**University of Sao Paulo
“Luiz de Queiroz” College of Agriculture**

Optimal nitrogen management to sugarcane production in different harvest seasons

Gerson José Marquesi de Souza Netto

Dissertation presented to obtain the degree
of Master in Science. Area: Crop Science

**Piracicaba
2019**

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To my wife Juliana, my son Henrique, and my parents Marli and Gerson, for all the unconditional love and support.

I DEDICATE

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“If you only do what you can do, you will
never be more than who you are.”

Jennifer Yuh Nelson

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RESUMO

Manejo otimizado de nitrogênio para cana-de-açúcar em diferentes épocas de corte

A cana-de-açúcar é colhida nove meses por ano no Brasil, com uma ampla variação no balanço hídrico, o que afeta significativamente a resposta ao nitrogênio (N). Contudo, uma única dose de aproximadamente 1,1 kg N por Mg de cana-de-açúcar produzida é usualmente utilizada durante esse período, aplicada em uma única vez algumas semanas após a colheita. Além disso, há uma tendência dos produtores em aumentar as doses de N em função do sistema brasileiro de colheita de cana crua. Este estudo objetiva testar a hipótese de que um manejo otimizado de N será alcançado por meio da averiguação de doses de N em cada época de colheita através do parcelamento ao invés de aplicação única. Cinco experimentos de campo foram conduzidos em cada época de colheita (começo de safra: abril a junho; meio de safra: julho a setembro; final de safra: outubro a dezembro) na região centro-sul do país durante a safra 2016/2017. O delineamento experimental foi uma curva de resposta a doses de N, sendo as doses definidas de acordo com a produtividade obtida na última colheita (0,8; 1,0; 1,2 e 1,4 kg N por Mg de cana-de-açúcar; mais um controle); tratamentos adicionais com parcelamento de N foram testados no começo e meio de safra, mas não no final de safra. A cana-de-açúcar colhida no início de safra apresentou a maior resposta a N quando comparada às áreas colhidas no meio ou final de safra. Maior potencial de resposta a N pode estar relacionado ao menor déficit hídrico sofrido nos locais colhidos em início de safra. O parcelamento de N mostrou potencial positivo, mas limitado de resposta ao aumentar a produtividade de colmos em 2,3 Mg ha⁻¹ no início de safra, mas não no meio de safra. Doses de 1,0; 0,8 e 0,8 kg N Mg⁻¹ podem ser recomendadas para áreas colhidas no inícios, meio e final de safra, respectivamente, no centro-sul do Brasil. A descoberta desse trabalho é que o manejo otimizado do nitrogênio deve considerar a época de corte visando ajustar as doses de N para produção rentável de cana-de-açúcar.

Palavras-chave: Condição tropical; Soqueira de cana-de-açúcar; Parcelamento de nitrogênio; Doses de nitrogênio

ABSTRACT

Optimal nitrogen management to sugarcane production in different harvest seasons

Sugarcane is harvested during nine months per year in Brazil with a wide range of water balance that ultimately affect response to nitrogen (N). However, a single N rate of approximately 1.1 kg N per Mg of sugarcane produced is used over the harvest season, applied as a single application few weeks after sugarcane harvest. In addition, there is a trend of growers to increase N rates in the green cane trash blanketing system (GCTB) of Brazil. This study aimed to test the hypothesis that optimal N management will be achieved by means of ascertaining N rates in each harvest season through split instead of single application. Five field trials were conducted in each harvest season (autumn: April to June; winter: July to September; and spring: October to December) across center-south region of Brazil in the 2016/2017 crop season. The experimental design was a N response curve with the N rates being defined according the yield obtained in the previous season (0.8; 1.0; 1.2 and 1.4 kg N per Mg sugarcane; plus an additional control); additional treatments with split N application were tested in autumn and winter, but not in spring. Sugarcane harvested during autumn presented higher response to N when compared to areas harvested in winter or spring. Higher responsiveness to N can be related to the lower water deficit suffered from sites harvested during autumn. Split application showed a limited but positive potential in increasing yields by 2.3 Mg ha⁻¹ during autumn, but not in winter. Nitrogen rates of 1.0, 0.8, and 0.8 kg N Mg⁻¹ can be recommended for sugarcane areas harvested respectively in autumn, winter and spring of center south, Brazil. The finding of this study is that optimal N management should consider the harvest time to ascertain N rates for profitable sugarcane production.

Keywords: Tropical conditions; Sugarcane ratoon; Splitting nitrogen; Nitrogen rates

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1 INTRODUCTION

Brazil is the world's largest producer of sugarcane with an area of 8.73 million hectares and a production of 633.26 million tons in the 2017/2018 crop season (CONAB, 2018). There is a trend to increase demand for renewable energy sources what will promote an intense expansion in bio-fuel production in the world (EISENTRAUT, 2010). Sugarcane is a feasible renewable energy source and assume a prominent position in Brazilian agricultural to attend the demand for ethanol of the first and second generation.

Nitrogen (N) is an element required in large amounts by sugarcane (CANTARELLA et al., 2007; FRANCO et al., 2011; THORBURN et al., 2017). However, improving N usage for growing bioenergy crops is a concern worldwide due to the potential of N fertilizers undergoes losses that causes water and air contamination (ERISMAN et al., 2010; CRUTZEN et al., 2008). To offset this concern, most of N applied as fertilizers must be incorporated in plant biomass or be immobilized in soil microbiota to reduce environmental risks.

Historically, sugarcane has a Nitrogen Use Efficiency (NUE) between 17 and 41 % (mean of 29 %), which is lower than the NUE of annual crops such as corn (GAVA 2003; FARONI 2008). The main causes of the low NUE are due to the lack of synchronize between the plant nitrogen (N) demand and N fertilization, as well as N-applications without considering the N provided by the mineralization of soil organic matter (CANTARELLA et al., 2007). In sugarcane areas, 26 % N applied is taken up by plants, 32 % is immobilized by soil microorganisms, and N-remaining is lost by ammonia volatilization, nitrate leaching and nitrous oxide emission in one agricultural year (OTTO et al., 2016).

It demonstrates that N applications with positive increment on sugarcane yield is inconstant and depend on soil management and climate conditions. Otto et al. (2016) analyzing data from 45 N-response curve experiments under sugarcane harvesting system verified that 75 % of the sites are moderately or not responsive to N fertilization, while 25 % show a high response to N fertilization. Therefore, in most cases increasing the N rate does not necessarily promotes increased productivity (CONTIN, 2007).

Strategies to increase NUE are required in sugarcane areas, such as: genetic improvement; use of crop rotation; soil straw maintenance; use of appropriate fertilizer source, method and time of N application (OTTO et al., 2016; CASTRO et al., 2016). Besides, recommendation system that will identify areas that are responsive or not to

N is also required (OTTO et al., 2013).

Sugarcane is harvested over nine months per year in Brazil, but a single N rate of approximately 1.1 kg N per Mg of sugarcane is used over the entire season. This N rate is based in the official recommendation bulletin of sugarcane production in the São Paulo State (SPIRONELLO et al., 1996), in which N rate is recommended exclusively by the expected yield approach. During the last years, sugarcane yield in center-south region of Brazil is declining, which can be related to the increase in mechanical planting and harvest, as well as reduced investments in renewal of sugarcane fields. Increasing N rates in the ratoon stage is one of the approaches that has being adopted by growers, with the hope of increasing sugarcane yields. However, the review of Otto et al. (2016) demonstrates that increasing N rates will not consistently increase yields, since only 25% of sugarcane sites in Brazil were highly responsive to N.

In ratoon areas of sugarcane cultivation in Brazil, usually N fertilization is performed few weeks after the harvest as a single application. However, in most cases there is an asynchrony between fertilizer application and maximum demand of N by the crop. In center-south Brazil, around 70-80% of sugarcane biomass is produced during the summer (Dezember to March), a period that also encompass the maximum period of nutrients uptake, including N (OLIVEIRA, 2011). Split application of N fertilizer in ratoon areas has a potential to deliver the N closer to the period of maximum demand, with potential to increase NUE and sugarcane yield. However, none study has tested split application of N fertilizer in sugarcane areas in Brazil.

Another aspect that can affect sugarcane response to N is the period of sugarcane harvest during the season. Sugarcane is harvested during autumn (March to June), winter (July to September) and spring (October to December). Considering the water balance in the center south region of Brazil, the water deficit increases in the order spring > winter > autumn (VITTI and MAZZA, 2002). This is directly correlated to the sugarcane yields obtained by sugarcane mills in center-south Brazil, which follows the order autumn > winter > spring (DEMATTE, 2005). Since water deficit can limit crops responsiveness to N and considering that sugarcane fields harvested in the spring will suffer severe water deficit, our hypothesis is that sugarcane harvested in autumn will present higher response to N than sugarcane harvested in winter or spring. It is possible that changing N rate according to the harvest season has potential to increase NUE and sugarcane yield as compared to the application of a similar N rate

over the entire cropping season, as performed nowadays.

This study aimed to test the hypothesis that optimal N management will be achieved by means of ascertaining N rates in each harvest season and through split instead of single application to deliver N closer to the period of maximum demand.

2 MATERIALS AND METHODS

2.1 Site characterizations

Fifteen field trials were carried out in commercial areas of sugarcane ratoon across center-south region of Brazil (States of São Paulo - SP, Goiás - GO and Mato Grosso do Sul - MS), in the 2016/2017 crop season (Figure 1). The trials were separated according to the harvest season of sugarcane in autumn (April to June, 2016), winter (July to September, 2016) and spring (October to December, 2016).

Autumn trials were located in Ivinhema-MS (Site 1), Orindiúva-SP (Site 2), Ipaussu-SP (Site 3), Suzanápolis-SP (Site 4) and Quirinópolis-GO (Site 5). While, winter trials were located in Angélica-MS (Site 6), Orindiúva-SP (Site 7), Sebastianópolis do Sul-SP (Site 8), Chavantes-SP (Site 9) and Olímpia-SP (Site 10); and spring trials in Angélica-MS (Site 11), Orindiúva-SP (Site 12), Ourinhos-SP (Site 13), Suzanápolis-SP (Site 14) and Olímpia-SP (Site 15), Figure 1.

Figure 1. Map showing the experimental trials located in Ivinhema-MS (Site 1), Orindiúva-SP (Site 2-7-12), Ipaussu-SP (Site 3), Suzanápolis-SP (Site 4-14), Quirinópolis-GO (Site 5), Angélica-MS (Site 6-11), Sebastianópolis do Sul-SP (Site 8), Chavantes-SP (Site 9) Olímpia-SP (Site 10-15) and Ourinhos-SP (Site 13).

Figure 2. Water balance (mm) and mean temperature (°C) in sugarcane areas with N application in autumn, winter and spring season. N¹: first N application; N²: second N application (split). SH: sugarcane harvest. Bar represents the mean of 3 months with positive and negative water balance.

All trials present climate classified as Aw (dry winter), except to sites 3, 9 and 13, which were classified as Cfa (always wet hot summer) by the Köppen classification. The weather data was obtained from the meteorological stations located close to the sites, and used to calculate the water balance for each site according to Rolim et al. (1998), using the methodology of Thornthwaite and Mather (1955) (Figure 2).

The sites presented an accumulated precipitation of 1,327.4; 1,245.7; 1,211.4; 1,176.3 and 1,097.0 (autumn); 1,071.0; 1,253.2; 1,249.8; 1,135.0 and 1,280.1 (winter); 1,247.7; 981.8; 1,435.2; 1,341.7 and 1,110.2 mm (spring), respectively from the 1st to 15th site. Temperature mean varied from 20.7 to 26.3 °C during the experimental period (Figure 2).

Prior to the installation of trials, soil samples were collected to physical (Camargo et al. 2009) and chemical characterization (Van Raij et al. 2001) from six positions (replication) at depths ranging from 0.0 to 1.0 m soil layer (i.e., 0.25 m depth intervals), in the sugarcane planting line in autumn (Table 1), winter (Table 2) and spring sites (Table 3).

Soils were classified as Oxisol in all areas, except to Orindiúva-SP (site 12) and Olímpia-SP areas (site 10 and 15) which were classified as Ultisols (Soil Survey Staff 2010), corresponding to Latossolo Vermelho and Argissolo in the Brazilian Soil

Classification System (Embrapa 2013), respectively. There was a wide variation in clay content in the sites (Table 1, 2 and 3).

Table 1. Soil chemical and physical attributes of sites installed in autumn season.

Harvest Time	Site	Depth cm	pH	P mg dm ⁻³	S mg dm ⁻³	K mg dm ⁻³	Ca mg dm ⁻³	Mg mmol _c dm ⁻³	Al mmol _c dm ⁻³	H+Al mmol _c dm ⁻³	CEC mmol _c dm ⁻³	V %	m %	Sand g kg ⁻¹	Silt g kg ⁻¹	Clay g kg ⁻¹
Autumn	Site 1	0-25	5.6	16.0	4.0	0.5	10.0	6.0	2.0	16.5	47.5	35.0	11.0	766.0	36.0	197.0
		25-50	4.9	9.0	4.0	0.3	4.0	2.0	5.0	6.3	48.3	13.0	44.0	758.0	18.0	224.0
		50-75	4.6	1.0	5.0	0.3	3.0	1.0	10.0	2.3	44.3	5.0	81.0	759.0	17.0	225.0
		75-100	4.3	1.0	6.0	0.1	3.0	1.0	10.0	2.1	49.1	4.0	83.0	753.0	22.0	225.0
	Site 2	0-25	5.1	9.0	8.0	<0.1	31.0	20.0	<1.0	11.0	62.1	82.0	2.0	822.0	27.0	151.0
		25-50	4.9	5.0	9.0	<0.1	8.0	4.0	<1.0	12.0	24.1	50.0	8.0	765.0	35.0	200.0
		50-75	6.3	2.0	13.0	<0.1	13.0	8.0	<1.0	11.0	32.1	66.0	5.0	763.0	12.0	225.0
		75-100	6.2	2.0	17.0	<0.1	10.0	6.0	<1.0	10.0	26.1	62.0	6.0	763.0	11.0	226.0
	Site 3	0-25	4.9	6.0	10.0	1.1	22.0	8.0	<1.0	52.0	83.1	37.0	3.0	73.0	226.0	701.0
		25-50	4.5	4.0	7.0	0.7	9.0	4.0	8.0	71.0	84.7	16.0	37.0	67.0	200.0	733.0
		50-75	4.5	3.0	4.0	0.4	7.0	3.0	8.0	71.0	81.4	13.0	43.0	61.0	187.0	752.0
		75-100	4.3	3.0	4.0	0.3	8.0	3.0	8.0	64.0	75.3	15.0	41.0	63.0	184.0	753.0
	Site 4	0-25	6.5	13.0	6.0	2.1	14.0	9.0	<1.0	11.0	36.1	70.0	4.0	803.0	21.0	176.0
		25-50	5.8	4.0	4.0	1.6	8.0	5.0	<1.0	20.0	34.6	42.0	6.0	770.0	19.0	211.0
		50-75	5.4	3.0	9.0	0.7	12.0	7.0	<1.0	18.0	37.7	52.0	5.0	696.0	27.0	277.0
		75-100	5.1	4.0	6.0	0.7	15.0	8.0	<1.0	22.0	45.7	52.0	4.0	710.0	14.0	276.0
	Site 5	0-25	5.3	18.0	20.0	2.0	13.0	6.0	<1.0	13.0	34.0	62.0	5.0	821.0	16.0	163.0
		25-50	4.7	14.0	16.0	1.9	4.0	3.0	2.0	15.0	23.9	37.0	18.0	802.0	22.0	176.0
		50-75	4.6	10.0	11.0	4.3	<3.0	2.0	2.0	12.0	21.3	44.0	18.0	783.0	30.0	187.0
		75-100	4.7	17.0	<4.0	0.2	<3.0	2.0	2.0	12.0	17.2	30.0	28.0	773.0	27.0	200.0

pH in CaCl₂ (0.01 mol L⁻¹); TC: total carbon; TN: total nitrogen; phosphorus (P; Resin method); cation exchange capacity (CEC); percentage of bases (V) and aluminum (m) on CEC.

Table 2. Soil chemical and physical attributes of sites installed in winter season.

Harvest Time	Site	Depth cm	pH	P mg dm ⁻³	S	K	Ca	Mg	Al mmol _c dm ⁻³	H+Al	CEC	V %	m	Sand	Silt g kg ⁻¹	Clay
Winter	Site 6	0-25	5.5	4.0	4.0	0.8	37.0	20.0	2.0	11.0	81.8	87.0	3.0	796.0	32.0	172.0
		25-50	5.0	3.0	4.0	0.4	18.0	7.0	2.0	13.0	53.4	76.0	7.0	781.0	17.0	202.0
		50-75	4.5	2.0	6.0	0.5	8.0	3.0	5.0	15.0	46.5	68.0	30.0	766.0	22.0	212.0
		75-100	4.2	1.0	22.0	0.5	4.0	2.0	7.0	13.0	39.5	67.0	52.0	709.0	17.0	274.0
	Site 7	0-25	5.6	8.0	12.0	0.2	19.0	7.0	<1.0	18.0	63.2	72.0	4.0	802.0	49.0	149.0
		25-50	5.2	14.0	12.0	<0.1	13.0	5.0	<1.0	20.0	59.1	66.0	5.0	764.0	60.0	176.0
		50-75	5.2	3.0	23.0	<0.1	11.0	6.0	<1.0	16.0	50.1	68.0	6.0	763.0	36.0	201.0
		75-100	5.3	3.0	26.0	<0.1	11.0	7.0	<1.0	15.0	49.1	69.0	5.0	785.0	22.0	193.0
	Site 8	0-25	5.2	8.0	5.0	3.0	25.0	8.0	0.0	21.0	57.0	63.0	0.0	724.0	25.0	151.0
		25-50	5.4	7.0	5.0	2.2	23.0	7.0	0.0	22.0	57.2	62.0	3.0	820.0	18.0	162.0
		50-75	5.3	7.5	5.0	2.6	24.0	7.5	0.0	21.5	57.1	62.5	1.5	772.0	21.5	156.5
		75-100	5.4	7.3	5.0	2.4	23.5	7.3	0.0	21.8	57.2	62.3	2.3	796.0	19.8	159.3
	Site 9	0-25	5.3	22.0	10.0	1.3	61.0	20.0	<1.0	47.0	129.3	64.0	1.0	114.0	210.0	676.0
		25-50	4.7	19.0	33.0	0.7	26.0	12.0	3.0	47.0	85.7	45.0	7.0	107.0	191.0	702.0
		50-75	4.1	3.0	46.0	0.3	9.0	5.0	16.0	109.0	123.3	12.0	53.0	110.0	226.0	664.0
		75-100	4.0	3.0	76.0	0.4	7.0	4.0	16.0	98.0	109.4	10.0	58.0	115.0	189.0	696.0
	Site 10	0-25	6.7	25.0	18.0	2.3	32.0	9.0	1.0	13.0	56.3	77.0	0.0	790.0	60.0	150.0
		25-50	5.6	5.0	47.0	2.9	7.0	7.0	1.0	16.0	32.9	51.0	6.0	694.0	81.0	225.0
		50-75	4.7	2.0	141.0	2.8	3.0	3.0	4.0	18.0	25.8	30.0	34.0	690.0	58.0	252.0
		75-100	4.5	2.0	153.0	2.2	3.0	3.0	6.0	22.0	28.2	22.0	49.0	669.1	79.2	251.0

pH in CaCl₂ (0.01 mol L⁻¹); TC: total carbon; TN: total nitrogen; phosphorus (P; Resin method); cation exchange capacity (CEC); percentage of bases (V) and aluminum (m) on CEC.

Table 3. Soil chemical and physical attributes of sites installed in spring season.

Harvest Time	Site	Depth Cm	pH	P mg dm ⁻³	S mg dm ⁻³	K	Ca	Mg	Al mmol _c dm ⁻³	H+Al	CEC	V %	m	Sand	Silt g kg ⁻¹	Clay
Spring	Site 11	0-25	5.9	29.0	12.0	1.0	33.0	19.0	<2.0	11.0	64.0	83.0	4.0	856.0	19.0	125.0
		25-50	4.7	<3.0	8.0	<0.9	14.0	4.0	<2.0	13.0	31.9	59.0	10.0	803.0	22.0	175.0
		50-75	4.2	<3.0	8.0	<0.9	4.0	2.0	<2.0	20.0	26.9	26.0	22.0	804.0	20.0	176.0
		75-100	4.1	<3.0	9.0	<0.9	2.0	2.0	4.0	15.0	19.9	25.0	45.0	793.0	32.0	175.0
	Site 12	0-25	5.3	10.0	28.0	1.2	32.0	10.0	<2.0	20.0	63.2	68.0	4.0	474.0	146.0	380.0
		25-50	5.4	5.0	13.0	2.4	21.0	8.0	<2.0	16.0	47.4	66.0	6.0	422.0	120.0	458.0
		50-75	5.7	4.0	9.0	<0.9	23.0	5.0	<2.0	16.0	44.9	64.0	6.0	420.0	124.0	456.0
		75-100	5.7	4.0	7.0	3.0	20.0	4.0	<2.0	13.0	40.0	68.0	7.0	412.0	106.0	482.0
	Site 13	0-25	5.5	15.0	8.0	2.7	59.0	18.0	<1.0	25.0	104.7	76.0	1.0	134.0	259.0	607.0
		25-50	5.3	13.0	26.0	0.4	30.0	13.0	<1.0	25.0	68.4	63.0	2.0	117.0	265.0	618.0
		50-75	5.3	12.0	29.0	<0.1	28.0	9.0	<1.0	25.0	62.1	60.0	3.0	71.0	285.0	644.0
		75-100	5.4	8.0	35.0	<0.1	25.0	7.0	<1.0	20.0	52.1	62.0	3.0	67.0	290.0	643.0
	Site 14	0-25	4.9	4.0	4.0	0.7	16.0	7.0	<0.1	13.0	36.7	65.0	4.0	829.0	20.0	151.0
		25-50	5.5	4.0	4.0	0.4	32.0	7.0	<0.1	10.0	49.4	80.0	2.0	786.0	13.0	201.0
		50-75	5.5	2.0	6.0	0.3	12.0	4.0	<0.1	10.0	26.3	62.0	6.0	781.0	19.0	200.0
		75-100	5.5	2.0	4.0	0.3	17.0	4.0	<0.1	11.0	32.3	66.0	4.0	784.0	15.0	201.0
	Site 15	0-25	5.4	43.0	10.0	3.5	23.0	15.0	<1.0	12.0	53.5	78.0	2.0	774.0	13.0	213.0
		25-50	5.4	25.0	6.0	4.3	18.0	12.0	<1.0	12.0	46.3	74.0	3.0	749.0	26.0	225.0
		50-75	5.0	8.0	42.0	4.9	11.0	9.0	<1.0	13.0	37.9	66.0	4.0	671.0	27.0	302.0
		75-100	4.9	4.0	67.0	4.0	8.0	6.0	<1.0	13.0	31.0	58.0	5.0	626.0	21.0	353.0

pH in CaCl₂ (0.01 mol L⁻¹); TC: total carbon; TN: total nitrogen; phosphorus (P; Resin method); cation exchange capacity (CEC); percentage of bases (V) and aluminum (m) on CEC.

All sites have been cultivated with sugarcane at least in the previous 20 years. Soil was prepared using the conventional system following plowing, disking, harrowing and furrowing. Lime and gypsum were applied before planting in all sites, aiming to achieve 60 % of base saturation. Lime rates varied from 0.8 to 4.0 Mg ha⁻¹. Fertilization was performed in the furrow with application of nitrogen, potassium and phosphorus following the recommendations of Spironello et al. (1996).

Sugarcane was planted using the varieties RB96-6928 and CTC4 in autumn and winter, respectively, which are classified as well adapted to tropical conditions with high-yield potential. A mix of varieties, RB86-7515 (site 11), IAC91-1099 (site 12), SP80-3280 (site 13), RB92-579 (site 14) and CTC4 (site 15), was planted in spring season (Table 4). The difference of varieties adopted in each harvest time was due to the maturation group of each variety, as well as the adaptation to the soil and weather condition of the region.

Table 4. Experimental information with date of previous harvest and trial harvesting, sugarcane variety and previous sugarcane yield (PSY) in 2015/2016.

Harvest Time	Site	Sugarcane previous harvest (2016)	Trial harvest (2017)	Sugarcane variety	PSY (Mg ha ⁻¹)
Autumn	Site 1	04/20	07/04	RB96-6928	90
	Site 2	06/15	04/20	RB96-6928	90
	Site 3	06/27	06/29	RB96-6928	90
	Site 4	05/28	04/21	RB96-6928	100
	Site 5	05/27	05/24	RB96-6928	110
Winter	Site 6	09/06	07/04	CTC 4	90
	Site 7	07/13	07/28	CTC 4	110
	Site 8	09/22	08/24	CTC 4	109
	Site 9	08/22	08/02	CTC 4	140
	Site 10	08/09	10/16	CTC 4	70
Spring	Site 11	12/01	11/24	RB86-7515	80
	Site 12	12/30	10/20	IAC91-1099	90
	Site 13	11/08	10/19	SP80-3280	140
	Site 14	10/28	10/16	RB92-579	90
	Site 15	11/10	10/30	CTC 4	100

2.2 Experimental design

The experimental design was complete randomized block design using four N-rates plus an additional control (without N) in all harvest seasons. Additional treatments with N-Total and N-split application were tested in autumn and winter season. The N

application was performed in the 1st sugarcane ratoon with four replications. Experimental units consisted of six sugarcane lines spaced at 1.5 x 1.5 (conventional design), with 9 m wide, 15 m length and 3.0 m of carriers between the plots.

The N rates were based on the sugarcane yield produced in the previous harvest, following the usual approach adopted by farmers. The common N rates adopted by most growers range from 1.0 to 1.2 kg N per Mg⁻¹ of sugarcane, while the official recommendation is 1.1 kg N Mg⁻¹ of sugarcane (SPIRONELLO et al., 1996). The N rates adopted in the experiments were 0.8; 1.0; 1.2 and 1.4 kg N per Mg⁻¹ of sugarcane in previous harvest (2015/2016).. Nitrogen fertilizers were applied up to 30 days after harvesting, applied over the sugarcane row with no incorporation and using ammonium nitrate (32%N). In the treatments with split application (in autumn and winter), 50% of N was applied after harvest and the remaining was applied in November (before the maximum growth stage), following the same procedures described previously. All sites received potassium at rate of 120 kg ha⁻¹.

2.3 Sugarcane yield measurements and data analysis

Sugarcane harvests were performed mechanically in four central lines of each plot. Sugarcane was harvested with a mechanical harvester, and the stalks were deposited and weighed in an truck equipped with an automatic weighing system (scale). The days of plant development in each trial were 440; 309; 367; 328; 362 (autumn); 301; 380; 336; 345; 434 (winter); 358; 294; 345; 353; and 354 (spring), respectively from the 1st to 15th site (Table 4). Stalks were weighted to estimate sugarcane yield in each plot (SY; Mg stalk ha⁻¹).

Ten stalks per plot were collected randomly to determine theoretical recoverable sugar (TRS; kg Mg sugar⁻¹), according to Fernandes (2003). Sugar yield (Mg sugar ha⁻¹) was calculated considering sugar concentration and sugarcane yield in each area.

The assumptions of normality and homogeneity of variance were evaluated respectively by the Shapiro Wilk-Test and Leneve-Test. Outliers were removed when identified by Grubs-Test. Data were submitted to analysis of variance (ANOVA) based on the F-test. When the F-Test was significant ($P < 0.1$), the effect of N-split was evaluated by the LSD-test ($P < 0.1$) and N rates by the Regression and plateau-Test ($P < 0.1$).

3 RESULTS

3.1 N application per site

The N rates fitted a positive response on sugarcane yield in autumn ($R^2 \geq 15\%$; $P < 0.1$), with the adequate N rate given at rate of 1.0 kg N Mg^{-1} in site 1 and 3 using plateau model, and linear response in site 2 (Figure 3 and Table 5). Nitrogen rates did not affect sugarcane yield on site 4 and 5 in the same season with mean production of 112.7 Mg ha^{-1} (Table 5).

In winter, N application fitted a quadratic response on sugarcane yield ($R^2 \geq 50\%$; $P < 0.1$), with yield decrease for N rates higher than 0.7 (site 8) and 0.8 kg N Mg^{-1} (site 10), Table 5 and Figure 3. The N application did not affect the others sites in winter, as well as there was not effect in any sites in spring (Tables 6 and 4).

In autumn, sugar yield was affected positively with N applications fitting a linear response in site 1 and 5 ($R^2 \geq 70\%$; $P < 0.1$), as well a quadratic response in site 3 with the maximum values given at 1.2 kg N Mg^{-1} (Figure 3 and Table 5). In winter, sugar yield also presented a quadratic response with N applications and decrease for N-rates higher than 0.5 kg N Mg^{-1} in site 8 (Table 4 and Figure 3). As expected, the N application also did not influence sugar yield in spring (Table 6).

In autumn, the N-split increased sugarcane yield in sites 1; 2 and 3, and promoted higher sugar yield in site 1; 3 and 4. However, in winter N-split decreased sugarcane production in site 6, and there was no effect on the other sites (Table 5). In spring there was no response to nitrogen management in any parameter (Table 6).

Figure 3. Sugarcane yield (SY, Mg stalk ha⁻¹; A and B) and sugar yield (Mg sugar ha⁻¹; C and D) in areas with N application (0; 0.8; 1.0; 1.2 and 1.4 kg N Mg⁻¹) in autumn and winter season. LM: linear model; QM: quadratic model; PL: plateau model.

The N applications did not affect TRS in all seasons (Table 5 and 6), except in site 4 that fitted a quadratic response with TRS decrease for N rates higher than 1.0 kg N Mg⁻¹ (Model in Table 5). Besides, N-split decreased TRS in site 4 (autumn) and site 8 (winter), Table 5.

Table 5. Sugarcane yield (SY; Mg stalk ha⁻¹), theoretical recoverable sugar (TRS; kg Mg sugar⁻¹) and sugar yield (Mg sugar ha⁻¹) in sugarcane areas with N applications (0.0; 0.8; 1.0; 1.2 and 1.4 kg N Mg⁻¹) and N-splitting (total and split) in autumn (Site 1 to 5) and winter season (Site 6 to 10).

	----- Autumn -----					----- Winter -----				
	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7	Site 8	Site 9	Site 10
N rates (kg N Mg⁻¹)	Sugarcane yield, SY (Mg stalk ha⁻¹)									
0.0	101.9	58.7	102.6	117.2	93.5	105.0	95.0	112.0	89.9	89.2
0.8	109.3	66.2	114.8	123.1	101.4	99.4	93.2	127.5	87.0	95.5
1.0	119.3	65.5	116.4	123.2	105.1	101.2	91.6	117.8	84.5	96.3
1.2	117.7	67.6	114.7	120.2	109.1	100.4	94.1	113.6	84.3	77.2
1.4	117.2	73.1	120.2	127.9	106.4	99.1	90.6	108.8	81.7	94.3
N-splitting										
Control	101.9c	58.7b	102.6c	117.2	93.5	105.0a	95.0	112.0	89.9	89.2
Total	112.3b	67.4a	115.1b	122.5	104.3	100.2b	94.0	113.9	85.2	89.2
Split	119.5a	68.8a	118.0a	124.7	106.7	99.9b	90.8	119.6	83.7	92.4
N rates (kg N Mg⁻¹)	Theoretical recoverable sugar, TRS (kg Mg sugar⁻¹)									
0.0	132.5	150.5	132.8	151.9	137.9	165.1	162.0	173.8	158.4	150.7
0.8	134.0	150.1	136.0	142.9	142.5	163.4	167.4	167.2	158.4	156.7
1.0	136.6	150.4	136.6	141.4	142.1	159.8	154.3	172.1	157.6	159.3
1.2	135.5	153.5	136.6	144.7	142.0	163.8	165.4	173.1	156.9	157.0
1.4	131.6	145.9	132.8	144.1	141.8	165.8	167.1	172.2	158.3	153.8
N-splitting										
Control	132.5	150.5	132.8	151.9a	137.9	165.1	162.0	173.8a	158.4	150.7
Total	133.3	151.4	135.1	142.6b	142.3	163.5	165.4	174.7a	156.1	157.8
Split	135.5	148.6	135.9	143.9b	141.9	162.9	161.7	167.6b	159.3	155.6
N rates (kg N Mg⁻¹)	Sugar yield, SY¹ (Mg sugar ha⁻¹)									
0.0	13.5	8.8	13.6	17.8	12.8	17.3	16.7	20.4	14.2	13.4
0.8	14.6	10.0	15.6	17.2	14.3	16.2	15.5	21.5	13.8	14.9
1.0	16.3	9.9	15.9	17.4	14.8	16.2	15.2	20.3	13.3	15.3
1.2	15.9	10.5	15.6	16.9	15.4	16.4	15.0	19.5	13.2	12.8
1.4	15.4	10.6	15.9	18.4	15.0	16.4	14.8	18.6	13.0	14.5
N-splitting										
Control	13.5b	8.8	13.6b	17.8	12.8b	17.3	16.7	20.4	14.2	13.4
Total	15.2a	10.3	15.5a	17.3	14.8a	16.4	15.5	20.1	13.3	14.1
Split	15.9a	10.3	16.0a	17.6	15.1a	16.3	14.6	19.7	13.4	14.6
Anova (P values)										
SY (N-rates)	<0.01 ^P	<0.01 ^L	<0.01 ^P	0.60	0.28	0.19	0.93	<0.01 ^Q	0.83	<0.01 ^Q
SY (N-splitting)	<0.01	<0.01	<0.01	0.53	0.16	<0.01	0.62	0.22	0.66	0.78
SY (Interaction)	0.94	0.59	0.18	0.52	0.83	0.67	0.97	0.16	0.11	0.11
TRS (N-rates)	0.21	0.38	0.33	<0.1 ^{Q,*}	0.78	0.62	0.41	0.11	0.97	0.45
TRS (N-splitting)	0.31	0.55	0.51	<0.1	0.43	0.88	0.87	<0.01	0.27	0.30
TRS (Interaction)	0.61	0.14	0.26	0.72	0.49	0.30	0.42	0.27	0.36	0.30
SY ¹ (N-rates)	<0.01 ^L	0.19	<0.01 ^Q	0.39	<0.1 ^L	0.56	0.33	<0.1 ^Q	0.83	0.27
SY ¹ (N-splitting)	<0.01	0.11	<0.01	0.77	<0.1	0.27	0.20	0.73	0.69	0.61
SY ¹ (Interaction)	0.94	0.78	0.21	0.90	0.48	0.66	0.54	0.34	0.12	0.11

Means were compared by the LSD-Test (N-splitting) and Regression-Test (N-rate), using a P of 1 %. * represents TRS quadratic model in site 4 ($y = 10.5x^2 - 19.8x + 151.8$, $R^2: 94\%$). L, Q and P represent linear, quadratic and plateau response, respectively.

Table 6. Sugarcane yield (SY; Mg stalk ha⁻¹), theoretical recoverable sugar (TRS; kg Mg sugar⁻¹) and sugar yield (Mg sugar ha⁻¹) in sugarcane areas with N applications (0.0; 0.8; 1.0; 1.2 and 1.4 kg N Mg⁻¹) in spring season.

----- Spring -----					
	Site 11	Site 12	Site 13	Site 14	Site 15
N rates (kg N Mg⁻¹)	Sugarcane yield, SY (Mg stalk ha⁻¹)				
0.0	73.9	46.6	109.5	83.2	69.7
0.8	80.2	50.2	116.1	91.2	66.8
1.0	75.3	50.3	105.4	93.4	67.2
1.2	73.8	49.6	110.7	95.5	70.3
1.4	78.1	54.3	118.6	97.7	72.7
	Theoretical recoverable sugar, TRS (kg Mg sugar⁻¹)				
0.0	146.1	165.8	162.4	152.1	154.8
0.8	147.6	169.1	162.3	162.0	144.6
1.0	151.9	169.0	164.6	167.1	152.8
1.2	148.6	167.6	165.2	165.0	148.3
1.4	149.6	166.9	160.8	171.5	138.0
	Sugar yield, SY¹ (Mg sugar ha⁻¹)				
0.0	10.8	7.7	16.7	12.7	10.8
0.8	11.3	8.5	18.7	14.8	9.7
1.0	11.4	8.5	17.3	15.4	10.2
1.2	11.5	8.3	18.1	15.5	10.3
1.4	11.5	9.0	19.0	17.2	10.0
Anova (P values)					
SY	0.49	0.11	0.54	0.50	0.82
TRS	0.66	0.79	0.41	0.21	0.11
SY ¹	0.59	0.18	0.23	0.23	0.79

Means were compared by Regression-Test (N-splitting), using a P of 1 %.

3.2 N application per season

Evaluating the general mean by season, N applications promoted linear response on sugarcane and sugar yield in autumn and spring seasons ($R^2 \geq 60\%$; $P < 0.1$). Nitrogen fertilization did not affect any of the parameters in winter season, which have shown the averages of 97 Mg ha⁻¹; 162.4 kg Mg sugar⁻¹ and 15.8 Mg sugar ha⁻¹, respectively for sugarcane yield, TRS and sugar yield (Table 7).

Figure 3. Sugarcane yield (SY, Mg stalk ha⁻¹; A) and sugar yield (Mg sugar ha⁻¹; B) in areas with N application (0; 0.8; 1.0; 1.2 and 1.4 kg N Mg⁻¹) in autumn and spring season. LM: linear model.

The N-split increased sugarcane yield in autumn representing a gain of 2.3 Mg stalk ha⁻¹ compared to N-total (Table 7). There was no N-split effect on winter for sugarcane yield, sugar yield, and TRS content (Table 7).

Table 7. General mean of sugarcane yield (Mg stalk ha⁻¹), theoretical recoverable sugar (kg Mg sugar⁻¹) and sugar yield (Mg sugar ha⁻¹) in sugarcane areas with N applications (N rates and N-splitting) in autumn, winter and spring season.

	Autumn	Winter	Spring		Autumn	Winter
	N rates (kg N Mg ⁻¹)				N splitting	
Sugarcane yield (Mg stalk ha ⁻¹)						
0.0	94.7	98.2	76.5	Control	105.3c	96.5
0.8	102.9	100.5	80.9	Total	113.4b	95.5
1.0	105.9	98.2	78.3	Split	115.7a	96.6
1.2	105.8	93.9	79.9			
1.4	108.9	94.9	84.3			
Theoretical recoverable sugar (kg Mg sugar ⁻¹)						
0.0	141.1	162.0	156.2	Control	138.4	159.0
0.8	141.1	162.6	157.1	Total	140.5	160.7
1.0	141.4	160.6	161.0	Split	140.4	159.8
1.2	142.4	163.2	158.9			
1.4	139.2	163.4	157.3			
Sugar yield (Mg sugar ha ⁻¹)						
0.0	13.3	16.4	11.7	Control	13.3b	16.4
0.8	14.3	16.3	12.6	Total	14.63a	15.8
1.0	14.8	16.0	12.5	Split	14.99a	15.7
1.2	14.8	15.3	12.7			
1.4	15.0	15.4	13.3			
Anova (P value)						
SY	0.001 ^L	0.17	0.04 ^L		0.001	0.84
TRS	0.22	0.76	0.42		0.78	0.70
SY ¹	0.001 ^L	0.36	0.01 ^L		0.001	0.56

Means were compared by the LSD-Test (N-splitting) and Regression-Test (N-rate), using a P of 1 %. ^L represent linear response.

4 DISCUSSION

Evaluating site by site, the major N-application responses were verified in autumn season, when 60% of the sites presented stalks or sugar yield increase. The three sites that had presented sugarcane yield response to N (sites 1; 2 and 3), were those that had less water deficit by the moment of the N application, demonstrating that the variety RB96-6928 is responsive to N fertilization in better condition of soil moisture. This condition is favorable to N movement in soil solution through the mass flow, promoting higher N availability and absorption by plants (EPSTEIN & BLOOM, 2006).

No N response was found in the other two seasons in site-by-site evaluation, and there was even stalk and sugar yield decrease in sites 6 and 8, respectively (winter season). Considering autumn and winter results, N fertilization with low soil moisture did not increase sugarcane yield. In spring season, a factor that may have affected the lack of N response was the severe water deficit that plants suffered during the maturation process. Usually, plants harvested in spring has a rapid initial development (due to adequate weather conditions), but enters the winter period with high leaf area index, which causes a severe water deficit. This is probably the cause of the low yields usually obtained by mills in the spring harvest period. These results corroborated with Castro (2016) that also verified low response to N fertilization in spring compared to other seasons.

Evaluating the trials set by season, both autumn and spring had linear increase of stalks and sugar yields by increasing N rates. Although spring season have had a different result evaluating the experiments together, it had a lower increment per N unit than the autumn model. Making an economic return assessment, considering the mean of previous yields, the real average rate used in spring was 100 kg N ha^{-1} . The cost of ammonium nitrate in November of 2018 was close to R\$1,300.00 Mg^{-1} , what would mean an investment of R\$406.00 ha^{-1} of N (equivalent to 1.0 kg N Mg^{-1}). Considering the price of sugarcane in the same period (R\$69.83 Mg^{-1}) and an stalk yield increasing index of $4.2 \text{ t kg N}^{-1} \text{ Mg}^{-1}$ for spring season, the return would be R\$293.29, meaning a loss of R\$112.71 ha^{-1} . However, with a stalk yield increasing index of $9.9 \text{ t kg N}^{-1} \text{ Mg}^{-1}$ for autumn and average N rate of 96 kg of N per unit of kg N Mg^{-1} , the return would be R\$691.32 and the cost R\$389.76, meaning a profit of R\$301.56.

Splitting nitrogen application had positive results in autumn increasing stalk

yield by 2.3 Mg ha^{-1} . Making an economic return assessment, the operational cost would have to be lower than $\text{R\$}160.61 \text{ ha}^{-1}$ to offset this management. Moreover, splitting N did not increase sugar yield in autumn, neither had influence in any parameter in winter. The lack of response in sugar yield may be related to late N applications stimulating biomass production and delaying sugarcane ripening. The positive effect of split N application in autumn can be related to the better water balance of sugarcane harvested in autumn, enhancing the response of sugarcane to N.

It was expected a positive effect of split application during harvest time of winter. The general idea was to supply half of N soon after sugarcane harvest, and the remaining (50%) close to the period of maximum sugarcane growth (Oliveira, 2011). However, different from expected, there was no yield gain by splitting N application in winter. Probably plants taken up N more efficiently in the split treatment, allowing a better growth during the summer. However, plants of the winter harvest time also suffered from intense water deficit during the maturation process, which can have limited sugarcane growth and the expression of yield response to the split N application. This outcome is an indicator that splitting N application will not promote yield gains in sugarcane harvested during winter, which is the main period of sugarcane harvest in center-south Brazil. In this study, our focus was to evaluate N splitting through soil application, but the limited effect observed herein suggest that future studies should evaluate N splitting through foliar fertilization.

Our results corroborate to Otto et al (2016), who found high variability in sugarcane response to N. In their review, only 25 % of the sites presented high responsiveness to N. Altogether, these results are an indicator that increasing N rates above the $1.1 \text{ kg N per Mg}^{-1}$ of sugarcane (official recommendation) will not promote yield gains in center-south Brazil.

We propose that N management should consider the harvest season of the sugarcane. In autumn season, from the five sites, one of them presented linear yield increase up to the rate of 1.4 Mg N Mg^{-1} , two of them had 1.0 Mg N Mg^{-1} as the optimal rate, and the other two demonstrated no response to N fertilization. This data suggest that adopting a N rate of 1.0 kg N Mg^{-1} is suitable for sugarcane harvested during autumn, which is close to the current N recommendation of 1.1 kg N Mg^{-1} in sugarcane ratoon (SPIRONELLO, 1996). However, considering the limited response to N obtained in sugarcane harvested in winter and spring, a N rate of 0.8 kg N Mg^{-1} should be recommended for those harvest seasons. The rate of 0.8 kg N Mg^{-1} is much lower

than the usual rate of 1.2 kg N Mg⁻¹ adopted nowadays for most growers during all sugarcane season in center-south Brazil. Considering the low effectiveness of N fertilizer in promoting yield gains of sugarcane, which is probably related to the low uptake of N-fertilizer by this crop (26%, OTTO et al., 2016), we suggest that future studies evaluate the reduction of N rates applied to the soil and the application of N to the leaves as a mean of increasing NUE in sugarcane systems.

5 CONCLUSIONS

Sugarcane harvested in autumn was more responsive to nitrogen than sites harvested in winter or spring. Higher responsiveness to nitrogen seems related to the lower water deficit suffered from sugarcane harvested in autumn as compared to winter and spring.

Data of the fifteen field trials evaluated herein support the recommendation of reducing the N rates to 1.0, 0.8, and 0.8 kg N Mg⁻¹ for sugarcane harvested respectively in autumn, winter, and spring of center-south Brazil. Split nitrogen application showed a limited potential in increasing yields by 2.3 Mg ha⁻¹ in sugarcane harvested in autumn.

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