BioEnergy Research (2018) 11:583–591
https://doi.org/10.1007/s12155-018-9917-0

CrossMark

Harvesting Systems, Soil Cultivation, and Nitrogen Rate Associated with Sugarcane Yield

Sérgio Gustavo Quassi de Castro [1] · Paulo Sérgio Graziano Magalhães [2] · Henrique Coutinho Junqueira Franco [1] · Miguel Ângelo Mutton [3]

Published online: 21 May 2018

Abstract

The adoption of mechanical harvesting of green cane gives rise to concerns as to whether systems developed under burnt cane harvesting are applicable to a green cane harvesting system. In particular, tillage, which is an integral part of the burnt cane system, may no longer be necessary, and the nitrogen fertilizer rates required may need to be replaced due to the large amounts of organic matter being returned to the soil after green cane harvesting. Mechanical harvesting is relatively new in Brazil and little is known about its effect on other sugarcane production strategies. This work aimed to evaluate sugarcane performance under not only different harvesting and cultivation systems, but also different nitrogen fertilizer rates over a 3-year period. The experimental design was a split plot with harvesting systems (burnt vs. green) as main plots, cultivation (interrow vs. no cultivation) as sub plots, and nitrogen rates as sub-sub plots. The harvesting systems produced similar sugarcane yields throughout the experimental period, which demonstrates that the harvest systems do not influence sugarcane yield. Mechanical tillage practices in interrow after harvesting had no impact on stalk yield or sugar quality, indicating no necessity for this operation in the following crop. Ratoon nitrogen fertilization promoted an increase of stalk and sugar yield, with highest yields obtained at the rate of 130 kg ha^{-1} N. However, there was no interaction between harvesting system and nitrogen rate.

Keywords Nitrogen fertilizer · *Saccharum spp*. · Sugar production · Green cane trash blanket

Introduction

In recent years, there has been a great advance in mechanized harvesting of sugarcane without prior burning (green cane harvesting) in Brazil. In 2015, 90% of the entire crop in the São Paulo State (Brazil's largest producer) was harvested green [1]. With this harvesting system, a significant quantity of dry matter (10 to 20 Mg ha^{-1}) [2–4] from the tops, dry, and green leaves, is deposited on the soil surface as a crop residue, depending on the variety, harvesting season, and environment [5].

The effect of this residue on sugarcane productivity is complex. Some studies indicate a negative effect of the straw on productivity [6, 7], while others show a positive effect [8, 9]. Thus, it is problematical whether green cane harvesting and associated trash retention will improve or reduce productivity, if consider that presence of sugarcane straw after the harvest has a direct effect on the quality indicators of soil (nutrient recycling, soil water storage, soil erosion control) feedstock indicators (reduce the weeds population, influence the biomass production) and bioenergy indicators (bioelectricity cogeneration) [10].

The sugarcane crop residue has benefits to the crop from the agronomic perspective, such as protecting the soil surface against the impact of raindrops, decreasing the risk of soil erosion, reducing the thermal range of the soil, higher retention of soil moisture, increase of carbon stock [11], and cycling of nutrients [12, 13]. However, the presence of trash may adversely affect productivity of sugarcane stalks caused by

Electronic supplementary material The online version of this article (https://doi.org/10.1007/s12155-018-9917-0) contains supplementary material, which is available to authorized users.

✉ Sérgio Gustavo Quassi de Castro
sergio.castro@ctbe.cnpem.br

1 Brazilian Bioethanol Science and Technology Laboratory (CTBE), Brazilian Center for Research in Energy and Materials (CNPEM), Campinas, SP 13083-970, Brazil

2 UNICAMP/FEAGRI – University of Campinas/School of Agriculture, Cidade Universitária "Zeferino Vaz", Campinas, SP 13083-970, Brazil

3 UNESP/FCAV – University of São Paulo State, Via de Acesso Prof. Paulo Donatto Castellane, s/n, Jaboticabal, SP 14884-900, Brazil

failure to sprout, especially in low temperature regions [14, 15]. Further, commercially cultivated varieties in Brazil have been genetically selected in burnt cane harvesting systems and there is little information on their adaptability for a green cane system [5, 16]. In addition, the lower incidence of solar radiation on the soil surface may increase proliferation of pests and diseases [17], and present a higher risk of fires in the surface crop residues after the harvest.

The quantity of N in the straw (40–120 kg ha^{-1}) resulting from green cane harvesting may represent a source of N for the crop in the next cycle of the ratoon [18]. However, since the C:N ratio of the straw is about 100:1 [19], this amount of N is slowly released, and its contribution to sugarcane next crop cycle nutrition is negligible, between 2 and 15% [20–23]. The N recommendation for green cane is not yet established in Brazil. Nevertheless, Penatti [24] recommended increasing the N dose in all areas harvested without burning by at least 20% compared to burnt cane. To fulfill these nutritional requirements, the N dose applied on sugarcane ratoons (without burning) is between 150 and 200 kg N ha^{-1} [25], defining the exact nitrogen doses, requires field experiments to determine crop response to N-fertilization [26].

In areas where sugarcane is mechanically harvested, soil compaction invariably occurs in the interrow, due to the traffic of heavy agricultural machines and implements [27]. Compaction reduces the total porosity and aeration of the soil, reduces rootstock sprouting, lowers productivity, and hence promotes a reduction in lifespan of the sugarcane. Therefore, farmers have been cultivating interrows after harvest using a deep-shank cultivator in the interrow, in order to loosen the soil after mechanized operations on the crop [28]. However, the benefits of this practice are arguable as increases [29], decreases [30], and no effect [31, 32] on productivity have been reported.

Thus, in order to answer some of the questions arising from the change to mechanical green cane harvesting, we undertook a study that interacted harvesting system, interrow tillage, and nitrogen rates over a 3-year period in a ratoon sugarcane crop.

Materials and Methods

The experiment was conducted in the northern area of the São Paulo state, Sales Oliveira county, Brazil (20° 52′ 31” S, 47° 57′ 56” W). The climate is tropical to subtropical (“Aw” based on Köppen’s climate classification) with mean annual rainfall and temperature of 1.553 mm and 21.4 °C, respectively. The soil is classified as an Acrudox clay texture [33], with initial chemical and physical characteristics (0.0–0.2 m) being: pH ($CaCl_2$)—4.9; organic matter—22 g dm^{-3}; P(resin)—21 mg dm^{-3}; K, Ca, Mg, and CEC, respectively, 0.11, 1.5, 0.5, and 5.47 cmol$_c$ dm^{-3}. Clay, silt, and sand contents were 719, 198, and 83 g kg^{-1}, respectively. The production environment was characterized as D on a scale from A to E, where A environment has more favorable conditions for sugarcane cultivation and E environment has more chemical and/or physical restrictions for sugarcane production.

The site had been under continuous sugarcane cultivation (*Saccharum spp.*) for 20 years and the average of crop lifespan is six crop seasons, with average yield of 80 Mg ha^{-1}. Until 2007, pre-harvest burning was practiced. In 2007, the sugarcane variety: SP81-3250 was planted after disc plowing, subsoiling, and disc harrowing. This variety is of medium maturation, has good sprouting, and accounts for 13% of the entire sugarcane area in mid-southern Brazil. In 2008, prior to harvest of the plant cane, the site was divided into two main plots (for green and burned cane). During the following cycles, sugarcane was mechanically harvested in both plots until 2011. Our investigation began in 2008 after harvesting the plant cane.

The experiment design was a randomized block with split-split plots with four replications: main plots constituted the harvesting systems (green or burnt cane); secondary treatments (split plots) refer to the use or not of mechanical cultivation of the post-harvest interrow; and tertiary treatments (split-split plots) are N rates (0, 30, 60, 90, 120, and 160 kg ha^{-1}) using ammonium nitrate (33% N). The treatments were repeated in the following years (2009 and 2010).

The experiment was conducted in an area of 5.7 ha. During the research period, the location of plots, split plots, and split-split plots was accurately determined using GNSS—global navigation satellite system (Suppl. Fig. 1). Each main plot consisted of 15 rows of sugarcane, 500 m long. Split plots (cultivation or no cultivation) were delimited by 10 central rows of 250 m, with the other 5 rows left as border between the plots, which allowed for the burning of cane plots and a maneuvering area for the harvester. Split-split plots were marked within the split plots, and comprised 5 central rows 10 m long. These central rows were marked from the initial 20 m of the split plots, setting a distance of 20 m between split-split plots.

In the period of the experiment, rainfall data (mm month^{-1}) was collected using a pluviometer located next to the experimental area, to calculate water balance during the experiment (Fig. 1).

Yearly, 10 days after the harvest (10 DAH) 150 kg ha^{-1} of K (KCl) was applied on the soil surface on both sides of the row in the plots. At 90 DAH, before the rainy season began, soil cultivation was carried out using a tractor-mounted (81 kW), double-tine cultivator, at 0.3 m working depth to the tillage plots. Finally, 120 DAH, the tertiary treatment (nitrogen application) was carried out where N was applied manually at the respective rates, at 0.1 m on each side of the row. One week prior to harvest, a biometric evaluation was conducted. The procedure consisted of harvesting 1 m of sugarcane of rows in each split-split plot, Fig. 1. The stalks were topped, detrashed, and weighed. These data were used to

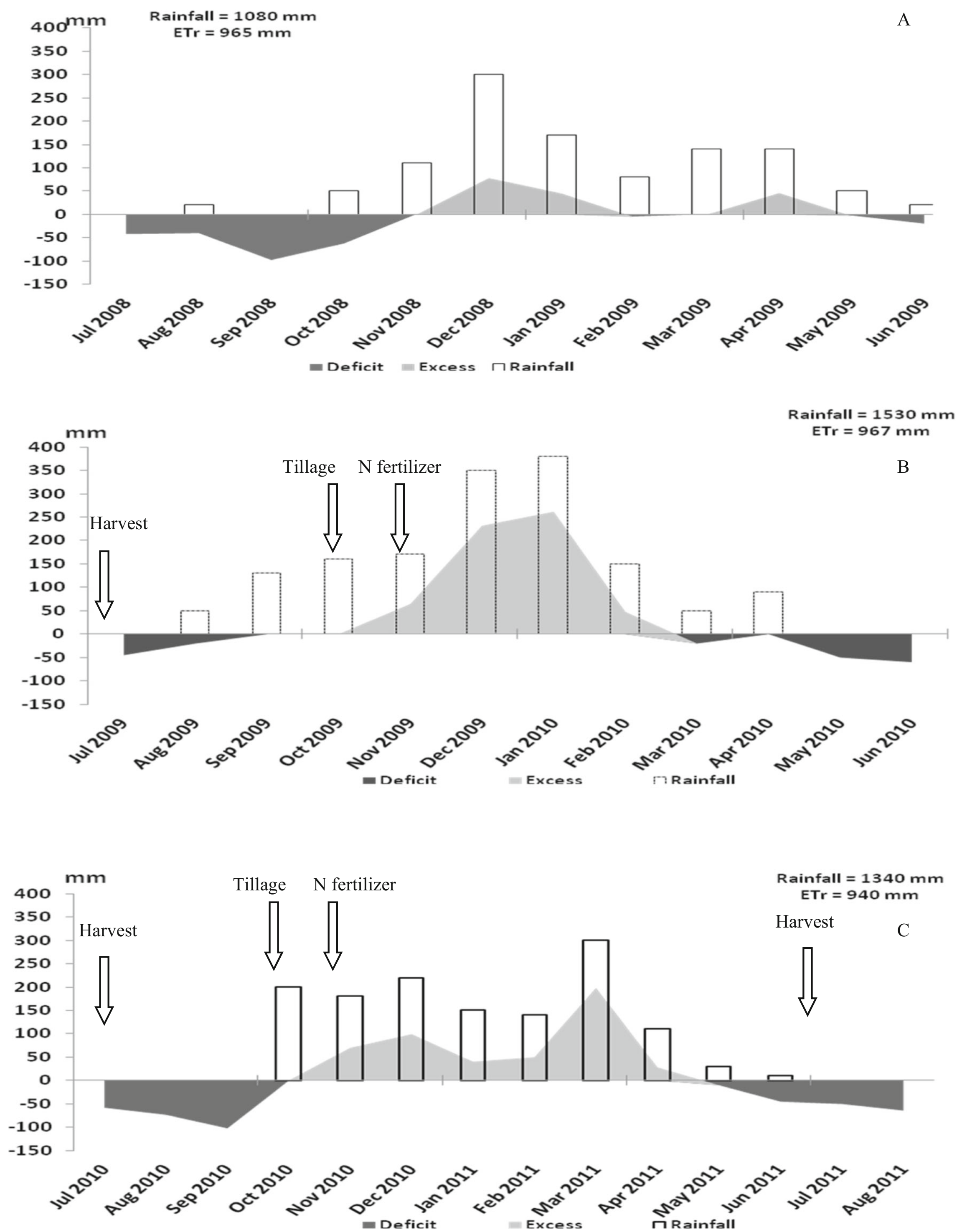

Fig. 1 Annual water balance during the experimental period: 2008–2009 (**a**); 2009–2010 (**b**); 2010–2011 (**c**)

estimate the yield per plot. To determine sugar content (Pol %), stalks obtained (five replications in each treatment) during the harvest operation (green or burnt cane) were crushed at the mill laboratory and analyzed by Fernandes, (2003) [34], and tons of Pol per hectare (TPH) (Mg ha^{-1} Pol) were calculated.

Statistical Analysis

The results of biometric evaluation and sugarcane technological parameters were submitted to a variance analysis (ANOVA) to partition the harvesting system, cultivation method, and N rates, using the *F* test. For harvest and crop practices, the Tukey test was applied with 5% probability. Polynomial regression analysis was adopted to compare nitrogen rates.

Results

Harvesting Systems

In general, the sugarcane yield was higher in the first year than other experimental years (Table 1). There was no statistical difference in yield between harvesting systems in each of the ratoons with the exception of 2010, where the burnt cane system had higher yield. However, when the average yield for the three seasons was calculated, there was no difference between the harvesting systems. The overall major reduction in yield from 2009 to 2010 (in average 26 Mg ha^{-1}), that infers a reduction of 23% in sugarcane yield. This yield reduction was associated with the weather conditions (Fig. 1), which in the first experimental year occurred less rainfall when compare in other years. Other reasons could be related to effects of sugarcane mechanical harvest (Table 2) in general trend for yields to reduce with later ratoons, for example, the higher values of post-harvest residues in green cane than burnt cane.

The presence of straw and tops in the biomass delivered to the mill may also modify technological parameters of the sugarcane, such as apparent sucrose content (Pol). In this experiment, the Pol varied with the harvesting system, the burnt cane having higher Pol values than the green cane in all years (Table 1). In this study, the time between burning and processing was less than 8 h, so the potential adverse effects of burning were limited. In contrast, losses through dehydration are likely to be minimal with green harvesting. However, with

Table 1 Effect of the harvest system, adoption or non-adoption of mechanical cultural practices of sugarcane management, and nitrogen rates on stalk height, stalk yield (TCH, tons of cane per hectare), cane Pol (%), TPH (tons of Pol per hectare)

Parameters year	Height (m)				Yield (TCH)				Pol (%)				TPH			
	2009	2010	2011	Average	2009	2010	2011	Average	2009	2010	2011	Average	2009	2010	2011	Average
Harvest systems																
Green cane	2.49	2.31	2.16	2.32	115	83B[#]	81	93	14.6 B	18B	16.5B	16.4B	16.8	15.1B	13.5B	15.1B
Burnt cane	2.48	2.30	2.19	2.32	110	89A	80	93	14.9A	18.4A	17.3A	16.9A	16.5	16.5A	14A	15.7A
$p > n$	ns	ns	ns	ns	ns	**	ns	ns	*	*	*	**	ns	*	*	*
LSD	0.2	0.19	0.1	0.15	10.6	5.1	3	5	0.23	0.28	0.50	0.25	1.66	0.85	0.42	0.21
Tillage practices																
With	2.49	2.32	2.15	2.32	112	85	81	92.7	14.8	18.2	17	16.7	16.6	15.5	13.7	15.3
Without	2.47	2.30	2.11	2.29	112	88	81	93.7	14.8	18.3	16.9	16.7	16.7	16.1	13.8	15.5
$p > n$	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
LSD	0.07	0.07	0.05	0.08	4.1	3.5	5.3	2.2	0.23	0.3	0.46	0.4	0.57	0.76	1.17	0.6
N rate (kg ha^{-1})																
0	2.35	2.19	1.8	2.11	100	69	58	75.7	14.9	18.3	16.5	16.6	15	12.7	9.8	12.5
30	2.43	2.26	2.06	2.25	128	81	72	93.7	14.8	18.2	17	16.7	16.1	14.7	12.3	14.4
60	2.51	2.33	2.14	2.33	112	87	81	93.7	14.5	18.3	17	16.6	16.4	16	13.8	15.4
90	2.54	2.36	2.19	2.36	117	92	90	99.7	14.1	18.1	17.1	16.4	17.3	16.6	15.5	16.5
120	2.55	2.37	2.21	2.38	118	95	91	101.3	14.7	18.4	16.8	16.6	17.3	17.5	15.4	16.7
160	2.52	2.34	2.32	2.39	119	94	91	101.3	14.9	18.1	17.1	16.7	17.8	17	15.5	16.8
$p > n$	**	**	**	**	**	**	**	**	ns	ns	ns	ns	**	ns	**	**
1 × 2	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
1 × 3	ns	ns	ns	ns	ns	ns	ns	ns	ns	*	ns	ns	ns	ns	ns	ns
2 × 3	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
1 × 2 × 3	ns	ns	ns	ns	ns	ns	ns	ns	*	ns	ns	ns	ns	ns	ns	ns
CV (%)	8	8	6	7	10	9	8	6	3	3	4	3	10	10	10	8

Interactions: 1—Harvest system; 2—Tillage practices; 3—N-fertilization

LSD least significant difference, *CV (%)* coefficient of variation

[ns] Non-significant

[*] Significant at 5%

[**] Significant at 1%

[#] Means within a column followed by the same letter are not different according to the "Tukey" test ($p > 0.05$)

green harvesting reductions in Pol concentration also can be affected by other factors, such as increased trash loads and impurities that burning will remove.

In terms of sugar yield (TPH), we found that the burnt cane system produced better results, largely because of increased Pol in all years (Table 1). However, considering the need to minimize the time between sugarcane burning and processing, it is important to recognize that the burnt system has less flexibility. Further, seasonal conditions during harvesting can have an important influence, particularly in burnt cane.

Tillage Practices

Soil cultivation of interrow over the 3 years had no effect on productivity or technological attributes (Pol)—Table 1. The lack of response of tillage practices in sugar and sugarcane yield over 3 years shows that the management of green cane the tillage operation in interrow of field is not important even considering the weight of harvest machine and the traffic carried out on crop lines during the harvesting.

Nitrogen Fertilization

Nitrogen rates promoted an increase in crop development (Table 1), both in stalk height, sugarcane yield (tons of cane per hectare—TCH) and sugar yield per hectare (TPH). However, there was no interaction between harvesting method and nitrogen rate with similar yields being recorded for the same N rate regardless of whether there was green or burnt cane harvesting.

For the stalk height parameter, a quadratic response resulted (Fig. 2), and throughout the 3 years, the lack of supply of nitrogen-based fertilizer (0 kg ha^{-1}) caused reduction of approximately 0.20 m in the height of the stalks (Table 1). Likewise, by comparing the effect of nitrogen fertilization on the height of the stalks during the 3 years, the average difference in height between the 0 and 160 kg ha^{-1} N was 0.28 m (Table 1). However, overall height and yields decreased in later ratoons although there were indications that height of stalks and sugar yields could be maintained to some extent in later ratoons with higher nitrogen rates (Figs. 3 and 4).

The results showed a quadratic correlation between N rate and yield, with a theoretical peak yield at rates close to 130–150 kg ha^{-1} N (Fig. 3). The high coefficient of determination of the response curve indicates a strong correlation between N rates and stalk yield (TCH). Over the 3 years of the experimental period, the plots that did not have N-fertilizer showed a reduction in sugarcane yield near 25% (26 Mg ha^{-1}) when compared with the plots that had the high rate of N-fertilizer (160 kg ha^{-1} —Fig. 3). According to the average sugarcane yield during all experimental period (Fig. 3), the N-fertilization improves 30% (22 Mg ha^{-1}) in stalk yield and the best N rate was near 140 kg ha^{-1} N. Therefore, there is a clean response of sugarcane gains (stalk and sugar) due the N application, but there is no correlation between the N-fertilization with harvest system or tillage practice.

Over the three ratoons (2009, 2010, 2011), nitrogen had no effect on the Pol. Nevertheless, the incremental rise in nitrogen rate showed a positive effect in TPH (Fig. 4), where the application of 120 kg ha^{-1} of nitrogen-based fertilizer resulted in additions of ~5 Mg ha^{-1} in TPH in the last year of the experiment (2011—4th crop). Therefore, the sugar gains are related to the technological quality (Pol), together with the N-fertilization applied associated with the harvest system (green cane or burnt cane).

Table 2 Average values of vegetable and mineral impurity in the harvest system evaluated

Parameters	Green cane			Burnt cane		
	2009	2010	2011	2009	2010	2011
Plant material (%)	9.2	6.2	6.0	3.8	3.1	3.3
Mineral (%)	0.4	0.7	0.4	0.65	0.9	0.7
PHR[1]	6.8	2.9	1.5	1.2	0.8	0.4
Soil moisture (%)[2]	28.1	28.3	27.9	22.0	22.1	21.3

[1] *PHR* Post-harvest residues (Mg ha^{-1})

[2] Samples of soil evaluated at 60 DAH—before the tillage practices

Discussion

The green cane harvest, which was done without fire, has increased in the last 10 years in Brazil, and accounted for approximately 85% of the 2014 sugarcane harvest [1]. In this context, it is important to have in the literature research studies that show the increases or decreases in sugarcane yield according to the harvest system [14, 15, 29]. In our research, the sugarcane harvest systems (green cane or burnt cane) did not influence the yields of stalks or sugar (Table 1). This result shows that the sugarcane harvest system is not correlated with the sugarcane crop longevity [35]; however, the green cane harvest along the years may reduce the sugarcane yield [36] due to ratoon damage during the sugarcane harvest.

The residual straw above the soil surface after the harvest increases the soil moisture [37], which was evaluated at 60 DAH—days after harvest. In green cane plots, the moisture was higher (6%) than in plots of burnt cane (Table 2). The maintenance of straw on the soil surface may contribute to sugarcane development and increase the productivity in areas that present no problem with altitude or low temperatures [9, 10], especially in crop years that have low rainfall accumulation, i.e., in 2009, the year of our research (Fig. 1a), when the green cane produced higher yield compared to burnt cane.

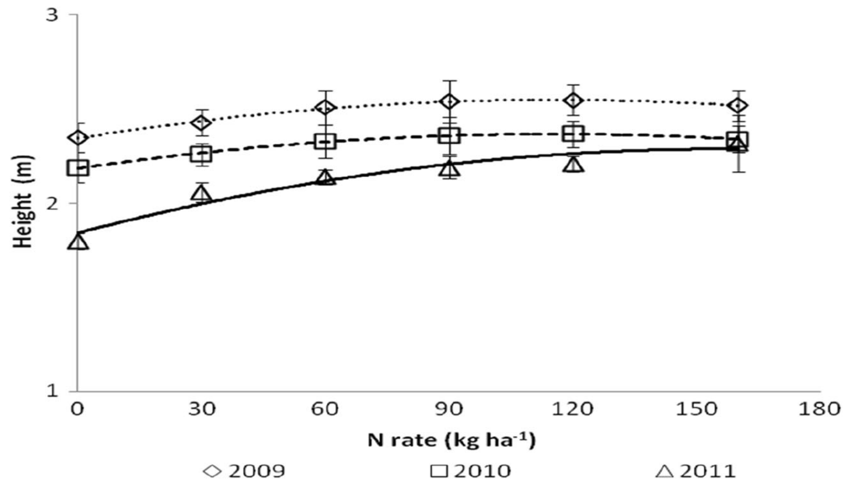

Fig. 2 Effect of N-fertilizer rates on stalk height in sugarcane. Regression equations: 2009: $y = 2.35 + 0.0035x - 0.00002x^2$ ($R^2 = 0.9956^{**}$); 2010: $y = 2.19 + 0.0032x - 0.00001x^2$ ($R^2 = 0.9956^{**}$); 2011: $y = 1.84 + 0.0057x - 0.00002 \times {}^2$ ($R^2 = 0.9343^{**}$)

In our research, the green cane harvest had more stalk losses and mineral and vegetal impurities (Table 2), effects that were described in other studies [36, 38–40]. The high stalk losses diminish the sugarcane yield [1, 35] and reduce ratoon sprouting in the crop cycle [39, 40].

The results of this work, although limited to one site and one soil type, indicate that the adoption of green cane harvesting may impose some adverse effects on productivity, but that these effects are likely to be relatively minor and will probably vary depending on soil type and seasonal conditions. The weather conditions associated with the harvest method adopted in a sugarcane field influence the plant growth and sugarcane yield. Furthermore, the trash residues on the soil surface are likely to reduce the soil temperature, which in turn contributes to improving moisture conservation in the soil under a green cane harvesting system. The 2009 season was characterized by an extended period of ideal growing conditions with adequate rainfall over the summer growing period, which extended into the crop maturation period (Fig. 1a). By contrast, the 2010 season had a wet

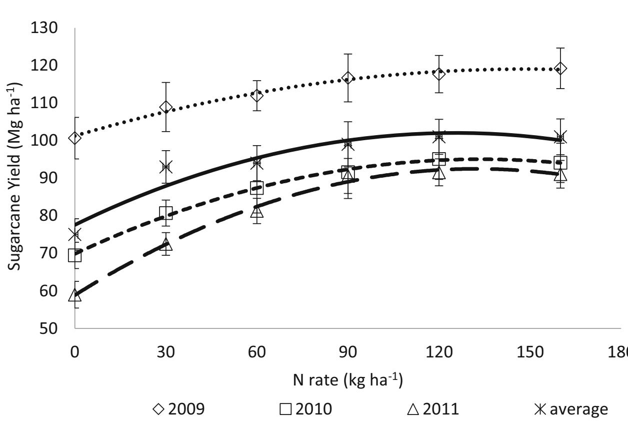

Fig. 3 Effect of N-fertilizer rates on stalk yield in sugarcane. Regression equations: 2009: $y = 101.23 + 0.239x - 0.0008x^2$ ($R^2 = 0.9869^{**}$); 2010: $y = 69.85 + 0.3769x - 0.0014x^2$ ($R^2 = 0.9969^{**}$); 2011: $y = 58.85 + 0.5085x - 0.0019 \times {}^2$ ($R^2 = 0.9951^{**}$); average: $y = 78.25 + 0.383x - 0.0015x^2$ ($R^2 = 0.9831^{**}$)

summer rainfall period between November and March (Fig. 1b). The significantly higher yield of burnt cane than green cane in 2010 could have been due to a number of factors associated with the 2009 crop harvest. First, proper growing conditions in 2008/2009 (Fig. 1a) produced a higher crop yield in 2009 (115 Mg ha^{-1}), as the soil moisture level in the green cane was higher than burnt cane, averaging 6% (Table 2).

Our results show that interrow cultivation after harvest has no effect on the productivity of the next crop in the cycle regardless of the harvesting system. Thus, given the conflicting results obtained from many studies on this subject [29–32], there is a need to investigate further at the conditions under which the studies were carried out to try to ascertain the reasons for the conflicting responses.

The first aspect that may account for the non-response to cultivation in sugarcane yield is that 30% of compaction energy is dissipated and attenuated by the physical passage of the harvest machine [41]. Another possible aspect mentioned in our research is that the sugarcane harvest occurred in a dry season (Fig. 1a–c), with low soil moisture. Furthermore, the experimental field soil had a high level of clay, which presents greater compaction resistance [29, 32], which eliminates the need for interrow cultivation after the harvest. In addition, experiments evaluating sugarcane roots have demonstrated that 80% of the roots are underneath the planting row, far from the interrow [42, 43], which may explain the lack of productivity increase from mechanical cultivation of the interrow.

The literature reports a clear response to nitrogen fertilizer in sugarcane ratoon, with maximum theoretical yields being obtained from 100 to 120 kg ha^{-1} N, in Brazil under a green cane harvesting system [25, 26]. However, the harvesting system had no effect on the response to N in our work. Recent studies in Australia [44] found similar responses to N, which were the same in a burnt and a green cane systems that had been in place for 15 years. Under the Brazilian conditions, at the first moment of straw decomposition, the microorganisms remove N from the soil to complete the total carbon decomposition, thus competing

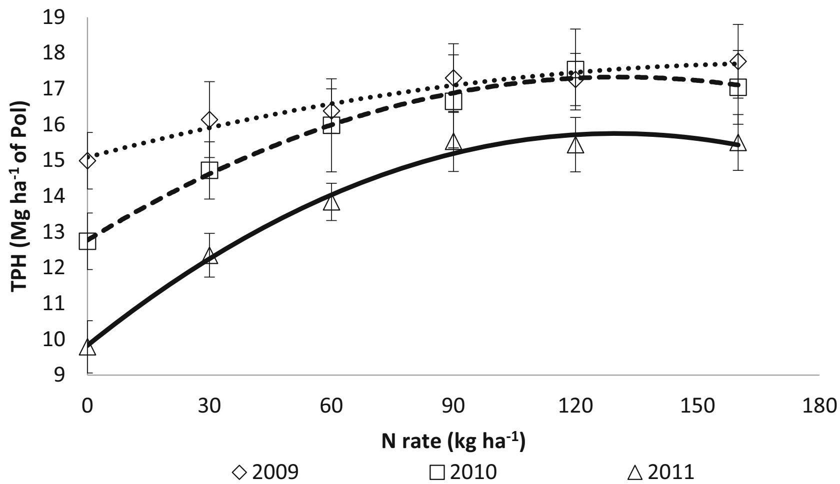

Fig. 4 Effect of N-fertilizer rates on sugar yield (TPH). Regression equations: 2009: $y = 15.09 + 0.03x - 0.00009x^2$ ($R^2 = 0.9635^{**}$); 2010: $y = 12.77 + 0.0696x - 0.0003x^2$ ($R^2 = 0.9919^{**}$); 2011: $y = 9.83 + 0.0913x - 0.0004x^2$ ($R^2 = 0.9908^{**}$)

with the sugarcane plant [23]. After 3 years of green cane harvesting, approximately 70% of all dry matter is decomposed allowing the release of nutrients such as K, Ca, and N [18]. Only 40 years after adoption of the green cane system can a stock of about 40 kg ha^{-1} of N in the soil be generated [23].

This tends to indicate that little reliance should be placed on obtaining a substantial supply of soil nitrogen under a green cane trash blanket harvesting system, due to the low mineralization of N content in straw [3, 45], which has a high C:N ratio: 100:1 [19]. On the other hand, the straw on the soil surface contributes to increasing the nutrient cycling [46] and to the chemical, physical, and microbiological attributes in the soil [10, 47], which can increase the sugarcane yield [48] or reduce the decline of stalk yield [49, 50].

The N-fertilization promoted increases in stalk height in each crop cycle (Fig. 2), where the rates that promote the highest yield and high stalk height were similar (Table 1), showing that N balance in the plant affects photosynthesis, formation, and root growth [51]; therefore, N is considered an essential element for plant nutrition and, in the case of sugarcane, is related to stalk production [52].

In our research, the N-fertilization increased the stalk yield [18, 25, 49, 53, 54], where during the experimental period the highest sugarcane yield was obtained after applying rates between 120 and 150 kg ha^{-1} N (Fig. 3), corroborating other authors [25, 26, 46], who suggest applying N rates near 150 kg ha^{-1} of N in green cane system. The average sugarcane yield (include 3 crop cycle) was obtained after applying an N rate of 130 kg ha^{-1} (Fig. 3), which corroborated the result reported by Fortes et al. (2013) [18] during the three crop cycles. Similar to the present findings, Castro et al. [49] showed gains near 21% in sugarcane yield produced by N rates of 130 kg ha^{-1}, during a harvest done in a dry season (in August) in the south central region of Brazil.

The sugar yield increased according to the N rate applied (Fig. 4). This effect is similar to sugarcane yield × N rate (Fig. 3), which corroborates prior research studies [8, 46, 55, 56] reporting that N-fertilization did not influence Pol; however, there was a positive response in sugar productivity associated with higher agricultural productivity (TCH). The mineral and vegetal impurities (Table 2) affect the pol and sugar yield (TPH)—Table 1), which were both higher in burnt cane than in green cane, an effect that was reported by other authors [29, 35, 37], which suggests that the technological parameters of the sugarcane crop were affected by harvest management.

Conclusion

The harvesting systems do not influence the sugarcane yield; however, the burnt cane presents better technological quality and sugar yield when compared to the green cane, due to the high index of visible and invisible losses as well as impurities during the harvest.

The performance of the mechanical cultivation in the ratoon crop does not differ from its non-performance in relation to the sugarcane and sugar yields, thus emphasizing the importance of analyzing the necessity of this operation after harvest.

Sugarcane plants obtained high stalk height, productivity, and sugar yield after applying N rates between 130 and 150 kg ha^{-1} N regardless of the harvest system adopted.

Funding Information This project was funded by FAPESP (State of São Paulo Research Foundation—Process 2013/01417-2), and CAPES (Higher Education Personnel of Improvement of Coordination), which supported the scholarship of the first author.

References

1. Belardo GC, Cassia MC, Silva RP (2015) Processos Agrícolas e Mecanização da Cana-de-Açúcar. Sociedade Brasileira de Engenharia Agrícola SBEA, Jaboticabal 608p
2. Franco HCJ, Pimenta MTB, Carvalho JLN, Magalhães PSG, Rossell CE, Braunbeck OA, Vitti AC, Kölln OT, Rossi Neto J (2013) Assessment of sugarcane trash for agronomic and energy

purposes in Brazil. Sci Agric 70(5):305–312. https://doi.org/10.1590/S0103-90162013000500004
3. Ferreira DA, Franco HCJ, Otto R, Vitti AC, Fortes C, Faroni CE, Garside AL, Trivelin PCO (2016) Contribution of N from green harvest residues for sugarcane nutrition in Brazil. GCB Bioenergy 8(5):859–866. https://doi.org/10.1111/gcbb.12292
4. Menandro LMS, Cantarella H, Franco HCJ, Kölln OT, Pimenta MTB, Sanches GM, Rabelo SC, Carvalho JLN (2017) Comprehensive assessment of sugarcane straw: implications for biomass and bioenergy production. Biofpr 11(3):488–504. https://doi.org/10.1002/bbb.1760
5. Landell MGA, Scarpari MS, Xavier MA, Anjos IA, Baptista AS, Aguiar CL, Silva DN, Bidoia MAP, Brancalião SR, Bressiani JA, Campos MF, Miguel PEM, Silva TN, Silva VHP, Souza Anjos LO, Ogata BH (2013) Residual biomass potential of commercial and pre-commercial sugarcane cultivars. Sci Agric 70(5):299–304. https://doi.org/10.1590/S0103-90162013000500003
6. Basanta MV, Dourado Neto D, Reichardt K, Bacchi OOS, Oliveira JCM, Trivelin PCO, Timm LC, Tominaga TT, Correchel V, Cássaro FAM, Pires LF, Macedo JR (2003) Management effects on nitrogen recovery in a sugarcane crop grown in Brazil. Geod 116:235–248. https://doi.org/10.1016/S0016-7061(03)00103-4
7. Prado RM, Pancelli MA (2008) Sugarcane ratoon response to nitrogen application in a no burn harvesting system. Bragantia 67: 951–959. https://doi.org/10.1590/S0006-87052008000400018
8. Trivelin PCO, Oliveira MW, Vitti AC, Gava GJC, Bendassolli JA (2002) Nitrogen losses of applied urea in the soil-plant system during two sugar cane cycles. Pesq. Agropec. Bras. 37:193–201. https://doi.org/10.1590/S0100-204X2002000200011
9. Carvalho JLN, Otto R, Franco HCJ, Trivelin PCO (2013) Input of sugarcane post-harvest residues into the soil. Sci Agric 70(5):336–344. https://doi.org/10.1590/S0103-90162013000500008
10. Carvalho JLN, Nogueirol RC, Menandro LMS, Bordonal RO, Borges CD, Cantarella H, Franco HCJ (2017) Agronomic and environmental implications of sugarcane straw removal: a major review. GCB Bioenergy 9(7):1181–1195. https://doi.org/10.1111/gcbb.12410
11. Cerri, CC, Galdos, MV, Maia, SMF, Bernoux M, Feigl BJ, Powlson, D, Cerri, CEP (2011) Effect of sugarcane harvesting systems on soil carbon stocks in Brazil: an examination of existing data. Eur J Soil Sci 62:23–28. doi: https://doi.org/10.1111/j.1365-2389.2010.01315.x
12. Oliveira MW, Trivelin PCO, Gava GJC, Penatti CP (1999) Sugarcane trash degradation. Sci Agric 56:803–809. https://doi.org/10.1590/S0103-90161999000400006
13. Franco HCJ, Bologna IR, Faroni CE, Trivelin PCO (2007) Macronutrients accumulation in sugarcane crop related to nitrogen fertilization and cultural residues incorporated to the soil at planting. Bragantia 66:669–674. https://doi.org/10.1590/S0006-87052007000400017
14. Wood AW (1991) Management of crop residues following green cane harvesting of sugarcane in north Queensland. Soil Till Res 20: 69–75
15. Bell, MJ, Halpin, N, Cunningham, G, Garside, AL, Kingston, G (1999) Effect of wet soil during early season ratoon establishment on sugarcane grown under different trash management systems in southern canelands. Proc. Aust. Soc. Sugar Cane Tech 21:139–148
16. Tavares OCH, Lima E, Zonta E (2010) Sugarcane growth and productivity under different tillage and crop systems. Acta Sci Agron 32:61–68. https://doi.org/10.4025/actasciagron.v32i1.2051
17. Dinardi Miranda LL, Fracasso JV (2013) Sugarcane straw and the populations of pests and nematodes. Sci Agric 70(5):305–310. https://doi.org/10.1590/S0103-90162013000500012
18. Fortes C, Vitti AC, Otto R, Ferreira DA, Franco HCJ, Trivelin PCO (2013) Contribution of nitrogen from sugarcane harvest residues and urea for crop nutrition. Sci Agric 70(5):313–320. https://doi.org/10.1590/S0103-90162013000500005
19. Robertson FA, Thorburn PJ (2007) Decomposition of sugarcane harvest residue in different climatic zones. Aust J Soi Res 45:1–11. https://doi.org/10.1071/SR06079
20. Gava GJC, Trivelin PCO, Vitti AC, Oliveira MW (2005) Urea and sugarcane straw nitrogen balance in a soil-sugarcane crop system. Pesq Agropec Bras 40:689–695. https://doi.org/10.1590/S0100-204X2005000700010
21. Vitti AC, Ferreira DA, Franco HCJ, Fortes C, Otto R, Faroni CE, Trivelin PCO (2010) Utilisation of nitrogen from trash by sugarcane ratoons. Sugarcane Internat 28:249–253
22. Fortes C, Trivelin PCO, Vitti AC, Ferreira DA, Franco HCJ, Otto R (2011) Recovery of nitrogen (15N) by sugarcane from previous crop residues and urea fertilisation under a minimum tillage system. Sug Tech 13(1):42–46. https://doi.org/10.1007/s12355-011-0074-4
23. Trivelin PCO, Franco HCJ, Otto R, Ferreira DA, Vitti AC, Fortes C, Faroni CE, Oliveira ECA, Cantarella H (2013) Impact of sugarcane trash on fertilizer requirements for São Paulo, Brazil. Sci Agric 70(5):345–352. https://doi.org/10.1590/S0103-90162013000500009
24. Penatti CP (2013) Adubação da cana-de-açúcar, 1a edn. Editora Ottoni, Piracicaba, SP
25. Cantarella H, Rossetto R (2014) Fertilizers for sugarcane. In: Cortez LAB (ed) Sugarcane bioethanol — R&D for Productivity and Sustainability. Edgard Blücher, São Paulo, pp 405–422
26. Otto R, Castro SAQ, Mariano E, Castro SGQ, Franco HCJ, Trivelin PCO (2016) Nitrogen use efficiency for sugarcane-biofuel production: what is the next? Bioen Res 9(4):1272–1289. https://doi.org/10.1007/s12155-016-9763-x
27. Garside AL, Poggio MJ, Park G, Salter B, Perna J (2009) Long-term Ingham and Mackay farming system experiments: comparison between non-tilled beds re-formed ceds. Proc. Aust. Soc. Sugar Cane Tech 31:282–295
28. Bianchini A, Magalhães PSG (2008) Evaluation of coulters for cutting sugar cane residue in a soil bin. Biosyst Eng 100(3):370–375. https://doi.org/10.1016/j.biosystemseng.2008.04.012
29. Souza ZM, Paixão ACS, Prado RM, Cesarin LG, Souza SR (2005) Residue management of the green sugarcane, productivity and broth quality of the sugarcane. R Ci Rur 35(5):1062–1068. https://doi.org/10.1590/S0103-84782005000500012
30. Oliveira VS, Rolim MM, Vasconcelos RFB, Costa YDJ, Pedrosa EMR (2010) Compactação de um Argissolo Amarelo Distrocoeso submetido a diferentes manejos. Rev B Eng Agric Amb 14(9):914–920. https://doi.org/10.1590/S1415-43662010000900002
31. Paulino AF, Medina CC, Azevedo MCB, Silveira KRP, Trevisan AA, Murata IM (2004) Chisel plowing in an Oxisol in post harvest of ratoon cane. R Bras Ci Solo 28(5):911–917. https://doi.org/10.1590/S0100-06832004000500013
32. Camilotti F, Andrioli I, Dias FLF, Casagrande AA, Silva AR, Mutton MA, Centurion JF (2005) Long-term effect of soil tillage systems with and without tillage of green-cane stump in soil physical properties. Eng. Agric 25(1):189–198. https://doi.org/10.1590/S0100-69162005000100021
33. Soil Survey Staff, (2014) Key to soil taxonomy, USDA-NRCS, agricultural handbook no. 436p. 12th ed. U.S. Government Printing Office, Washington, DC, USA
34. Fernandes AC (2003) Calculations in the sugarcane agroindustry. STAB, Piracicaba 260p
35. Cassia MT, Silva RP, Paixão CSS, Bertonha RS, Cavichioli FA (2014) Basecutter blades wear in quality of mechanized harvesting. Rev Ci Rural 44(6):987–993. https://doi.org/10.1590/S0103-84782014000600006
36. Reis, GN (2009) Perdas na colheita mecanizada da cana-de–açúcar crua em função do desgaste das facas do corte de base. Tese

(Doutorado em Agronomia) – Faculdade de Ciências Agrárias e Veterinárias, Jaboticabal – SP 89p.
37. Souza GC, Souza ZM, Cooper M, Tormena CA (2015) Controlled traffic and soil physical quality of an Oxisol under sugarcane cultivation. Sci Agric 72(3):270–277. https://doi.org/10.1590/0103-9016-2014-0078. Científica, 34(1):31-38.
38. Segato, SV, Pinto, AS, Jendiroba, E, Nobrega, JCM (2006) Atualização em produção de cana-de-açúcar. Piracicaba: CP 2, 415p
39. Magalhães, PSG, Braunbeck, AO (2010) Colheita de cana-de-açúcar e palha. Cortez, LAB (Org.). Bioetanol de Cana-de-Açúcar, P&D para Produtividade e Sustentabilidade, Blucher São Paulo
40. Gray GR, Magalhães PSG, Braunbeck AO (2009) Pantographic suspension for sugar cane base cuter. Rev. Ci. Rural 39(3):766–771
41. Braida JA, Reichert JM, Veiga M, Reinert DJ (2006) Resíduos vegetais na superfície e carbono orgânico do solo e suas relações com a densidade máxima obtida no ensaio Proctor. Rev. Bras. Ci. Solo 30(4):605–614. https://doi.org/10.1590/S0100-06832006000400001
42. Otto R, Trivelin PCO, Franco HCJ, Faroni CE, Vitti AC (2009) Root system distribution of sugarcane as related to nitrogen fertilization, evaluated by two methods: monolith and probes. R. Bras. Ci. Solo 33(3):601–611. https://doi.org/10.1590/S0100-06832009000300013
43. Otto R, Franco HCJ, Faroni CE, Vitti AC, Trivelin PCO (2009) Sugarcane root and shoot phytomass related to nitrogen fertilization at planting. Pesq. Agropec. Bras. 44(4):398–405. https://doi.org/10.1590/S0100-204X2009000400010
44. Hurney AP, Schroeder B (2012) Does prolonged green cane trash retention influence nitrogen requirements of the sugarcane crop in the wet tropics. Proc. Aust. Soc. Sugar Cane Tech 34:1–9
45. Vitti AC, Franco HCJ, Trivelin PCO, Ferreira DA, Otto R, Fortes C, Faroni CE (2011) Nitrogen derived from fertilization and straw for plant cane nutrition. Pesq. Agropec Bras 46(3):287–293
46. Fortes C, Trivelin PCO, Vitti AC (2012) Long term decomposition of sugarcane harvest residues in Sao Paulo state, Brazil. Biomass Bioenergy 42:189–198. https://doi.org/10.1016/j.biombioe.2012.03.011
47. Oliveira APP, Thorburn PJ, Biggs JS, Lima E, Anjos LHC, Pereira MG, Zanotti NE (2016) The response of sugarcane to trash retention and nitrogen in Brazilian coastal tableland: a simulation study. Exper Agricult 52(1):69–86. https://doi.org/10.1017/S0014479714000568
48. Aquino GSD, Medina CDC, Porteira Junior AL et al (2015) Root system and productivity of sugarcane ratoon associated to different quantities of straw. Pesq. Agropec. Brassica 50(12):1150–1159. https://doi.org/10.1590/S0100-204X2015001200004
49. Castro SGQ, Franco HJC, Mutton MA (2014) Harvest managements and cultural practices in sugarcane. Rev Bras Ci Solo 38:299–306. https://doi.org/10.1590/S0100-06832014000100030
50. Oliveira APP, Lima E, Anjos LC, Zonta E, Pereira MG (2014) Sugarcane harvesting systems: current knowledge about modifications of attributes in tableland soils. Rev B Eng Agríc e Amb 18(9):939–947. https://doi.org/10.1590/1807-1929/agriambi.v18n09p939-947
51. Taiz L, Zeiger E (2009) Fisiologia vegetal, 4th edn. Artmed, Porto Alegre 819p
52. Thorburn PJ, Biggs JS, Webster AJ, Biggs IM (2011) An improved way to determine nitrogen fertiliser requeriments of sugarcane crops to meet global environmental challenges. Plant Soil 339:51–77. https://doi.org/10.1007/s11104-010-0406-2
53. Franco HCJ, Otto R, Vitti AC, Faroni CE, Oliveira ECA, Fortes C, Ferreira DA, Kolln OT, Garside AL, Trivelin PCO (2015) Residual recovery and yield performance of nitrogen fertilizer applied at sugarcane planting. Sci Agric 72(6):528–534. https://doi.org/10.1590/0103-9016-2015-0170
54. Rhein AFL, Pincelli RP, Arantes MP, Dellabiglia WJ, Kolln OT, Silva MA (2016) Technological quality and yield of sugarcane grown under nitrogen doses via subsurface drip fertigation. Rev Bras Eng Agríc Amb 20(3):209–214. https://doi.org/10.1590/1807-1929/agriambi.v20n3p209-214
55. Korndorfer GH, Valle MR, Martins M, Trivelin PCO (1997) Aproveitamento do nitrogênio da uréia pela cana-planta. Rev. Bras. Ci. Solo 21(1):23–26
56. Castro SGQ, Decaro Junior ST, Franco HCJ, Magalhães PSG, Mutton MA (2016) Best practices of nitrogen fertilization management for sugarcane under green cane trash blanket in Brazil. Sugar Tech 19(1):51–56. https://doi.org/10.1007/s12355-016-0443-0