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Decision-making on the optimum timing for nitrogen fertilization on sugarcane ratoon

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ABSTRACT: Low efficiency of nitrogen from fertilizers is a major concern worldwide, threatening the sustainability of sugarcane production. The N use efficiency (NUE) by sugarcane can be improved by adopting better fertilizing management practices, reducing environmental impacts. This work evaluated the effects of varying N rates and time of application on stalks and sugar yield in ratoon harvested early in the crop season. The experimental design was a randomized block in a 2 × 4 factorial design and a control (no N) with five replications, including two application times (45 or 90 DAH – days after harvest) and four N rates (50, 100, 150, or 200 kg N ha^{-1}). The time of N fertilizer application promoted differences in stalk yield, as the cumulative yield of two harvests was increased by 8 % (15 Mg ha^{-1}) at 45 DAH when compared to the application at 90 DAH. The application performed at 45 DAH augmented sugar yield by 10 % (2.8 Mg ha^{-1} of sugar) in relation to 90 DAH. The N rates that promoted the highest sugarcane yield were, respectively, 122 and 144 kg N ha^{-1} in the first and second crop cycles. The average economical rates obtained for the first and second agricultural cycles were, respectively, 104 and 127 kg N ha^{-1}, demonstrating that the gains by applying high amounts of fertilizers (rates above 150 kg N ha^{-1}) may not cover the investment.

Keywords: N fertilization, green cane, sugarcane yield, economical rate

Introduction

The Brazilian sugar-energy sector is composed of sugarcane cultivation and industrial processing to obtain sugar, ethanol, and bioelectricity. Currently, the sugarcane area (plant and ratoon cane) exceeds 9 million hectares, accounting for approximately 40 % of the total area planted with sugarcane worldwide (FAO, 2015). The advance of sugarcane production in Brazil has increased the demand for fertilizers and consumption of NPK fertilizers rose by 50 % from 2000 to 2015 (Castro et al., 2016).

Sugarcane uses about 100 to 150 kg N ha^{-1} to produce 100 Mg ha^{-1} of stalks (Thorburn et al., 2005). To fulfil these nutritional requirements, the N rate applied on sugarcane ratoons is between 120 and 200 kg N ha^{-1} (Cantarella and Rossetto, 2014). Studies have shown increases in stalk yield of sugarcane in Brazil due to N fertilization (Rhein et al., 2016; Otto et al., 2016), but there are differences in the N rate needed to maximize economic productivity, where gains justify investments in fertilization (Otto et al., 2016).

The sugarcane harvest season in the central-southern region of Brazil occurs from Apr to Nov, during which N fertilization occurs on the ratoons in a single application, usually a few days after harvesting (Otto et al., 2016). Therefore, there is a lack of synchrony between the time of fertilizer application and crop nutritional demand in sugarcane ratoon (Mariano et al., 2015), mainly because most biomass and N uptake occur in the rainy season from Dec and Mar (Oliveira et al., 2013; Franco et al., 2011). When sugarcane is harvested in June (winter season), fertilization is carried out during a dry season (June – Aug), a long dry period, decreasing sugarcane response to N fertilizer (Bahrani et al., 2009). Since N movement in the soil is by mass flow (Taiz and Zeiger, 2009), moisture contributes to greater N uptake by the plant (Malhi et al., 2001).

This work has the hypothesis that for the sugarcane harvested at the beginning of crop season, N fertilization applied 45 DAH promotes an increase in stalks and sugar yield when compared to application at 90 DAH. To test this hypothesis, we evaluated the effects of varying N rates and application times on the yield of stalks and sugar in ratoon harvested at the beginning of the harvesting season.

Materials and Methods

The experiment was carried out during two crop seasons (first ratoon 2013/2014 and second ratoon 2014/2015) located in Sales Oliveira in São Paulo State (20°52′31″ S, 47°57′56″ W, 650 m) in central-southern Brazil, at a commercial area with more than 18 years of sugarcane cultivation. The variety used was RB855156, which has high tillering and high productivity, and was ranked among the top ten most planted varieties in the central-southern region.

The experimental design was randomized block involving five replications of a 2 × 4 factorial design and an unfertilized control (without N fertilizer), totaling 45 plots. The first factor was the times of N-fertilizer application (45 or 90 DAH) and the second factor was N rates (50, 100, 150 or 200 kg N ha^{-1}). Each plot consisted of six sugarcane rows 14 m long and with 1.50 m of interrow spacing.

After the first harvest (Apr 2013) and before the installation of treatments, the soil was characterized chemically and physically, according to methodology described by Raij et al. (2001). The soil was classified as a Rhodic Eutrustox clay texture (Soil Souvey Staff, 2014), with initial chemical and physical characteristics (0.0-0.2 m) with pH ($CaCl_2$) – 5.4, organic matter – 41 g dm^{-3}, P(resin) – 12 mg dm^{-3}, K, Ca, Mg and CEC, respectively, 2, 52, 11 and 101 $mmol_c$ dm^{-3}. Clay, silt and sand contents were 695, 239 and 66 g kg^{-1}, respectively. The production environment was characterized as A2/B1 on a scale from A to E, where A environment has conditions that are more favorable for sugarcane cultivation and E environment has more chemical and/or physical restrictions for sugarcane production.

The N source was ammonium nitrate NH_4NO_3 (330 g N kg^{-1}, 33-00-00). Nitrogen was applied in both sides of the sugarcane row at 0.08 m soil depth (Castro et al., 2016), 45 and 90 DAH, plots also received 200 kg ha^{-1} of potassium chloride KCl (0-0-60, 60 % K_2O) applied superficially in one side of the row 30 d after N fertilization.

During crop growth, at 45, 90, 120, and 150 DAH, the number of tillers was counted in each plot, representing the primary tillering phase (45, 90 120 DAH) and elongation of stalks (150 DAH).

The yield was quantified by biometric evaluation before mechanical harvest, where the number of stalks in four central rows in each plot was counted and stalks were collected. The stalks were husked and tops were cut off and weighed for yield calculation. Technological parameters were quantified by analyzing the apparent sucrose content (POL) as described by Fernandes (2003) and sugar yield was calculated. The procedures were repeated in the second crop year (2014/2015).

Throughout the experimental period, climatological data were monitored at an automatic meteorological station installed near the experimental area. Water balance (Figure 1) was calculated using the methodology proposed by Thornthwaite and Mather (1955).

The results were submitted to the analysis of variance and, whenever significant, the means were compared by the Tukey test with a confidence level of 95 % (p < 0.05). The polynomial regressions were used to compare N rates. The economical rate was calculated by the derivative of the equation $Y = -ax^2 + bx + c$. The result was compared with the price relation between the fertilizer in US$ Mg^{-1} of fertilizer and sugarcane in US$ Mg^{-1}, as described below:

$$\frac{\partial_y}{\partial_x} = b - 2ax = \left(\frac{fertilizer\ cost\ (U\$\$Mg)}{sugarcane\ return\ (U\$\$Mg)}\right)$$

Results

Sugarcane yield

The application time and N rate interaction showed no effect on yield in both years and cumulative yield (Table 1). The cumulative yield was higher when N was applied at 45 DAH compared to 90 DAH. Yields in the 2013/2014 crops were also higher when N was applied at 45 DAH. The second year did not present difference in yield comparing the two application strategies. The increase of N rates in the first and second harvests and cumulative yield resulted in quadratic effects (Table 1). The maximum cumulative yield was reached at 133 kg N ha^{-1} (Figure 2) and in the first and second year maximum, values ranged from 122 to 144 kg N ha^{-1}, respectively (Figure 2). Considering the results of two years, sugarcane yield decreased 30 % (53 Mg ha^{-1}) in plots that did not receive N-fertilizer in relation to the other plots that received N-fertilizer (Figure 2).

Sugar yield

The interaction of application time and N rate did not influence sugar yield during the experimental period

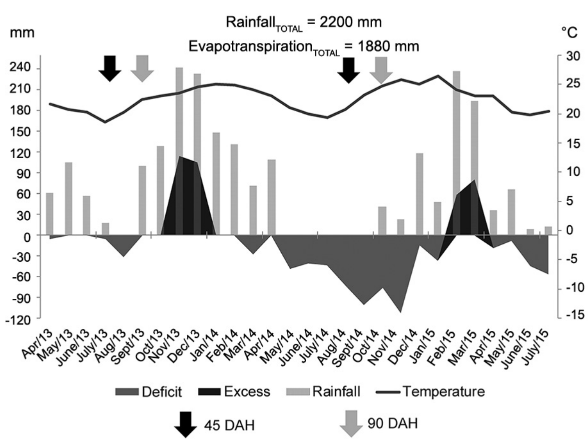

Figure 1 – Water balance, rainfall and temperature during the experimental period (2013-2015).

Table 1 – Analysis of variance of treatments and their interaction on stalk and sugar yield in 2013/2014 and 2014/2015 seasons and cumulative yields.

Treatments	Stalk yield			Sugar yield		
	2013/2014	2014/2015	Cumulative	2013/2014	2014/2015	Cumulative
	F values					
Application time (T)	7.79**	0.31^{NS}	8.48**	6.07*	0.64^{NS}	4.58*
N rates (R)	4.38**	9.34**	9.37**	3.57*	8.23**	3.91**
T × R	2.28^{NS}	1.29^{NS}	3.69^{NS}	1.82^{NS}	1.65^{NS}	2.36^{NS}
CV (%)	16	17	14	18	17	14

CV = coefficient of variation; NS = non-significant; *significant at 5 % (p < 0.05); **significant at 1 % (p < 0.01).

(Table 1) thereby data is not presented. However, the application time in the 2013/2014 season showed differences in yield and cumulative sugar yield (Table 1). The application time of 45 DAH promoted the highest sugar yield in both seasons and cumulative crop harvests (Table 2). The increase of N rates resulted in a quadratic effect in both years and cumulative sugar yields. The highest cumulative sugar yield was obtained by 157 kg N ha^{-1} and maximum sugar was reached in the 2013/2014 and 2014/2015 seasons, respectively, when fertilization rates were 121 and 188 kg N ha^{-1} (Figure 3).

Economical N rate

The average economical rates obtained for the first and second agricultural seasons (Table 3) were respectively, 103 and 128 kg N ha^{-1}, with the maximum economical N rate of 132 kg N ha^{-1} when sugarcane prices were high and ammonium nitrate prices were low. The minimum economical N rate was 99 kg N ha^{-1} when fertilizer price was over 350 US\$ Mg^{-1} demonstrating that gains of applying high amounts of fertilizers (rates above 150 kg N ha^{-1}) may not cover the investment (fertilizer purchase).

Discussion

The time of N fertilizer application caused differences in stalk yield (Table 2). The cumulative yield of two harvests was increased by 8 % (15 Mg ha^{-1}) at 45 DAH when compared to the application at 90 DAH. Other studies (Fortes et al., 2013a; Otto et al., 2013; Rhein et al., 2016) have also reported increased sugarcane yield due to N-fertilization. The adequate supply of N contributes to stalk yield (Thorburn et al., 2011), whereas the lack of N affects processes such as photosynthesis and formation and development of roots (Taiz and Zeiger, 2009).

In general, the first sugarcane ratoon cycle presents a greater response potential to N application compared to response in sugarcane subsequent ratoons (Franco et al., 2015), also presented in this study where maximum yields required rates over 122 kg N ha^{-1} (Figure 2). This occurred due to lower incidences of tillering failure (data not shown), a better established and more vigorous root system capable of providing adequate nutrient and water uptake. Mechanically harvested sugarcane fields are commonly damaged by heavy and intense machinery traffic on the rows, increasing sprouting failures (Tavares et al., 2010) and decreasing ratoon yields consequently compromising responses to N fertilization.

The findings in this study are consistent with previous studies (45 publications). Otto et al. (2016) reported that yield increased due to N fertilization in 76 % of the studies, in some cases with more than 25 % in stalk yield increase. This could be linked to many factors, such as climate, soil texture, cropping season and timing on fertilizer application (Otto et al., 2016).

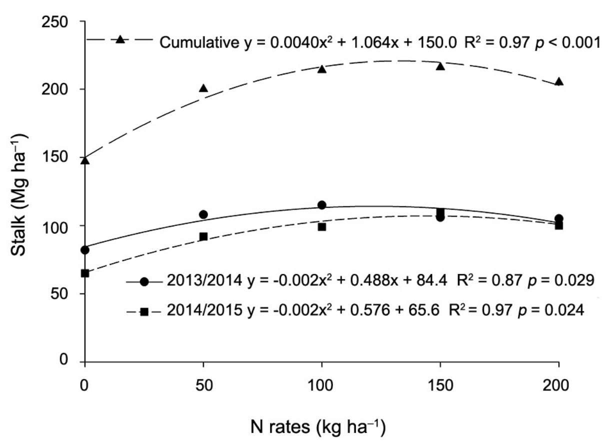

Figure 2 – Effect of N rate on sugarcane stalk yield first and second ratoons (2013/14 and 2014/15) and cumulative sugarcane stalk yield in two crop seasons.

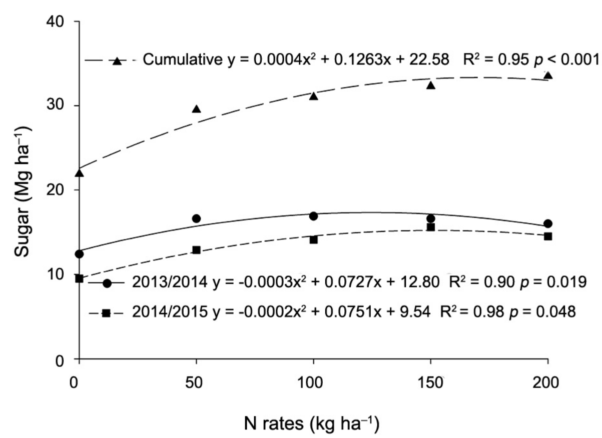

Figure 3 – Effect of N rate on sugarcane sugar yield first and second ratoons (2013/14 and 2014/15) and cumulative sugarcane sugar yield in two crop seasons.

Table 2 – Effect of N application time on stalk and sugar yields in 2013/2014 and 2014/2015 seasons and cumulative yields.

Treatments	Stalk yield			Sugar yield		
	2013/2014	2014/2015	Cumulative	2013/2014	2014/2015	Cumulative
	Mg ha^{-1}					
45 DAH	111 a[†]	95 a	205 a	16.8 a	13.6 a	30.4 a
90 DAH	96 b	92 a	190 b	14.6 b	13.0 a	27.6 b

[†]Means in a column followed by the same letter are not different according to the Tukey test ($p > 0.05$).

Table 3 – N economical rate relationship with sugarcane and N fertilizer price during two crop seasons (2014 and 2015).

Sugarcane Price (US$ Mg^{-1})	Ammonium Nitrate Price (US$ Mg^{-1})			Mean
	Low Price (< 300)	Mean Price (300 < 350)	High Price (> 350)	
	N economical rate (kg ha^{-1})			
Year 2014				
Low price (11)	106	102	99	102
Mean price (16)	108	103	101	104
High price (21)	109	106	103	106
Year 2015				
Low price (11)	128	124	121	124
Mean price (16)	130	128	123	127
High price (21)	132	131	128	130

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Traditionally N fertilizer is applied by a single application immediately after harvesting in sugarcane crops in Brazil (Otto et al., 2016). Therefore, sugarcane harvested from May to July is fertilized in a dry season with short photoperiod, causing asynchrony between the time of higher demand for nutrients and the time when it is supplied (Franco et al., 2011; Mariano et al., 2015). The cumulative stalk yield was affected by the N application time. In our research, since the 2013/2014 season presented difference in yields due to fertilization timing, the effects were pronounced in the sum of the years (Table 2), leading to a higher yield when N was applied at 45 DAH compared to 90 DAH.

This effect could be verified when analyzing the effect of application time on sugarcane yield in the 2013/2014 year, as stalk yields were higher during the application at 45 DAH compared to 90 DAH (Table 2). On the other hand, in the 2014/2015 season, stalk yield was not affected by the application time (Table 2).

The 2014/2015 crop was much drier than the 2013/2014 crop and not only rainfall was a limiting factor, but also water balance, as in the second season, even after rainfall events, water deficit remained until Feb/2015, 210 and 255 days after first and second applications, respectively (Figure 1). This low amount of water available represented a more severe limitation than rainfall, leading to a decrease of N use-efficiency, affecting production, especially since it occurred during the maximum biomass accumulation period of the year when photoperiod and luminosity are at their highest.

To understand this difference, we need to consider that a temporal difference (~80 days) of maximum N absorption and maximum biomass production due to N application (Oliveira et al., 2013). In our study, in the first year, when the N fertilizer was applied at 45 DAH, soil moisture (Figure 1) contributed to N uptake by the plant (Oliveira et al., 2013; Mariano et al., 2015).

This may explain the difference in stalk yield due to fertilization timing in the first season, because N use-efficiency is controlled by a series of edaphoclimatic factors, as rainfall increases the capacity of N uptake by plants enhancing the nutritional status (Marschner, 2012) and thereafter yield (Silveira et al., 2007; Uribe et al., 2013). The absence of response to N application in the second year (Table 2) is associated with a drought that occurred in 2014 (Figure 1) as described above, which influenced some reactions in the soil-plant-atmosphere system (release of nutrients, solubilization of fertilizer granules in the soil solution, and reduction in soil N mineralization for the 2015 growing season), which are dependent on soil moisture, temperature and reactions mediated by microorganisms (Cantarella et al., 2008; Otto et al., 2013). Another aspect that explains lack of sugarcane response to N fertilization in the second year is associated to relationship between the drought and sugarcane response to N fertilizer (Bahrani et al., 2009; Rhein et al., 2016), as the increase of soil dryness (long dry season) decreased sugarcane response to N fertilization.

Therefore, during the sugarcane growth period, from Nov to Jan (Figure 1), the sugarcane fertilized at 45 DAH had all period to grow and produce biomass, while the plants fertilized at 90 DAH had to use part of the maximum growth period to take in N and then start to produce and accumulate biomass.

Sugarcane was also responsive to N rates. The quadratic effects were reported for the first and second seasons and cumulative stalk yield (Figure 2). Although the application time and N rate interaction were no significant, effects on application time were only noticed when N rates were higher than 100 kg ha^{-1} of N considering the crop production of two harvest seasons.

The quadratic responses to N rates indicate that, even though sugarcane is a responsive crop to N, its production is not only limited by this nutrient but also by a series of edaphoclimatic factors, mainly drought, in our case. Regression equations reported that a maximum stalk yield was reached at 133 kg N ha^{-1} on the cumulative yield and 122 and 144 kg N ha^{-1} for the 2013/2014 and 2014/2015 seasons, respectively. The results show a production limitation, as little or no response can be noted after a certain N rate.

Other authors (Borges et al., 2016; Otto et al., 2016; Rhein et al., 2016) have also reported the effect on sugarcane yield and quadratic effect generated by increased N rates. This response may be explained by an increase in tillering, plant height, number of stalks, and plant diameter (Borges et al., 2016), leading to greater biomass accumulation.

The technological quality of sugarcane was not affected by the N rates, as also reported by other authors (Fortes et al., 2013b; Franco et al., 2015; Borges et al., 2016; Rhein et al., 2016). The technological quality of the sugarcane is not directly influenced by the management of N fertilization in sugarcane ratoon (Fortes et al., 2013b; Franco et al., 2015), but it increases when stalk yield is increased since sugar yield calculation takes in consideration stalk yield (Franco et al., 2010; Fortes et al., 2013b). However, there is information in the literature that application of high N rates may decrease the sucrose content by increasing the plant water content (dilution effect) and increase energy consumption to the detriment of greater vegetative development (Wiedenfeld, 2008).

However, different from reports in the literature on the use of N and increased yield, the economical rate to be applied in sugarcane fields was calculated from the regression curves associated with the relationship between fertilizer and sugarcane price (Table 3). In this context, in the first and second agricultural cycles, the average economical rates were, respectively, 104 and 127 kg N ha^{-1}.

Optimum N rates vary according to soils, weather conditions, and cropping practices. Our research showed that the adjustment of time of N-fertilizer application increased sugarcane yield. The difference of ~30 kg N ha^{-1} represents savings on fertilizer use without decreasing crop yield. In the Brazilian economic scenario, this gain would mean an average of ~26 US$ ha^{-1}, which is a significant revenue when considering the total sugarcane ratoon area in central-southern Brazil. The application of more economical N rates in sugarcane fields in central-southern Brazil allows saving US$ ~145 million per year for the Brazilian sugarcane industry.

Therefore, an alternative arises for N fertilizer management in sugarcane ratoon, based on defining the N application time with adjustments of the N rate (Otto et al., 2016). When sugarcane is harvested at the beginning of the season with soil moisture, gains in stalk and sugar yield (Table 2) may be obtained by applying N rates below 150 kg N ha^{-1} (Table 3) and when N-fertilizer is applied until 45 DAH. On the other hand, stalk, and sugar yield may decrease when the N-fertilizer is applied during a period of water deficit.

Conclusions

The importance of N fertilization in sugarcane is highly debatable given the lack of a consensus to reach the highest stalk and sugar yields according to the N rate. This study reported a quadratic response to the increase of N rates in which maximum cumulative sugarcane yield was obtained with 133 kg N ha^{-1}. The application time of N fertilizer promoted differences in stalk and sugar yields in the first year and in the cumulative results. The application at 45 DAH showed higher yield than at 90 DAH. The second year and drier season did not present such results. To maximize production, not only days after harvest should be taken into consideration, but also the amount of water in the system. Our results show that the N application time is only significant in a fertilization management if the amount of water is enough to promote plant growth and nutrient uptake in an early stage. When water is the most limiting factor, N response is the same, regardless if the N fertilizer is applied at 45 or 90 DAH.

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Authors' Contributions

Conceptualization: Castro, S.G.Q., Kölln, O.T., Franco, H.C.J. Data acquisition: Castro, S.G.Q., Rossi Neto, J. Data analysis: Castro, S.G.Q., Rossi Neto, J., Borges, B.M.M.N. Design of Methodology: Castro, S.G.Q., Kölln, O.T. Writing and editing: Castro, S.G.Q., Rossi Neto, J., Kölln, O.T., Borges, B.M.M.N., Franco, H.C.J.

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