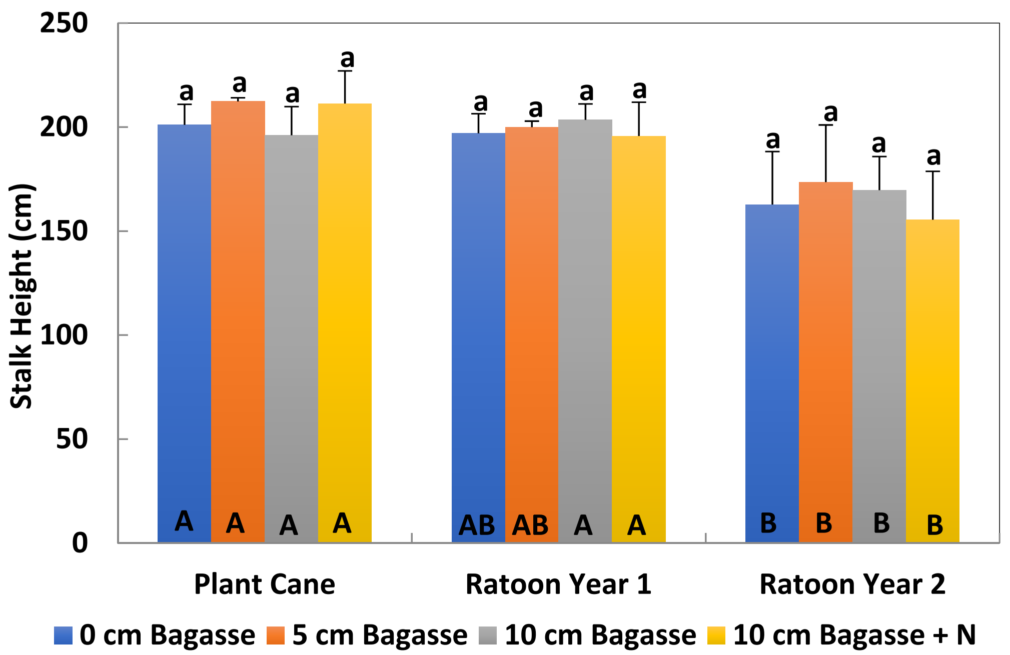

Figure 2. Stalk height for plant cane and two ratoons (mean and standard deviation). Different lower case letters within the same crop year are significantly different ($p < 0.05$). The same treatment with different upper case letters for plant cane and two ratoons are significantly different ($p < 0.05$).

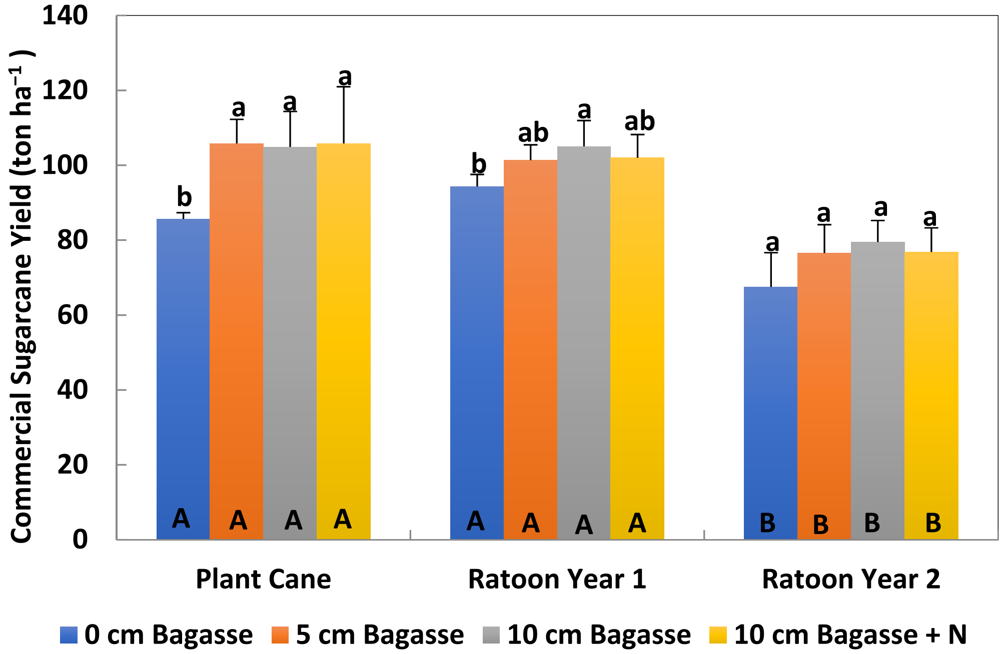

Figure 3. Commercial sugarcane −yield for plant cane and two ratoons (mean and standard deviation). Different lower case letters within the same crop year are significantly different ($p < 0.05$). The same treatment with different upper case letters for plant cane and two ratoons are significantly different ($p < 0.05$).

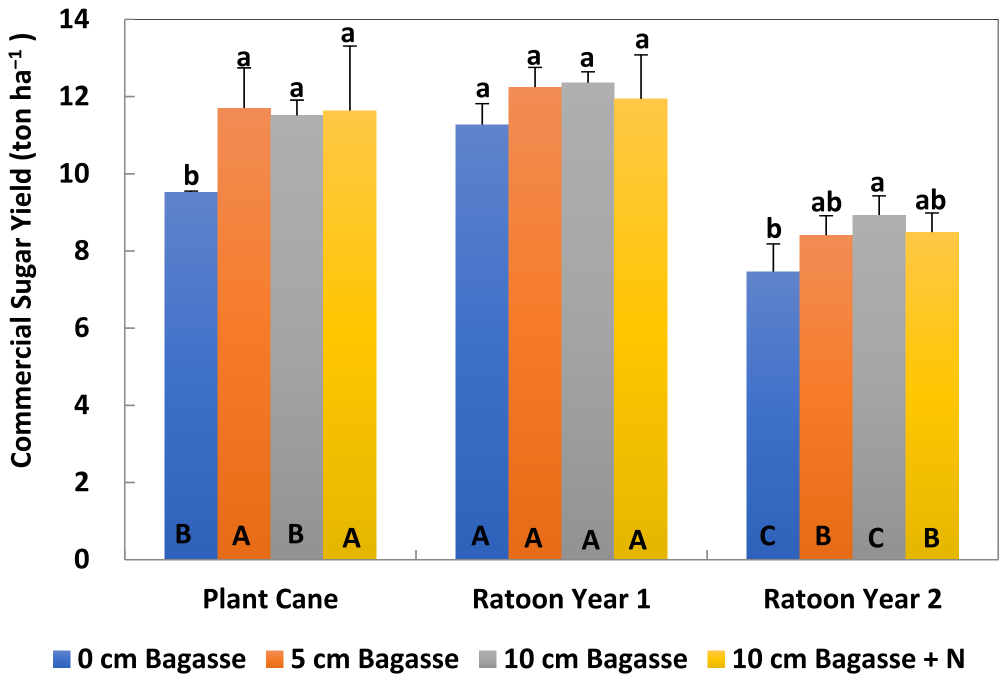

Figure 4. Commercial sugar yield for plant cane and two ratoons (mean and standard deviation). Different lower case letters within the same crop year are significantly different ($p < 0.05$). The same treatment with different upper case letters for plant cane and two ratoons are significantly different ($p < 0.05$).

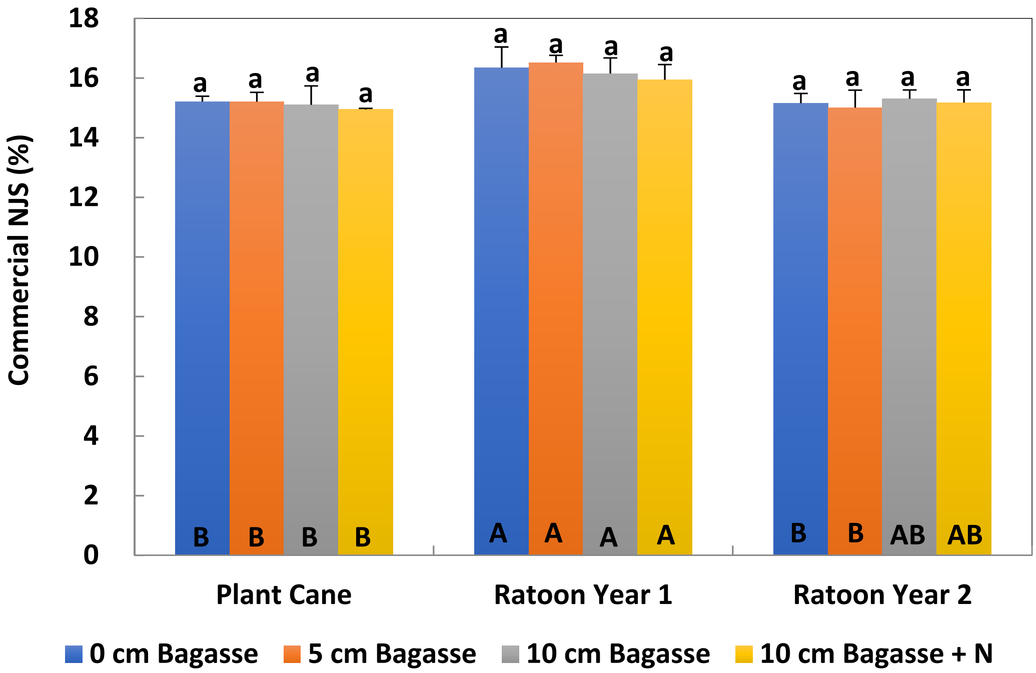

Figure 5. Commercial NJS% for plant cane and two ratoons (mean and standard deviation). Different lower case letters within the same crop year are significantly different ($p < 0.05$). The same treatment with different upper case letters for plant cane and two ratoons are significantly different ($p < 0.05$).

A significant positive correlation was determined between plant-cane sugarcane, sugar yield, and leaf Si concentrations (Table 6). However, no significant correlations were found between leaf Si concentrations, sugarcane, and sugar yield for the two ratoon crops (Table 6). There was a significant negative correlation between leaf Fe, plant-cane sugarcane, and sugar yield (Table 6). However, leaf Fe showed a significant positive correlation with the first-ratoon sugarcane yield and stalk height but a significant negative correlation with the first-ratoon sucrose content (Table 6). Leaf P and Ca had a significant positive correlation with first-ratoon stalk diameter (Table 6). Leaf P also showed a significant positive correlation with second-ratoon stalk height (Table 6). Leaf Mn presented a significant negative correlation with second-ratoon sugar yield (Table 6).

Table 6. Spearman correlation coefficients between yield parameters and leaf nutrient concentrations for sugarcane over the three crop years.

Parameters	Stalk Diameter	Stalk Height	Commercial Cane Yield	Sucrose Content	Commercial Sugar Yield
			Plant Cane		
Leaf N	0.09	0.18	−0.34	−0.01	−0.48
Leaf P	0.12	0.36	0.24	−0.15	0.24
Leaf K	0.47	0.42	−0.07	−0.02	−0.01
Leaf Ca	0.41	−0.12	0.13	0.4	0.29
Leaf Mg	0.11	−0.06	0.01	0.35	0.08
Leaf Fe	−0.48	−0.46	−0.57 *	0.1	−0.58 *
Leaf Cu	0.22	0.33	0.17	−0.06	0.23
Leaf Mn	−0.05	0.37	0.08	−0.15	0.03
Leaf Zn	0.45	−0.04	−0.48	0.42	−0.45
Leaf Si	−0.3	0.13	0.57 *	−0.05	0.5 *

Table 6. *Cont.*

Parameters	Stalk Diameter	Stalk Height	Commercial Cane Yield	Sucrose Content	Commercial Sugar Yield
			First Ratoon		
Leaf N	−0.16	0.58	0.6	−0.01	−0.01
Leaf P	0.8 **	−0.46	−0.42	0.18	−0.27
Leaf K	0.23	0.5	0.32	−0.07	0.36
Leaf Ca	0.62 *	−0.34	0.11	−0.06	0.13
Leaf Mg	0.34	−0.39	−0.01	0.22	0.04
Leaf Fe	−0.51	0.58 *	0.6 *	−0.76 ***	0.29
Leaf Cu	0.13	0.47	0.57	−0.04	0.51
Leaf Mn	0.17	−0.4	−0.24	−0.3	−0.31
Leaf Zn	0.37	−0.2	0.17	−0.15	0.15
Leaf Si	0.1	−0.13	0.04	−0.06	0.04
			Second Ratoon		
Leaf N	−0.4	−0.28	−0.1	−0.25	−0.28
Leaf P	−0.32	0.62 *	−0.25	0.16	−0.15
Leaf K	0.27	0.01	−0.04	0.06	0.08
Leaf Ca	−0.35	−0.41	−0.1	−0.13	−0.34
Leaf Mg	−0.16	0.34	−0.15	0.28	−0.06
Leaf Fe	−0.06	−0.49	0.28	−0.34	0.13
Leaf Cu	−0.37	0.25	−0.36	0.12	−0.38
Leaf Mn	−0.44	0.23	−0.53	0.22	−0.68 *
Leaf Zn	−0.35	0.44	0.06	−0.02	−0.05
Leaf Si	−0.2	−0.28	0.14	−0.39	0.11

* Significant at the 0.05 probability level; ** Significant at the 0.01 probability level; *** Significant at the 0.001 probability level.

4. Discussion

4.1. Leaf Nutrient Concentrations

Leaf N, P, K, Fe, Cu, Mn, and Si concentrations ranged between marginal to high values for all treatments and the control during the plant cane year and two ratoon crops (Tables 4 and 5). Only Mg and Zn concentrations were in the deficient and very deficient ranges. Nitrogen concentrations were marginal for all treatments compared with the control in the plant cane year, which could be due to the wide C:N ratio of bagasse (65.88), which may have initially immobilized N from the soil [21], thus reducing soil available N for sugarcane uptake. However, the possible N immobilization did not significantly decrease N leaf concentrations compared with the control for plant cane crop. As N mineralized from bagasse over time, concentrations of N for all treatments and the control were in the same category for the two ratoon crops. However, since bagasse only contains 0.51% of N, no significant changes were observed in N leaf concentrations between treatments and the control.

Several previous studies have shown that the addition of sugarcane bagasse and press mud enhanced P availability and helped increase the uptake of P by the crop in an Inceptisol of North India [22,23]. However, no significant increase in leaf P concentrations was observed due to bagasse application in our study. Moreover, concentrations of P for all treatments presented a marginal level, while the control was in the sufficient level in the first ratoon. Potassium leaf concentrations maintained in the sufficient to sufficient plus levels for all treatments and the control over the three crop years. The significant decrease in K leaf concentrations in the first ratoon crops was probably due to the crop cycle effect (Table 3). Since K has a high mobility in sandy soils, the soil available K for sugarcane uptake was leached out more in the first ratoon than in the other two crop years due to heavier rainfalls in the first ratoon. The total rainfall was reported as 19.91 cm during the grand-growth period of the first ratoon, while it was 16.46 cm and 14.83 cm for plant cane and the second ratoon, respectively (Florida Automated Weather Network Data). Magnesium deficiency has been determined to be a chronic problem in sugarcane grown on sandy soils in South Florida [24,25]. Since leaf Mg deficiencies were detected in the plant cane crops of this study, Mg fertilizer was applied for the two ratoon crops, which increased the Mg leaf concentrations in the first ratoon crops. However, Mg deficiencies were still present in the second ratoon crops.

Based on the recommendations for commercial sugarcane production in South Florida, Fe, Cu, Mn, and Zn fertilizer were applied only once for the plant cane crops. Iron, Cu, and Mn leaf concentrations were in the sufficient or sufficient plus category for all treatments and the control over the three crop years. Bagasse application had no effects on Fe and Cu leaf concentrations since there were no significant differences between all treatments and the control in each crop year. However, bagasse application might increase Mn availability and assist in Mn uptake by sugarcane since significant increases were observed in Mn leaf concentrations for all treatments in the plant cane year. Although Zn fertilizer was applied, Zn deficiencies were still detected for all treatments and the control over the three crop years except the control in the plant cane year. The addition of bagasse could increase soil organic matter content but may have also contributed to Zn deficiencies since Zn can form organic matter complexes (chelation), which bind Zn to bagasse and make it unavailable for plant uptake in the plant cane year [26,27]. Silicon is a beneficial nutrient for sugarcane and has been determined to increase sugarcane yield on soils with low soluble Si [28,29]. For instance, an average increase of 20% in sugarcane yield with calcium silicate application to sugarcane grown on organic soils has been documented [30]. In our study, sugarcane grown with bagasse application had higher levels of Si leaf concentrations compared with the control in every crop year. The higher application rates of bagasse significantly increased the concentration of Si compared with the control in plant cane crops. The results suggest that bagasse application, particularly a higher application rate of bagasse, had a positive effect on Si plant nutrition. Although leaf Si concentrations decreased in the two ratoon crops, the bagasse application treatments still presented sufficient Si levels, which indicated that one-time bagasse application could be beneficial for the entire sugarcane production cycle (plant cane and two ratoons).

4.2. Sugarcane Yield Parameters

The positive response in sugarcane and sugar yield in the plant cane harvest with a single application of bagasse might be attributed to its beneficial effects on soil physio-chemical conditions. Bagasse is an organic material with high OM (95.77%) and low BD (0.11 g cm^{-3}), which could increase soil OM levels, reduce soil BD, and improve water retention [13,31,32]. The improved soil environment could have supported a better cane root system development, which might have contributed to significantly greater sugarcane biomass and sugar yield. In addition, the results of leaf Si concentrations suggested that bagasse application increased sugarcane Si nutrition. Silicon is an important nutrient for sugarcane growth and has been reported to increase sugarcane yield [26,28]. Thus, the relatively high amounts of Si (0.4 g kg^{-1}) provided by bagasse could result in improved sugarcane yield. The significant positive correlation found between plant-cane sugarcane and sugar yield with leaf Si also confirmed this finding. The increase in sugarcane biomass yields was accompanied by improved sugar yield. However, bagasse application did not significantly affect sugarcane height and diameter or the sucrose contents over the three crop years.

Our results showed that bagasse application increased sugarcane biomass and sugar yield by approximately 23% in the plant cane year, while bagasse applied at a higher rate (10 cm bagasse) presented a significant increase in the first-ratoon sugarcane yield and in the second-ratoon sugar yield. Thus, a higher application rate of bagasse (10 cm bagasse) is recommended for use as a soil organic amendment on mineral soils since it was more likely to increase commercial sugarcane and sugar yield over the three crop years. Overall, the positive effects of utilizing bagasse on sugarcane growth and yield were likely due to the improvements to soil physical properties (lower BD and higher WHC because of increased soil OM) and enhanced Si supply. The effects of bagasse application on the other nutrient levels were relatively small as shown in the results of leaf concentrations. Although bagasse contains macro and micronutrients, and the nutrients would be released as bagasse decomposes over time, our results indicated that the additional nutrients derived from bagasse were not above sugarcane requirements and did not have a significant effect on leaf nutrition compared with the control.

5. Conclusions

Overall, the single application of bagasse had a beneficial effect on commercial sugarcane and sugar yield on mineral soils of South Florida. A higher application rate of bagasse (10 cm bagasse) was recommended to be used as a soil organic amendment on mineral soils since it was more likely to increase commercial sugarcane and sugar yield over the three crop years. Bagasse application enhanced Si supply, which likely caused the increase in Si plant nutrition and improved sugarcane productivity. Significant effects of bagasse on the other nutrient levels were not detected compared with the control. The split-application of additional N fertilizer at 336 kg ha^{-1} in the form of ammonium nitrate did not show a significant increase in commercial yield compared to the 10 cm bagasse application in all three years of sugarcane production (plant cane, first and second ratoon). The cost of hauling the material and dewatering (drying) bagasse are potential expenses that also need to be given full consideration prior to adopting the practice. Long-term field studies to determine how often it is necessary to apply bagasse to the mineral soils and economic analyses of applying bagasse need to be further investigated to gain a deeper understanding of the effects of bagasse as a soil amendment to grow sugarcane on mineral soils in South Florida.

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Appendix A

Table A1. Sugarcane leaf nutrient sufficiency ranges for defining nutrient management categories (McCray and Mylavarapu, 2010).

Sufficiency Category *	N	P	K	Mg	Si	Fe	Mn	Zn	Cu
			%				mg kg^{-1}		
Very Deficient	<1.6	<0.17	<0.80	<0.11	<0.20	<40	<12	<13	<2.0
Deficient	1.60–1.79	0.17–0.18	0.80–0.89	0.11–0.12	0.20–0.49	40–49	12–15	13–14	2.0–2.9
Marginal	1.8–1.99	0.19–0.21	0.90–0.99	0.13–0.14	0.50–0.59	50–54	16–19	15–16	3.0–3.9
Sufficient	2.00–2.30	0.22–0.26	1.00–1.30	0.15–0.24	0.60–0.80	55–80	20–60	17–25	4.0–6.0
Sufficient Plus	2.31–2.60	0.27–0.30	1.31–1.60	0.25–0.32	0.81–1.00	81–105	61–100	26–32	6.1–8.0
High	>2.60	>0.30	>1.60	>0.32	>1.00	>105	>100	>32	>8.0

* Very Deficient: Estimated production losses > 25%, Deficient: Estimated production losses 6–25%. Marginal: Estimated production losses 1–10%. Leaf nutrient concentrations are for top visible dewlap blades (without midrib). Suggested sampling period is June–July.

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