agronomy

MDPI

Article

Productive Potential of Nitrogen and Zinc Fertigated Sugarcane

Fernando Nobre Cunha [1,*], Marconi Batista Teixeira [1], Edson Cabral da Silva [1], Nelmício Furtado da Silva [1], Cicero Teixeira Silva Costa [2], Vitor Marques Vidal [1], Wilker Alves Morais [1], Leonardo Nazário Silva dos Santos [1], Fernando Rodrigues Cabral Filho [1], Daniely Karen Matias Alves [1], Jaqueline Aparecida Batista Soares [1] and Luiz Fernando Gomes [1]

1 Hydraulics and Irrigation Laboratory, Federal Institute of Education, Science and Technology Goiano (IFGoiano)-Campus Rio Verde, Rodovia Sul Goiana, Km 01, Zona Rural, Rio Verde-GO 75909-120, Brazil; marconibt@gmail.com (M.B.T.); edsoncabralsilva@gmail.com (E.C.d.S.); nelmiciofurtado@gmail.com (N.F.d.S.); vmarquesvidal@gmail.com (V.M.V.); wilker.alves.morais@gmail.com (W.A.M.); leonardo.santos@ifgoiano.edu.br (L.N.S.d.S.); fernandorcfilho10@gmail.com (F.R.C.F.); daniely_karen@hotmail.com (D.K.M.A.); jaquelineab.soares@gmail.com (J.A.B.S.); luizfernandoz4@hotmail.com (L.F.G.)

2 Irrigation Laboratory, Federal Institute of Education, Science, and Technology of Mato Grosso do Sul, (IFMS)-Campus Naviraí, R. Hilda, 203-Conj. Hab. Boa Vista, Naviraí-MS 79950-000, Brazil; ctsc2007@hotmail.com

* Correspondence: fernandonobrecunha@hotmail.com; Tel.: +55-(64)-3620-5600

Received: 7 June 2020; Accepted: 23 July 2020; Published: 29 July 2020

check for updates

Abstract: The relevance of sugarcane (*Saccharum officinarum* L.) in the agribusiness is irrefutable because it not only contributes greatly to the development of countries but is also an important source of job creation and income generation. The objective of this study was to evaluate the stalk productivity (SP) and sugar and alcohol yields of plant and ratoon crops of sugarcane (variety IACSP 95-5000) under N and Zn fertigation treatments using a central pivot, in Cerrado Red Latosol soil. The experiment was conducted under field conditions, in the municipality of Jataí, Goiás (GO), Brazil. A randomized block design was used, with a 4×5 split-plot arrangement and three replications. The fertilization treatments consisted of four doses of N (0, 60, 120, and 180 kg ha^{-1}) and five doses of Zn (0, 2.5, 5.0, 7.5, and 10.0 kg ha^{-1}) in plant and ratoon crops. N fertilization treatments, in the form of urea, were divided into three applications from 60 days after planting. Zn fertilization, in the form of Zn sulfate, was applied in a single application. Sugarcane was harvested 330 days after planting. The productivity (SP) was determined by weighing the stalks present in the respective subplots. Sugar and alcohol yields were calculated from the amount of raw sugar determined in the technological analysis. The sugar and alcohol yields of sugarcane (variety IACSP 95-5000) were improved with the fertigation of 180 kg ha^{-1} of N, in relation to Zn doses. Compared with the control (without N fertigation), sugarcane productivity (plant and ratoon crops) increased by 38.90% and 13.70% when treated with 180 kg ha^{-1} of N at the Zn dose of 10 kg ha^{-1}. Sugarcane (variety IACSP 95-5000) has productive performance, sugar and alcohol yield, optimized and maximized when fertigated with 10 kg ha^{-1} of zinc and 180 kg ha^{-1} of nitrogen.

Keywords: *Saccharum* spp.; alcohol yield; Oxisol; cerrado

1. Introduction

The relevance of sugarcane in the Brazilian agribusiness is irrefutable because it not only contributes greatly to the development of the country but is also an important source of job creation and income generation. Despite investments in the dissemination of technologies to improve the quality of the final product, additional scientific research may still contribute greatly to the maximization of the production process [1,2].

Such technologies include the use of irrigation to mitigate the effect of water scarcity, and the use of fertigation to increase the efficient use of nutrients in sugarcane production. Despite these technologies being interesting and viable alternatives, they are still rarely used in sugarcane producing countries. Irrigation promotes economic, social, and environmental sustainability, and is also an important tool to increase sugarcane productivity [3–7]. The use of fertilizers via irrigation (fertigation) reduces losses without increasing production costs, moreover, irrigation alone greatly affects the stalk, sugar, and alcohol yield variables, but fertigation usually intensifies these increases [8–11], and has thus become a relevant technique to supply the water and nutrients required by sugarcane. Due to the importance of this technique, a further understanding of the characteristics related to water and nutrient supply may contribute to significant improvements of sugarcane management systems to obtain higher yields [12].

Nitrogen (N) and zinc (Zn) have been shown to have varied effects on sugarcane (cane-plant), and significant increases in productivity and yield may or may not be associated with the use of these nutrients. Although this ambiguity and the importance of these nutrients are recognized, studies on the association of N and Zn, mainly administered via irrigation water (fertigation), remain limited [13–16].

Therefore, the objective of this study was to evaluate the stalk productivity (SP) and sugar and alcohol yields of plant and ratoon crops of sugarcane (variety IACSP 95-5000) under N and Zn fertigation treatments using a central pivot, in Cerrado Red Latosol soil.

2. Material and Methods

The sugarcane (*Saccharum officinarum* L) experiment was conducted under field conditions at an average altitude of 907 m in an area of the Raízen Mill, in the municipality of Jataí, Goiás (GO), Brazil (17°44′2.62′ S and 51°39′6.06′ W). The area is characterized, which is irregularly distributed throughout the year, by an annual rainfall of ~1800 mm, with rain from October to April and little to no rain from May to September. According to the classification described by Köppen [17], the local climate is tropical savannah with a dry winter (Aw). The minimum and maximum temperatures range from 12 to 15 °C and 35 to 37 °C, respectively. The average temperature during the experiment was 23.50 and 23.20 °C, average relative humidity was 66.35 and 65.50%, and average rainfall was 115.60 and 103.10 mm, in plant and ratoon crops, respectively (Figure 1).

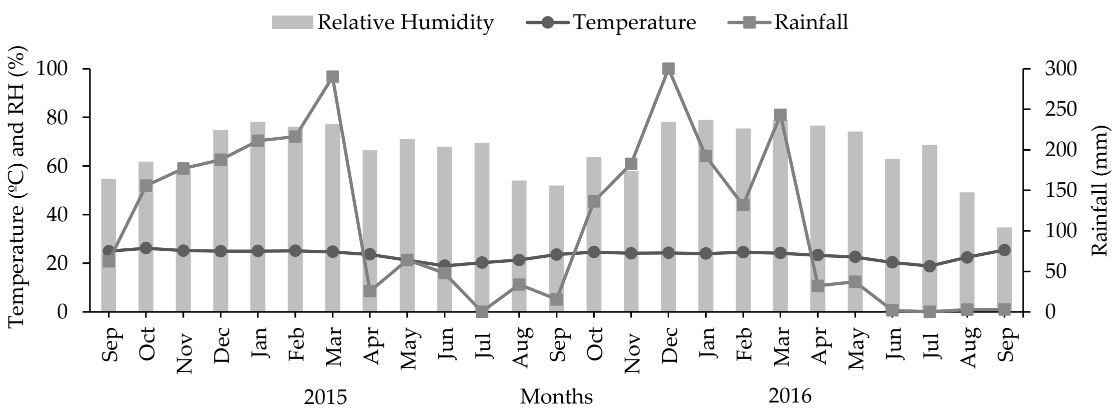

Figure 1. Monthly data on temperature, rainfall, and relative humidity (RH) throughout the experimental period in Jataí-GO, 2015/16. Source: INMET Normal Station-Jataí-GO.

The soil in the experimental area is classified as dystrophic Red Latosol, is very clayey, and in the Cerrado phase [18]. The characteristics and classifications of the soils in the experimental area are described in Table 1.

Table 1. Physical, chemical, and hydrographic characteristics, and the textural and granulometry classifications of the soil in the experimental area, Jataí-GO.

Layer [1] m	pH $CaCl_2$	OM g dm^{-3}	P	S	K	Ca	Mg	Al	H+Al	CEC	V %
			mg dm^{-3}				mmol$_c$ dm^{-3}				
0.0–0.1	5.4	81	33	4.0	4.8	5.4	81	33	4.0	4.8	5.4
0.1–0.2	5.6	75	12	7.0	4.7	5.6	75	12	7.0	4.7	5.6
0.2–0.4	5.7	74	16	12.0	4.8	5.7	74	16	12.0	4.8	5.7
Layer m		**B**			**Cu**		**Fe**	**Mn**		**Zn**	
					mg dm^{-3}						
0.0–0.1		0.22			1.2		73	3.9		1.0	
0.1–0.2		0.16			1.0		46	1.8		1.2	
0.2–0.4		0.20			1.1		55	2.9		0.2	
Layer	**Granulometry (g kg^{-1})**				**FC**		**PWP**	**Textural Classification**			
m	**Sand**	**Silt**	**Clay**		**%**						
0.0–0.1	96	82	822		46.3		22.6	Very clayey			
0.1–0.2	97	82	822					Very clayey			
0.2–0.4	85	71	845		45.8		22.6	Very clayey			

[1] For soil determinations, soil samples with undeformed structure were collected in Uhland rings of 6.34 cm in diameter and 5 cm in height. FC: Field capacity; PWP: permanent wilting point; P, K, Ca, and Mg: Resin; S: Calcium phosphate 0.01 mol L^{-1}; Al: KCl 1 mol L L^{-1}; H+Al: SMP; B: hot water; Cu, Fe, Mn, and Zn: DTPA; OM: Organic matter; pH: in $CaCl_2$; CEC: Cation exchange capacity; V: Saturation of CEC by bases.

A randomized block design was used, with a 4 × 5 split-plot arrangement and three replications. The fertilization treatments consisted of four doses of N (0, 60, 120, and 180 kg ha^{-1}) and five doses of Zn (0, 2.5, 5.0, 7.5, and 10.0 kg ha^{-1}) in plant and ratoon crops. The size of the experimental plot was of 0.2 ha. The fertilization treatments were established considering the indication of 60 kg ha^{-1} of N and 5 kg ha^{-1} of Zn [19]. N fertilization treatments, in the form of urea, were divided into three applications from 60 days after planting (applied in phenophase of tillering). Zn fertilization, in the form of Zn sulfate, was applied in a single application (applied after planting). The urea and Zn sulfate applied by pivot. All treatments were fertilized in the furrow with P_2O_5 (100 kg ha^{-1}) in the form of triple superphosphate, K_2O (80 kg ha^{-1}) in the form of potassium chloride, and micronutrients, except Zn, according to soil analysis results and recommendations by Sousa and Lobato [19].

The variety used in the experiment was IACSP95-5000, under plant cane conditions. This variety is mainly characterized by a high agricultural production, upright position, excellent ratoon sprouting, high sucrose content, resistance to the major diseases, favorable tillering and canopy closure in medium environments, and does not flower or exhibit tumbling [20].

Soil was prepared using the conventional system, through ploughing and harrowing, followed by the opening of the planting furrows. Planting was mechanized, carried out commercially, and following the recommended number of buds per meter for the specific variety used.

Irrigation was performed by a central pivot, model PC 08-64/03-647/01-646/L4 + AC, made of galvanized steel, under low pressure, with 12 support towers. Irrigation was applied over a total area of 139.31 ha at a speed of 268 m h^{-1} in the last tower, applying a minimum gross blade of 1.35 mm (for one turn to 100%). The irrigation was managed using the IRRIGER® software.

Sugarcane degree (°) Brix was monitored in the field in the four weeks prior to harvesting. The maturation index (MI) was determined using a portable refractometer to establish the sugarcane time of harvesting, MI classified according to Rosseto [21].

Sugarcane was harvested 330 days after planting. The stalk production (SP) was determined by weighing the stalks present in the respective subplots, quantifying the stalk weight within 2 m of the two central lines. For this, the stalks were cut as close as possible to the soil. The stalks were then spread out and the pointers were detached. The stalks were weighed on a hook-type digital scale (Soil Control) with an accuracy of 0.02 kg and a capacity of 50 kg.

A total of 10 stalks were randomly sampled from each plot at harvest and sent to the laboratory of agro-industrial processes of the Raízen Plant, in Jataí, GO, for determination of sugar and alcohol yields, using to the CONSECANA system [22].

Sugar and alcohol yields were calculated from the amount of raw sugar determined in the technological analysis, following [23], using Equations (1) and (2), respectively:

$$\mathrm{RAç} = \frac{\mathrm{PCC} \times \mathrm{SP}}{100}, \tag{1}$$

where RAç indicates the sugar yield (kg ha^{-1}); PCC indicates the amount of raw sugar (%) contained in the stalks as determined by the laboratory; SP indicates the stalk production (t ha^{-1}).

$$\mathrm{RA} = ((\mathrm{PCC} \times \mathrm{F}) + \mathrm{ARL}) \times \mathrm{Fg} \times 10 \times \mathrm{SP}, \tag{2}$$

where RA indicates the alcohol yield (m^3 ha^{-1}); PCC indicates the amount of raw sugar (%) contained in the stalks as determined by the laboratory; F indicates the stoichiometric transformation factor of sucrose into one molecule of glucose and one molecule of fructose, equal to 1.052; ARL indicates the free reducing sugars (%), whose values vary from 0.70% to 0.85%, (the distillery uses 0.7 for high PCC values); Fg indicates the Gay Lussac factor, equal to 0.6475; SP indicates the stalk production (t ha^{-1}).

The data were subjected to analysis of variance and the F test ($p < 0.05$). Significant findings were subjected to a regression analysis of the N and Zn fertilization levels using the SISVAR® statistical software [24].

3. Results and Discussion

The productivity (SP) of plant crops in response to the N doses was adjusted using the linear model, with $R^2 > 92.90\%$ (Figure 2A). Compared with the control (0 kg ha^{-1} of N), the SP increased by 10.30%, 13.90%, 15.10%, 13.80%, and 12.90% when treated with 60 kg ha^{-1} of N and increased by 30.90%, 41.80%, 45.20%, 41.30%, and 38.90% when treated with 180 kg ha^{-1} of N, at the Zn doses of 0, 2.5, 5.0, 7.5, and 10.0 kg ha^{-1}, respectively. The SP also increased by 0.20, 0.32, 0.36, 0.35, and 0.35 t ha^{-1} for each 1 kg ha^{-1} increase in N at the Zn doses of 0, 2.5, 5.0, 7.5, and 10.0 kg ha^{-1}, respectively (Figure 2A).

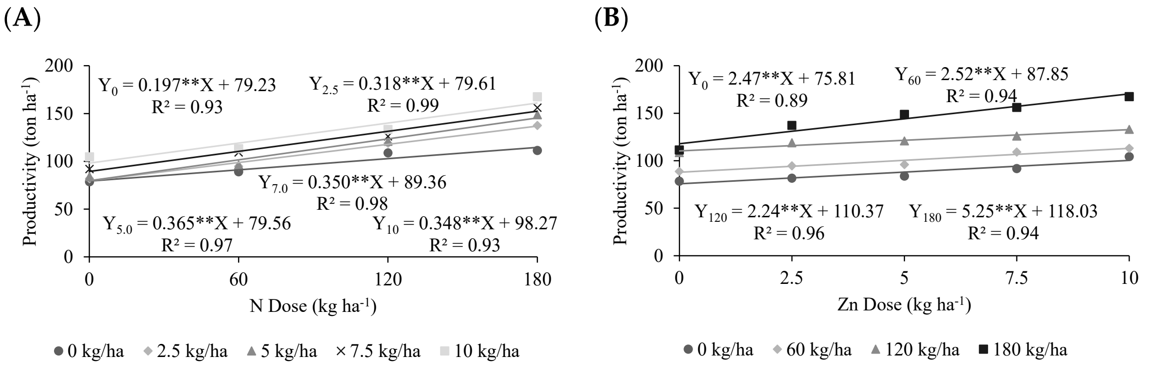

Figure 2. Sugarcane productivity (plant crops) in response to nitrogen (**A**) and zinc (**B**) fertigation doses, under field conditions in Jataí, GO, Brazil. ** significant at $p < 0{,}01$ probability according to the F test. Doses of Zn, Y_0: 0 kg ha^{-1} of Zn, $Y_{2.5}$: 2.5 kg ha^{-1} of Zn, $Y_{5.0}$: 5.0 kg ha^{-1} of Zn, $Y_{7.5}$: 7.5 kg ha^{-1} of Zn and Y_{10}: 10 kg ha^{-1} of Zn (**A**). Doses of N, Y_0: 0 kg ha^{-1} of N, Y_{60}: 60 kg ha^{-1} of N, Y_{120}: 120 kg ha^{-1} of N, Y_{180}: 180 kg ha^{-1} of N (**B**).

Teodoro et al. [25] reported that the marginal substitution rate of irrigation water for N is not fixed, and increases as the irrigation depth decreases, but only to a certain level. These authors also reported that the response of sugarcane to N fertilization, based on the straight line that limits the production region, increases in direct relation to the water availability of the soil.

Joris [26] observed that the absorption of N from fertilizer is lower in medium textured soil than in clayey soil when applied in similar quantities and times; thus concluding that high doses of N (above 120 kg ha^{-1}) can increase sugarcane SP in responsive environments. In the present study, N significantly increased the SP and sucrose content of sugarcane (plant crops), thus consequently increasing the sugar yield, under the Zn applications. In addition, a relationship exists between productivity and evapotranspiration in sugarcane, therefore, sugarcane growth and development are directly proportional to the transpired water [27,28]. These findings indicate that N and Zn fertigation can significantly improve sugarcane SP.

The SP of plant crops in response to the Zn doses was adjusted using the linear model, with $R^2 > 88\%$ (Figure 2B). Compared with the control (0 kg ha^{-1} of Zn), the SP increased by 6.10%, 5.60%, 4.20%, and 7.70% when treated with 2.5 kg ha^{-1} of Zn and increased by 24.60%, 22.30%, 16.90%, and 30.80% when treated with 10 kg ha^{-1} of Zn at N doses of 0, 60, 120, and 180 kg ha^{-1}, respectively. Sugarcane SP also increased by 2.47, 2.52, 2.24, and 5.25 t ha^{-1} for each 1 kg ha^{-1} increase in Zn at N doses of 0, 60, 120, and 180 kg ha^{-1}, respectively (Figure 2B).

The application of nutrients via irrigation water promoted a significant increase in sugarcane productivity (>22%). In addition to a productivity of 152 t ha^{-1}, sugarcane extracts 1.4 kg ha^{-1} of Mn and 2.3 kg ha^{-1} of Zn [29,30]. This SP is similar to the results obtained in the present study in the fertigation treatment with 7.5 kg ha^{-1} of Zn and 180 kg ha^{-1} of N, and is lower than the fertigation treatment with 10.0 kg ha^{-1} of Zn and 180 kg ha^{-1} of N (Figure 2B).

An increased nutrient supply (N and Zn) has been shown to result in vigorous sugarcane growth [31], consequently resulting in sugarcane plants with maximum height and diameters, and improved total recoverable sugar (TRS) and sugarcane SP. In the present study, the productivity of sugarcane fertigated with the highest doses of N and Zn was >160 t ha^{-1}. Becari [32] reported that Zn application resulted in a sugarcane SP of 157 t ha^{-1}, which was 21.7% higher than the productivity (of variety SP 81−3 250) obtained in the controls planted in Red Latosol with low Zn content.

The SP of ratoon crops in response to the N doses was adjusted using the linear model, with $R^2 > 82\%$ (Figure 3A). Compared with the control (0 kg ha^{-1} of N), the SP increased by 8.70%, 6.60%, 6.90%, 6.10%, and 4.60% when treated with 60 kg ha^{-1} of N and increased by 26.20%, 19.80%, 20.60%, 18.30%, and 13.70% when treated with 180 kg ha^{-1} of N, at the Zn doses of 0, 2.5, 5.0, 7.5, and 10.0 kg ha^{-1}, respectively. Sugarcane SP also increased by 0.14, 0.12, 0.14, 0.13, and 0.11 t ha^{-1} for each 1 kg ha^{-1} increase in N at the Zn doses of 0, 2.5, 5.0, 7.5, and 10.0 kg ha^{-1}, respectively (Figure 3A).

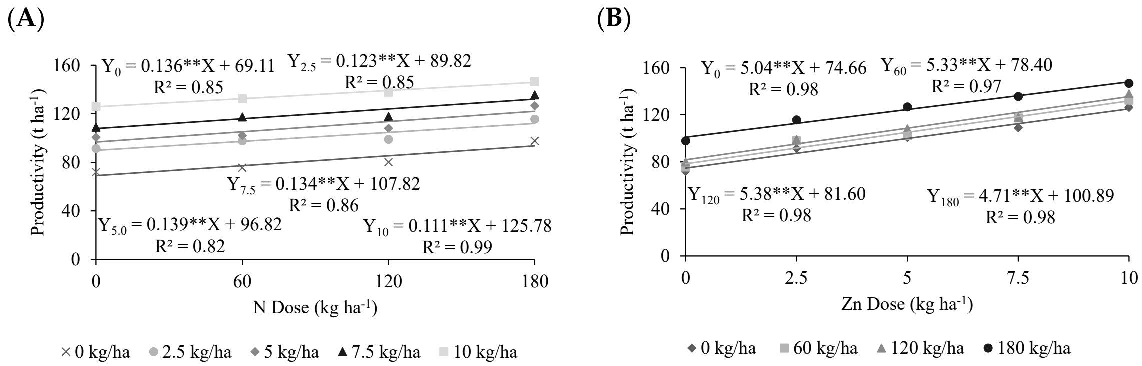

Figure 3. Sugarcane productivity (ratoon crops) in response to nitrogen (**A**) and zinc (**B**) fertigation doses under field conditions in Jataí, GO, Brazil. ** significant at $p < 0{,}01$ probability according to the F test. Doses of Zn, Y_0: 0 kg ha^{-1} of Zn, $Y_{2.5}$: 2.5 kg ha^{-1} of Zn, $Y_{5.0}$: 5.0 kg ha^{-1} of Zn, $Y_{7.5}$: 7.5 kg ha^{-1} of Zn and Y_{10}: 10 kg ha^{-1} of Zn (**A**). Doses of N, Y_0: 0 kg ha^{-1} of N, Y_{60}: 60 kg ha^{-1} of N, Y_{120}: 120 kg ha^{-1} of N, Y_{180}: 180 kg ha^{-1} of N (**B**).

Orlando Filho et al. [33] evaluated the cumulative effect of increasing doses of N fertilization on the productivity of plant cane and three consecutive ratoon cycles and reported increases of 20%

and 30% for doses of 60 and 120 kg ha^{-1} of N, respectively, compared to the control. The inadequate management of a sugarcane field, especially with regards to N fertilization, can result in decreases in both crop productivity and longevity [34].

The SP of ratoon crops in response to the Zn doses was adjusted using the linear model, with R^2 > 97% (Figure 3B). The SP increased by 10.10%, 10.10%, 9.90%, and 7.90% when treated with 2.5 kg ha^{-1} of Zn at N doses of 0, 60, 120, and 180 kg ha^{-1}, respectively. Sugarcane SP also increased by 5.00, 5.30, 5.40, and 4.70 t ha^{-1} for each 1 kg ha^{-1} increase in Zn at N doses 0, 60, 120, and 180 kg ha^{-1}, respectively (Figure 3B).

Nutrient availability in the soil is one of the major factors that limits the mean productivity of sugarcane [35–37]. Although fertilization is used to increase the soil nutrient availability, it can have a significant impact on the production costs of sugarcane, accounting for up to 25% of these costs.

The sugar yield of plant crops in response to the N doses was adjusted using the linear model, with R^2 > 92% (Figure 4A). Compared with the control (0 kg ha^{-1} of N), the sugar yield increased by 12.00%, 14.90%, 15.80%, 14.70%, and 14.30% when treated with 60 kg ha^{-1} of N and increased by 36.10%, 44.70%, 47.60%, 43.90%, and 42.80% when treated with 180 kg ha^{-1} of N, at the Zn doses of 0, 2.5, 5.0, 7.5, and 10.0 kg ha^{-1}, respectively. The sugar yield increased by 0.06 t ha^{-1} for each 1 kg ha^{-1} increase in N at the Zn dose of 10 kg ha^{-1} (Figure 4A). The maximum sugar yield (>23 t ha^{-1}) was obtained in the fertigation treatment with 10 kg ha^{-1} of Zn and 180 kg ha^{-1} of N. Gouveia Neto [38] evaluated the sugar yield of sugarcane (plant crops) irrigated and fertilized with 130 kg ha^{-1} and reported a mean sugar yield of 17.79 t ha^{-1}.

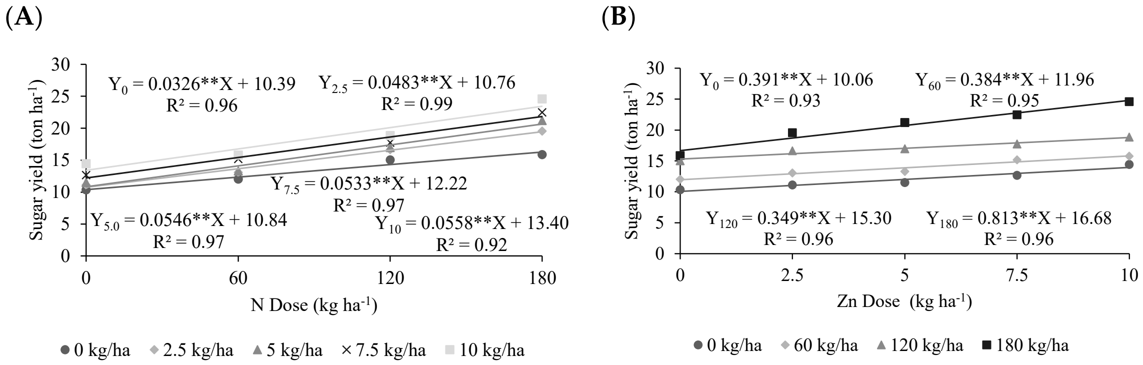

Figure 4. Sugar yield of sugarcane (plant crops) in response to nitrogen (**A**) and zinc (**B**) fertigation doses, under field conditions in Jataí, GO, Brazil. ** significant at p < 0,01 probability according to the F test. Doses of Zn, Y_0: 0 kg ha^{-1} of Zn, $Y_{2.5}$: 2.5 kg ha^{-1} of Zn, $Y_{5.0}$: 5.0 kg ha^{-1} of Zn, $Y_{7.5}$: 7.5 kg ha^{-1} of Zn and Y_{10}: 10 kg ha^{-1} of Zn (**A**). Doses of N, Y_0: 0 kg ha^{-1} of N, Y_{60}: 60 kg ha^{-1} of N, Y_{120}: 120 kg ha^{-1} of N, Y_{180}: 180 kg ha^{-1} of N (**B**).

Sugarcane crops fertigated with high doses of N usually presented significant increases in sugar productivity (>22 t ha^{-1}), because sugarcane tends to show improved growth and development, which are normally associated with increases in the final values of alcohol and sugar production, in response to nutrient application via irrigation water [11,39].

The sugar yield of plant crops in response to the Zn doses was adjusted using the linear model, with R^2 > 93% (Figure 4B). Compared with the control (0 kg ha^{-1} of Zn), the sugar yield increased by 7.00%, 6.10%, 4.60%, and 8.20% when treated with 2.5 kg ha^{-1} of Zn and increased by 28.00%, 24.30%, 18.60%, and 32.80% when treated with 10 kg ha^{-1} of Zn, at N doses of 0, 60, 120, and 180 kg ha^{-1}, respectively. The sugar yield of sugarcane also increased by 0.39, 0.38, 0.35, and 0.81 t ha^{-1} for each 1 kg ha^{-1} of Zn increase at N doses of 0, 60, 120, and 180 kg ha^{-1}, respectively (Figure 4B).

The sugar yield of ratoon crops in response to the N doses was adjusted using the linear model, with R^2 > 84% (Figure 5A). Compared with the control (0 kg ha^{-1} of N), the sugar yield increased by 10.70%, 7.90%, 7.90%, 7.30%, and 6.20% when treated with 60 kg ha^{-1} of N and increased by 32.00%, 23.60%, 23.70%, 21.80%, and 18.70% when treated with 180 kg ha^{-1} of N, at the Zn doses of 0, 2.5, 5.0, 7.5, and 10.0 kg ha^{-1}, respectively. The sugar yield of sugarcane fertigated with 10 kg ha^{-1} of Zn indicated an increase of 0.02 t ha^{-1} for each 1 kg ha^{-1} increase in N at the N dose of 180 kg ha^{-1} (Figure 5A).

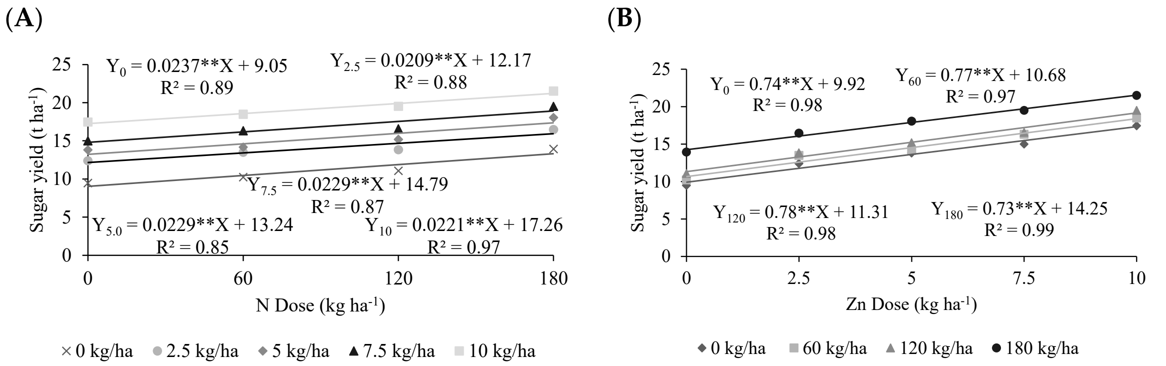

Figure 5. Sugar yield of sugarcane (ratoon crops) in response to nitrogen (**A**) and zinc (**B**) fertigation doses, under field conditions in Jataí, GO, Brazil. ** significant at $p < 0{,}01$ probability according to the F test. Doses of Zn, Y_0: 0 kg ha^{-1} of Zn, $Y_{2.5}$: 2.5 kg ha^{-1} of Zn, $Y_{5.0}$: 5.0 kg ha^{-1} of Zn, $Y_{7.5}$: 7.5 kg ha^{-1} of Zn and Y_{10}: 10 kg ha^{-1} of Zn (**A**). Doses of N, Y_0: 0 kg ha^{-1} of N, Y_{60}: 60 kg ha^{-1} of N, Y_{120}: 120 kg ha^{-1} of N, Y_{180}: 180 kg ha^{-1} of N (**B**).

Maschio [40] observed a gross sugar yield variation between 19.5 and 27.5 t ha^{-1} and lower raw sugar yields were reported for the varieties RB855453 (22.0 t ha^{-1}), CTC8 (21.6 t ha^{-1}), CTC14 (20.4 t ha^{-1}), and SP81−3 250 (19.5 t ha^{-1}).

The sugar yield of ratoon crops in response to the Zn doses was adjusted using the linear model, with $R^2 > 97\%$ (Figure 5B). The sugar yield increased by 10.70%, 10.50%, 10.20%, and 8.50% when treated with 2.5 kg ha^{-1} of Zn at N doses of 0, 60, 120, and 180 kg ha^{-1}, respectively. The sugar yield of sugarcane also increased by 0.74, 0.77, 0.78, and 0.73 t ha^{-1} for each 1 kg ha^{-1} increase in Zn at N doses of 0, 60, 120, and 180 kg ha^{-1}, respectively (Figure 5B).

The alcohol yield of plant crops in response to the N doses was adjusted using the linear model, with $R^2 > 92\%$ (Figure 6A). Compared with the control (0 kg ha^{-1} of N), the alcohol yield increased by 11.90%, 14.80%, 15.80%, 14.60%, and 14.20% when treated with 60 kg ha^{-1} of N and increased by 35.86%, 44.53%, 47.49%, 43.86%, and 42.67% when treated with 180 kg ha^{-1} of N, at the Zn doses of 0, 2.5, 5.0, 7.5, and 10.0 kg ha^{-1}, respectively. The alcohol yield of sugarcane increased by 0.04 m^3 ha^{-1} for each 1 kg ha^{-1} increase in N at the Zn dose of 10 kg ha^{-1} (Figure 6A).

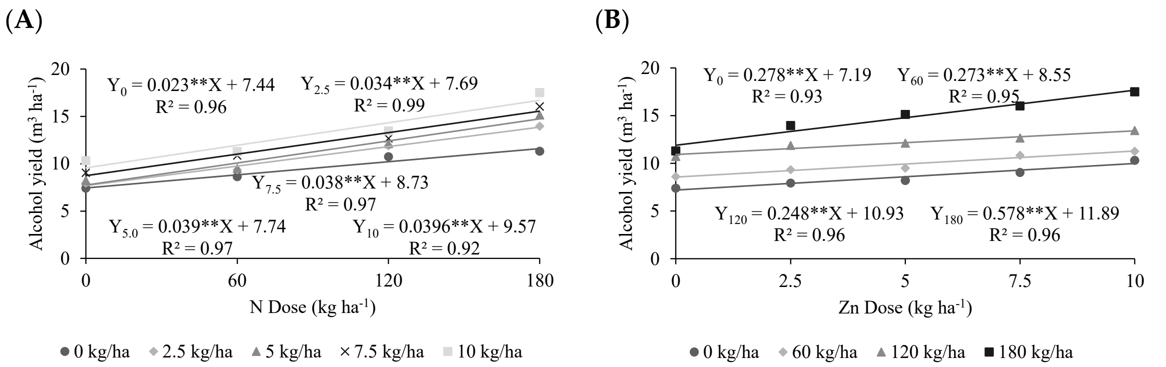

Figure 6. Alcohol yield of sugarcane (plant crops) in response to nitrogen (**A**) and zinc (**B**) fertigation doses, under field conditions in Jataí, GO, Brazil. ** significant at $p < 0{,}01$ probability according to the F test. Doses of Zn, Y_0: 0 kg ha^{-1} of Zn, $Y_{2.5}$: 2.5 kg ha^{-1} of Zn, $Y_{5.0}$: 5.0 kg ha^{-1} of Zn, $Y_{7.5}$: 7.5 kg ha^{-1} of Zn and Y_{10}: 10 kg ha^{-1} of Zn (**A**). Doses of N, Y_0: 0 kg ha^{-1} of N, Y_{60}: 60 kg ha^{-1} of N, Y_{120}: 120 kg ha^{-1} of N, Y_{180}: 180 kg ha^{-1} of N (**B**).

The maximum alcohol yield (>15 m^3 ha^{-1}) was found in sugarcane fertigated with 10 kg ha^{-1} of Zn and 180 kg ha^{-1} of N. Alcohol yields 12 m^3 ha^{-1} have been observed in sugarcane irrigated and fertilized with N doses >100 kg m^3 ha^{-1} [39,41].

The alcohol yield of plant crops in response to the Zn doses was adjusted using the linear model, with R^2 > 93% (Figure 6B). Compared with the control (0 kg ha^{-1} of Zn), the alcohol yield increased by 6.96%, 6.00%, 4.60%, and 8.17% when treated with 2.5 kg m^3 ha^{-1} of Zn and increased by 27.80%, 24.20%, 18.50%, and 32.70% when treated with 10 kg ha^{-1} of Zn, at N doses of 0, 60, 120, and 180 kg m^3 ha^{-1}, respectively. The alcohol yield also increased by 0.28, 0.27, 0.25, and 0.58 m^3 ha^{-1} for each 1 kg ha^{-1} increase in Zn at N doses of 0, 60, 120, and 180 kg ha^{-1}, respectively (Figure 6B).

Chandiposha et al. [42] reported increases in plant height, stem diameter, productivity, and sugar and alcohol yields in sugarcane due to the additional availability of N and Zn. Increased N and Zn doses have been shown to increase the accumulation of stalk dry matter, total aerial dry matter, and the number and length of internodes; thus improving the growth of plants and resulting in higher sugar and alcohol yields [11,41,43].

The alcohol yield of ratoon crops in response to the N doses was adjusted using the linear model, with R^2 > 84.8% (Figure 7A). Compared with the control (0 kg ha^{-1} of N), the alcohol yield increased by 10.57%, 7.82%, 7.89%, 7.21%, and 6.10% when treated with 60 kg ha^{-1} of N and increased by 31.70%, 23.40%, 23.70%, 21.60%, and 18.40% when treated with 180 kg ha^{-1} of N, at the Zn doses of 0, 2.5, 5.0, 7.5, and 10.0 kg ha^{-1}, respectively. The alcohol yield of sugarcane fertigated with 10 kg ha^{-1} of Zn indicated an increase of 0.01 m^3 ha^{-1} for each 1 kg ha^{-1} increase in N at the N dose of 180 kg ha^{-1} (Figure 7A).

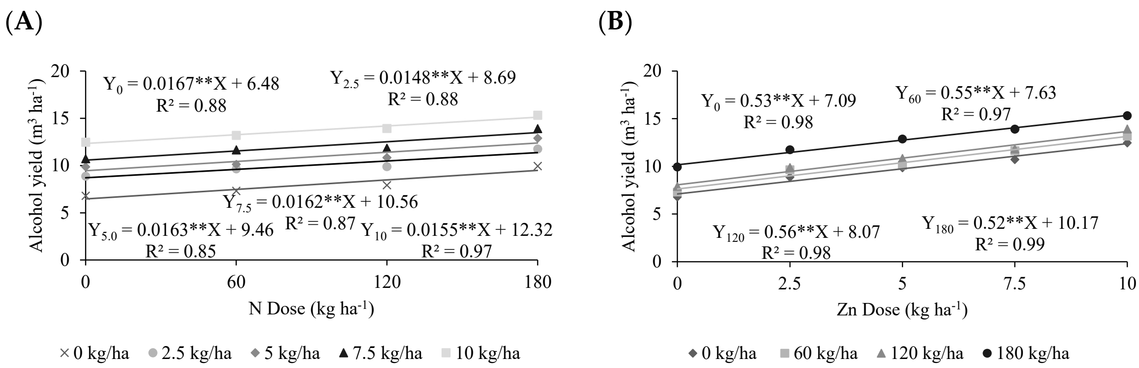

Figure 7. Alcohol yield of sugarcane (ratoon crops) in response to nitrogen (**A**) and zinc (**B**) fertigation doses, under field conditions in Jataí, GO, Brazil. ** significant at p < 0,01 probability according to the F test. Doses of Zn, Y_0: 0 kg ha^{-1} of Zn, $Y_{2.5}$: 2.5 kg ha^{-1} of Zn, $Y_{5.0}$: 5.0 kg ha^{-1} of Zn, $Y_{7.5}$: 7.5 kg ha^{-1} of Zn and Y_{10}: 10 kg ha^{-1} of Zn (**A**). Doses of N, Y_0: 0 kg ha^{-1} of N, Y_{60}: 60 kg ha^{-1} of N, Y_{120}: 120 kg ha^{-1} of N, Y_{180}: 180 kg ha^{-1} of N (**B**).

Carvalho et al. [44] reported increases in the gross yield of alcohol and SP in response to an increased irrigation level. Other studies also reported increased growth, productivity, technological quality, and gross yields of alcohol and sugar in sugarcane fertigated with N [41,45–47].

The alcohol yield of ratoon crops in response to the Zn doses was adjusted using the linear model, with R^2 > 97% (Figure 7B). The alcohol yield increased by 10.67%, 10.48%, 10.23%, and 8.43% when treated with 2.5 kg ha^{-1} of Zn at N doses of 0, 60, 120, and 180 kg ha^{-1}, respectively. The alcohol yield of sugarcane also increased by 0.53, 0.55, 0.56, and 0.52 m^3 ha^{-1} for each 1 kg ha^{-1} increase in Zn at N doses of 0, 60, 120, and 180 kg ha^{-1}, respectively (Figure 7B).

Azevedo [48] researched plant cane and reported a maximum gross alcohol yield of 11.50 m^3 ha^{-1} with a total quantity of water of 1043 mm. Cunha et al. [41] reported that the gross alcohol yield increased by 0.03 m^3 ha^{-1} for each 1% increase in water replacement in sugarcane.

4. Conclusions

The sugar and alcohol yield of sugarcane (plant crops) in relation to zinc doses is potentiated with the use of 180 kg ha^{-1} nitrogen fertigation, in which the increments are significant (0.81 ton ha^{-1} and 0.58 m^3 ha^{-1}) for each 1 kg ha^{-1} increase in Zn, in the other doses (0, 60, 120 kg ha^{-1} of N), these increases practically do not vary (0.37 ton ha^{-1} and 0.27 m^3 ha^{-1}).

Compared with the control (without N fertigation), the sugarcane productivity (plant and ratoon crops) increased by 38.90% and 13.70% when treated with 180 kg ha^{-1} of N at the Zn dose of 10 kg ha^{-1}.

Compared with the control (without Zn fertigation), the sugarcane productivity (plant and ratoon crops) increased by 30.80% and 31.83% when treated with the maximum dose of zinc and N, respectively; the increase in sugarcane productivity is the same in plant and ratoon crops that shows the benefit of Zn fertigation.

The sugar and alcohol yields of sugarcane (variety IACSP 95-5000) were improved with the fertigation of 180 kg ha^{-1} of N, in relation to Zn doses. The recommended Zn dose for irrigated sugarcane or with high doses of N fertilization is 10 kg ha^{-1}.

The recommendation of highest doses of zinc and nitrogen in sugarcane (plant and ratoon crops) had the greatest effects on the productive potential of the crop, providing better sugar and alcohol yields. Sugarcane (variety IACSP 95-5000) has the productive performance, sugar and alcohol yield, optimized and maximized when fertigated with 10 kg ha^{-1} of zinc and 180 kg ha^{-1} of nitrogen.

Author Contributions: The authors F.N.C., M.B.T., E.C.d.S., N.F.d.S., C.T.S.C., V.M.V., W.A.M., L.N.S.d.S., F.R.C.F., D.K.M.A., J.A.B.S. and L.F.G. have contributed equally to the research design, development, and the writing of the manuscript. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by National Council for Scientific and Technological Development–CNPq grant number 305218, Ministry of Science, Technology, Innovation, and Communications–MCTIC grant number 446999, the Coordination for the Improvement for Higher Level Personnel-CAPES, the Research Support Foundation of the State of Goiás-FAPEG and the APC was funded by Federal Institute of Education, Science, and Technology Goiano (IFGoiano) - Campus Rio Verde.

Acknowledgments: The authors thank the National Council for Scientific and Technological Development (CNPq); the Coordination for the Improvement for Higher Level Personnel (CAPES); the Research Support Foundation of the State of Goiás (FAPEG); the Ministry of Science, Technology, Innovation, and Communications (MCTIC); the Raízen Plant Jataí unit; and the Federal Institute of Education, Science, and Technology Goiano (IFGoiano) - Campus Rio Verde, for the financial and structural support to conduct this study.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Costa, M.C.G. Eficiência Agronômica de Fontes Nitrogenadas na Cultura da Cana-de-Açúcar em Sistema de Colheita sem Despalha a Fogo. Master's Thesis, Escola Superior de Agricultura "Luiz de Queiróz", Piracicaba, Brazil, 2001; p. 79.
2. Regis, J.A.V.B. Adaptabilidade e Estabilidade Fenotípica de Clones de Cana-de-Açúcar em Dois Ciclos Produtivos. Master's Thesis, Universidade Estadual Paulista, Júlio de Mesquita Filho, UNESP, Ilha Solteira, Brazil, 2016; p. 56.
3. Inman, B.N.G. Sugarcane water stress criteria for irrigation and drying off. *Field Crops Res.* **2004**, *89*, 107–122. [CrossRef]
4. Dantas Neto, J.; Figueredo, J.L.C.; Farias, C.H.A.; Azevedo, H.M.; Azevedo, C.A.V. Resposta da cana -de -açúcar, primeira soca, a níveis de irrigação e adubação de cobertura. *Rev. Bras. Eng. Agrícola Ambient.* **2006**, *10*, 283–288. [CrossRef]
5. Salassier, B. Manejo da Irrigação na Cana-de-Açúcar. Available online: http://www.agencia.cnptia.embrapa.br/Repositorio/Cana_irrigada_producao_000fi (accessed on 20 February 2020).
6. Dalri, A.B.; Cruz, R.L. Produtividade da cana-de-açúcar fertirrigada com N e K via gotejamento subsuperficial. *Irrig. Botucatu* **2008**, *28*, 516–524. [CrossRef]
7. Mussi, R.F.; Alves Junio, J.; Evangelista, A.W.P.; Casaroli, D.; Flores, R.A. Produção de cana-de-açúcar irrigada e fertirrigada com efluente urbano de Goiânia-GO. *Rev. Agrotecnologia Ipameri* **2017**, *8*, 46–54. [CrossRef]

8. Dalri, A.B.; Cruz, R.L. Efeito da frequência de irrigação subsuperficial por gotejamento no desenvolvimento da cana-de-açúcar (*Saccharum* spp.). *Irrig. Botucatu* **2002**, *7*, 29–34. [CrossRef]
9. Moura, M.V.P.S.; Farias, C.H.A.; Azevedo, C.A.V.; Pontes Neto, J.; De Azevedo, H.M.; Pordeus, R.V. Doses de adubação nitrogenada e potássica em cobertura na cultura da cana-de-açúcar, primeira soca, com e sem irrigação. *Ciência Agrotécnica* **2005**, *29*, 753–760. [CrossRef]
10. Roberts, T.L. Improving nutrients use efficiency. *Turk. J. Agric. For.* **2008**, *32*, 177–182.
11. Da Silva, N.F.; Cunha, F.N.; De Oliveira, R.C.; Moura, L.M.D.F.; De Moura, L.C.; Teixeira, M.B.; Bastos, F.J.D.C. Crescimento da cana-de-açúcar sob aplicação de nitrogênio via gotejamento subsuperficial. *Rev. Bras. Agric. Irrig.* **2014**, *8*, 1–11. [CrossRef]
12. Rhein, A.F.L. Produtividade e Qualidade da Cana-de-Açúcar Sob Doses de Nitrogênio Via Fertirrigação Subsuperficial por Gotejamento. Ph.D. Thesis, Faculdade de Ciências Agronômicas, Universidade Estadual Paulista, Botucatu, Brazil, 2012; p. 117.
13. Anderson, D.L.; Bowen, J.E. *Nutrição da Cana de Açúcar*; POTAFOS: Piracicaba, São Paulo, Brazil, 1992; p. 40.
14. Farias, C.H.A. *Otimização do Uso da Água e do Zinco na Cana-de-Açúcar em Tabuleiro Costeiro Paraibano. Universidade Federal de Campina Grande*; Centro de Tecnologia e Recursos Naturais: Campina Grande, Brazil, 2006; p. 142.
15. Cunha, F.N. Crescimento e Rendimento da Cana-de-Açúcar Submetida a Diferentes Níveis de Água por Gotejamento. Master's Thesis, Instituto Federal Goiano, Goiânia, Brazil, 2014; p. 76.
16. Mellis, E.V.; Quaggio, J.A.; Teixeira, L.A.J. *Boletim Zinco: Cana-de-Açúcar. Iniciativa Nutriente Zinco (ZNI)*; IAC: Campinas, São Paulo, Brasil, 2014; pp. 1–6.
17. Köppen, W. Köppen Climate Classification. Geography about. Available online: http://geography.about.com/library/weekly/aa011700b.htm (accessed on 2 February 2020).
18. Santos, H.G.; Jacomine, P.K.T.; Anjos, L.H.C.; Oliveira, V.Á.; Oliveira, J.B.; Coelho, M.R.; Lumbreras, J.F.; Cunha, T.J.F. *Sistema Brasileiro de Classificação de Solo. Empresa Brasileira de Pesquisa Agropecuária*, 3rd ed.; Centro Nacional de Pesquisa de Solos: Rio de Janeiro, Brazil, 2013; p. 353.
19. Sousa, D.M.G.; Lobato, E. *Cerrado: Correção do Solo e Adubação*, 2nd ed.; Embrapa Informação Tecnológica/Embrapa-CPA: Brasília, Brazil, 2004; p. 416.
20. Chaves, V.A.; Dos Santos, S.G.; Schultz, N.; Pereira, W.; Sousa, J.S.; Monteiro, R.C.; Reis, V.M. Desenvolvimento Inicial de Duas Variedades de Cana-de-açúcar Inoculadas com Bactérias Diazotróficas. *Rev. Bras. Ciência Solo* **2015**, *39*, 1595–1602. [CrossRef]
21. Rossetto, R. Maturação da Cana-de-Açúcar. Available online: http://www.agencia.cnptia.embrapa.br/gestor/cana-de-acucar/arvore/CONTAG01_90_22122006154841.html (accessed on 10 January 2020).
22. CONSECANA. *Manual de Instruções. Conselho dos Produtores de Cana-de-Açúcar, Açúcar, Álcool do Estado de São Paulo*, 5th ed.; CONSECANA: Piracicaba, Brazil, 2006; p. 112.
23. Caldas, C. *Manual de Análises Selecionadas Para Indústrias Sucroalcooleiras*; Sindicato da Indústria e do Álcool do Estado de Alagoas: Maceió, Brazil, 1998; p. 424.
24. Ferreira, D.F. Sisvar: A computer statistical analysis system. *Ciência Agrotecnologia* **2011**, *35*, 1039–1042. [CrossRef]
25. Teodoro, I.; Dantas Neto, J.; Souza, J.L.; Lyra, G.B.; Brito, K.S.; Sá, L.A.; Santos, M.A.L.; Sarmento, P.L.V.S. Isoquantas de produtividade da cana-de-açúcar em função de níveis de irrigação e adubação nitrogenada. *Irrig. Botucatu* **2013**, *18*, 387–401. [CrossRef]
26. Joris, H.A.W. Nitrogênio na Produção de Cana-de-Açúcar: Aspectos Agronômicos e Ambientais. Ph.D. Thesis, Instituto Agronômico, IAC, Campinas, Brazil, 2015; p. 134.
27. Franco, H.C.J.; Otto, R.; Vitti, A.C.; Faroni, C.E.; Oliveira, E.C.A.; Fortes, C.; Ferreira, D.A.; Kölln, O.T.; Garside, A.L.; Trivelin, P.C.O. Residual recovery and yield performance of nitrogen fertilizer applied at sugarcane planting. *Sci. Agric.* **2015**, *72*, 528–534. [CrossRef]
28. Leal, D.P.V. Evapotranspiração da Cana-de-Açúcar e Fotossíntese Acumulada em Biomassa e energia, Para Diferentes Variedades, Disponibilidades Hídricas no Solo e Ciclos de Cultivos. Master's Thesis, Escola Superior de Agricultura Luiz de Queiroz, Universidade de São Paulo, Piracicaba, Brazil, 2012.
29. Sousa, S.F.G.; Marasca, I.; Paludo, V.; Silva, P.R.A.; Lanças, K.P. Produtividade da cultura de cana de açúcar com e sem a aplicação de fósforo em profundidade utilizando equipamento de preparo profundo mecanizado. *Energ. Agric. Botucatu* **2015**, *30*, 258–263.

30. Tasso Junior, L.C.; Marques, M.O.; Camilotti, F.; Silva, T. Extração de macronutrientes em cinco variedades de cana-de-açúcar cultivadas na região centro-norte do estado de São Paulo. In *Açúcar, Álcool e Subprodutos*; STAB: Piracicaba, Brazil, 2007; Volume 25, pp. 6–8.
31. Udayakumar, S.; Baskar, K.; Saliha, B.B. Impact of fertilisation on yield and quality of ratoon sugarcane in theni district (India). *J. Int. Acad. Res. Multidiscip.* **2014**, *2*, 9.
32. Becari, G.R.G. Resposta da Cana-Planta à Aplicação de Micronutrientes. Ph.D. Thesis, Instituto Agronômico IAC, Campinas, Brazil, 2010; p. 79.
33. Orlando Filho, J.; Rodella, A.A.; Beltrame, J.A.; Lavorenti, N.A. Doses, fontes e formas de aplicação de nitrogênio em cana-de-açúcar. *STAB* **1999**, *17*, 39–41.
34. Vitti, A.C.; Trivelin, P.C.O.; Gava, G.J.C.; Penatti, C.P.; Bologna, I.R.; Faroni, C.E.; Franco, H.C.J. Produtividade da cana-de-açúcar relacionada ao nitrogênio residual da adubação e do sistema radicular. *Pesqui. Agropecuária Bras.* **2007**, *42*, 249–256. [CrossRef]
35. Trivelin, P.C.O. Utilização do Nitrogênio pela Cana-de-Açúcar: Três Casos Estudados com o Uso do Traçador 15N. Ph.D. Thesis, Escola Superior de Agricultura Luiz de Queiroz, Universidade de São Paulo, Piracicaba, Brazil, 2000; 143p.
36. Marafon, A.C.; Endres, L. Adubação Silicatada em Cana-de-Açúcar. Aracaju: Embrapa Tabuleiros Costeiros. Available online: http://www.infoteca.cnptia.embrapa.br/handle/doc/914935 (accessed on 21 January 2020).
37. Esperancini, M.S.T.; Afonso, P.F.N.; Gava, G.J.C.; Villas Boas, R.L. Dose ótima econômica de nitrogênio em cana-de-açúcar aplicada via fertirrigação por gotejamento. *Irriga* **2015**, *1*, 28–39. [CrossRef]
38. Gouveia, N.C.G. Rendimento Agroindustrial da Cana-de-Açúcar sob Suplementação Hídrica e Parcelamento de Nitrogênio. Ph.D. Thesis, Universidade Federal de Campina Grande, Campina Grande, Brazil, 2012; p. 145.
39. Júnior, A.S.D.A.; Bastos, E.A.; Ribeiro, V.Q.; Duarte, J.A.L.; Braga, D.L.; Noleto, D.H. Níveis de água, nitrogênio e potássio por gotejamento subsuperficial em cana-de-açúcar. *Pesqui. Agropecuária Bras.* **2012**, *47*, 76–84. [CrossRef]
40. Maschio, R. *Produtividade da Água em Biomassa e Energia para 24 Variedades de Cana-de-Açúcar*; Escola Superior de Agricultura, Luiz de Queiroz: Piracicaba, Brazil, 2011; p. 87.
41. Cunha, F.N.; Silva, N.F.; Sousa, A.E.C.; Teixeira, M.B.; Soares, F.A.L.; Vidal, V.M. Yield of sugarcane submitted to nitrogen fertilization and water depths by subsurface drip irrigation. *Rev. Bras. Eng. Agr. Amb.* **2016**, *20*, 841–846. [CrossRef]
42. Chandiposha, M.; Kunedzimwe, N.; Munyaradzi, G.; Chiriman'ombe, D. Comparisons of sugar blend 1 plus fertilizer over straight fertilizer as basal application on growth and yield of sugarcane (*Saccharum officinarum* L.). *Int. J. Agron. Agric. Res.* **2014**, *4*, 89–93.
43. Alloway, B.J. *Zinc in Soils and Crop Nutrition*; International Zinc Association (IZA): Brussels, Belgium, 2004; p. 116.
44. De Carvalho, C.M.; De Azevedo, H.M.; Neto, J.D.; Farias, C.H.D.A.; Silva, C.T.S.; Filho, R.R.G. Rendimento de açúcar e álcool da cana-de-açúcar submetida a diferentes níveis de irrigação. *Rev. Bras. Ciências Agrárias* **2009**, *4*, 72–77. [CrossRef]
45. Sanchez-Roman, R.M.; Silva, N.F.; Cunha, F.N.; Teixeira, M.B.; Soares, F.A.L.; Ribeiro, P.H.P. Produtividade da cana-de-açúcar submetida a diferentes reposições hídricas e nitrogênio em dois ciclos. *Irriga* **2015**, *1*, 198–210. [CrossRef]
46. Da Silva, N.F.; De Moura, L.C.; Cunha, F.N.; Ribeiro, P.H.; Carvalho, J.J.; Teixeira, M.B. Qualidade industrial da cana-de-açúcar fertirrigada sob diferentes lâminas de água no sudoeste goiano. *Rev. Bras. Agric. Irrig.* **2014**, *8*, 280–295. [CrossRef]
47. Da Silva, N.F.; Cunha, F.N.; Teixeira, M.B.; Soares, F.A.L. Crescimento vegetativo da cana-de-açúcar submetida a lâminas de irrigação e fertirrigação nitrogenada via gotejamento subsuperficial. *Rev. Bras. Agric. Irrig.* **2015**, *9*, 79–90. [CrossRef]
48. Azevedo, H.M. Resposta da Cana-de-Açúcar a Níveis de Irrigação e de Adubação de Cobertura Nos Tabuleiros da Paraíba. Ph.D. Thesis, UFCG, Campina Grande, Brazil, 2002; p. 112.