Research Findings

Single sugarcane stalk from Ivinhema, Mato Grosso do Sul, Brazil. Photo by the authors.

Management Practices of Potassium Fertilization to Improve Sugarcane Yields in Central-South Brazil

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Abstract

Sugarcane (*Saccharum* spp.) demands high amounts of potassium (K) for profitable yields, but high K application rates could challenge agronomic K efficiency due to leaching and salinity damage to young roots. This study hypothesized that a split dose rather than just a basal K application could represent a better strategy, especially in soils with low cation exchange capacity (CEC). The objective was to evaluate sugarcane performance as a function of ascending K application rates, and the crop's response to split K application on soils varying in CEC and texture in Central-South Brazil.

Field trials were set up in three locations during 2016 to 2018: Chavantes, São Paulo (site 1, clay texture); Valetim Gentil, São Paulo (site 2, sandy-loam texture); and Ivinhema, Mato Grosso do Sul (site 3, sandy-loam texture). At each site, crop response was tested with potassium oxide (K_2O) rates ranging from 0-240 kg K_2O ha^{-1}. Additional treatments compared seven combinations of an intermediate K dose (120 kg K_2O ha^{-1}) split into basal (B) and

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a later top-dressing (TD) application 60-90 days after planting (0/120; 20/100; 40/80; 60/60; 80/40; 100/20; and 120/0, B/TD kg K_2O ha^{-1}, respectively). Tiller density, stalk yield and recoverable theoretical sugar content (RTSC) were determined in the plant-cane and first ratoon cycles. Sugarcane stalk yields ranged from 93-125 Mg ha^{-1}, and from 80-130 Mg ha^{-1}, across all sites for plant-cane and ratoon cycles, respectively.

Significant differences in sugarcane yields occurred between the three sites, and between crop cycles. Generally, crop response to K application dose was very weak, and significant only on the clay soil of site 1, indicating a more significant reliance on soil K reserves rather than on current K application. Split K dose affected sugarcane performance only at site 3 on sandy-loam soil, where yields significantly peaked under a B/TD combination of 40/80 kg K_2O ha^{-1} and tended to decline towards the two extreme combinations (0/120, and 120/0). However, no response to splitting could be observed at the two other sites.

The results of the present study highlight the need for precise determination of soil fertility in terms of texture, composition of the clay minerals, CEC, and total and available soil K status. Consequently, the design of K application management should be founded on crop requirements for target yields, and on the current need to maintain or replenish soil K status. Split K application appears a reasonable strategy on sandy soils; however, further research is required to determine the appropriate intensity of splitting during the crop cycle, taking into consideration the economic implications.

Keywords: Clay; leaching; *Saccharum* spp.; sandy-loam; split K application.

Introduction

Brazil is the world's largest sugarcane producer with an annual production of 633 million tonnes. In 2018, the total harvested area was 8.73 million hectares with a mean yield of 72.5 Mg ha^{-1} (CONAB, 2018). Recent expansion of sugarcane production in Brazil has led to a shift towards cultivation on sandy soils with low cation exchange capacity (CEC). Sugarcane potassium (K) requirements are very high and most of the K consumed in Brazil is imported. The consumption of nitrogen (N), phosphorus (P)

Fig. 1. Symptoms of K deficiency in a sugarcane field managed with low K rates on a high caption exchange capacity (CEC) soil from Belize, Central America. Photos by the authors.

and K fertilizers in Brazil totaled 15 million tonnes, with K fertilizers solely accounting for 5.7 million tonnes (IPNI, 2017).

Sugarcane crop demands for K are huge compared to other crop species such as maize (Kingston, 2014). Potassium plays a key role in osmoregulation, which is important for cell extension, stomata movement and enzyme activation (Epstein, 1972; Shukla *et al.*, 2009; Kingston, 2014). The K is particularly required for carbohydrate metabolism and translocation (Zörb *et al.*, 2014). Leite *et al.* (2016) recently estimated that 2.7 kg K is required to produce 1 Mg of stalk. Thus, about 325 kg ha^{-1} of K_2O can be required to produce 100 Mg ha^{-1} by highly demanding sugarcane varieties (FAOSTAT, 2017). This level of K requirement is in agreement with previous studies (Franco *et al.*, 2008; Kingston, 2014; de Oliveira *et al.*, 2016; da Silva *et al.*, 2018). In addition, K requirements change dramatically according to the crop development stage, peaking significantly during the period of sugar accumulation in the stalk (Kingston, 2014; Leite *et al.*, 2016).

The efficiency of K fertilization depends on K availability in the soil solution, on the soil capacity to retain K, and on the presence of K-containing crop residues (Ernani *et al.*, 2007). Total K uptake by sugarcane stalks ranges from 2.0 to 3.0 kg K_2O Mg^{-1}, while K accumulation in the stalks averages at 1.85 kg K_2O Mg^{-1} (Oliveira, 2011). Symptoms of K deficiency include chlorosis, which occurs first at the end of the young expanded leaves and gradually moves to the internal parts of the leaves. Symptoms of K deficiency are usually related to imbalances, such as inadequate K application on soils with low K level. In this situation, K deficiency can be observed on high CEC soils with a history of imbalanced K application (Fig. 1), as well as in sandy, low CEC soils, that have not received K application at planting (Fig. 2).

Sugarcane response to K application rates is usually positive, however, it varies depending on the amount of exchangeable K in the soil. Rosseto *et al.* (2004) verified a linear sugarcane response to K fertilization in seven of ten experiments. Reis Junior (2001), who observed a positive sugarcane yield response to K fertilization in 73 of 106 studies carried out on varying soil types with different K levels, suggested that interactions between K, calcium (Ca) and magnesium (Mg) might interfere with sugarcane response to K fertilization and should therefore be considered in K fertilization recommendations.

Due to operational and cost issues, sugarcane growers usually perform just a single application of K fertilizers during sugarcane crop establishment. In soils with low CEC, such as sandy soils, this application method presents a high potential for rapid K loss through leaching. In addition, there is a considerable risk of high-salinity damage to seedlings due to heavy K application at planting (Ernani *et al.*, 2007). For this reason, at sugarcane establishment, where high K rates are usually applied, it is recommended to split K dose into two applications; basal (B) at planting, and a later one as a top-dress (TD) (Alvarez and Freire, 1962; Spironello *et al.*, 1997). This practice has become more common in Central-South Brazil, where the TD fertilization usually accompanies a soil leveling operation performed to improve the operation of mechanical harvesting (Fig. 3).

Several previous studies have demonstrated significant yield gains of 10-15 Mg ha^{-1} when K fertilization is split, compared to a single application at planting (Casagrande *et al.*, 1983; Lana *et al.*, 2004). Nevertheless, less encouraging results have shown no significant yield gain from split K application, although maximum yields were obtained with lower K_2O rates when compared to a single application (Otto *et al.*, 2010).

Fig. 2. Symptoms of severe K deficiency in a sugarcane field managed with no K application at planting on a sandy soil in Lins, São Paulo, Brazil. Photos by the authors.

Fig. 3. Conventional practices for K fertilization in Brazilian sugarcane fields. Left: K application at planting at the bottom of the furrow. *Source:* Authors, 2019. Right: TD K application during soil leveling. *Source:* Canaonline, 2019.

Yield gains obtained from split application could be the result of lower leaching losses, reduction of root injury caused by salinity, or a better synchrony between the timing of K application and crop requirements. Despite this argument in support of split K application, most sugarcane growers in Brazil still perform a single K application at planting. However, the present trend of increasing K rates in order to compensate for the substantial K removal from soils – during sugarcane cropping – can intensify the negative economic and environmental consequences of heavy K fertilization.

The present study hypothesized that split K application is a better strategy than a single application at planting, especially in sandy soils with low CEC. The objective was to evaluate sugarcane yield and recoverable theoretical sugar content (RTSC) as related to K rates and split K application, in soils varying in CEC and texture, under Brazilian field conditions.

Material and methods

Experimental design

Three field trials were set up under field conditions during the 2016 to 2018 crop season: site 1 in Chavantes, São Paulo (23º3'54.56 ''S; 49º45'9.49''W); site 2 in Valetim Gentil, São Paulo (20°27'46,79"S; 50°06'15,60"W); and site 3 in Ivinhema, Mato Grosso do Sul (22°17'09.19''S; 53°40'30.50"W), Brazil (Fig. 4). These areas present a climate classification Cfa (site 1) and Aw (sites 2 and 3), according to the Köppen classification. The average temperature during the period of study was 21.2, 22.5 and 23.0 ºC with an average rainfall of 1,339, 1,194 and 1,534 mm in sites 1, 2, and 3, respectively.

Prior to establishment of the experiments, soil samples were randomly collected from six locations at each site at depths ranging from 0-100 cm, at 25 cm intervals. Soil samples were homogenized and submitted for chemical and physical analyses according to van Raij *et al.* (2001) and Camargo *et al.* (2009) (Table 1). Soil texture was classified as clay (site 1) and sandy clay loam (sites 2 and 3), with soil K levels ranging from 1.3-2.0 $mmol_c\ dm^{-3}$

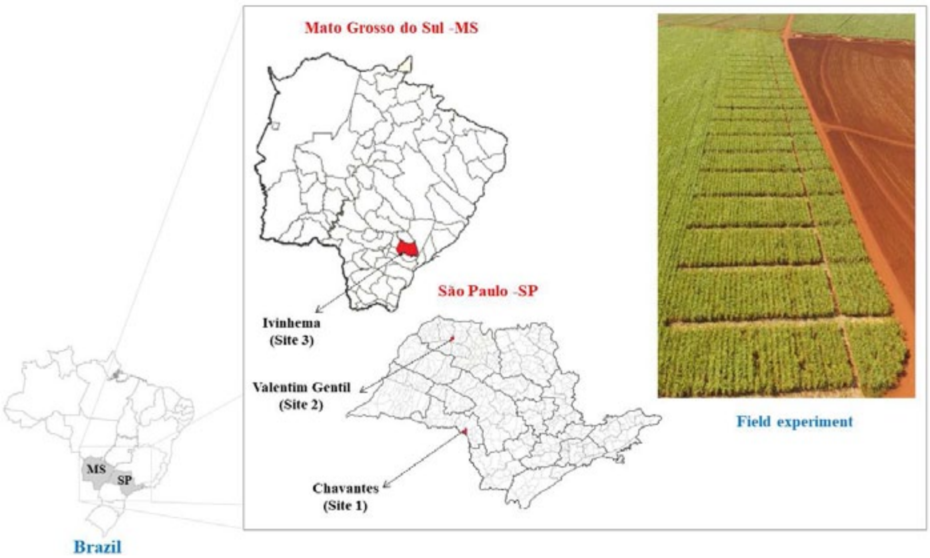

Fig. 4. Location of the field trials in Chavantes, São Paulo (Site 1), Valetim Gentil, São Paulo (Site 2) and Ivinhema, Mato Grosso do Sul (Site 3), in Brazil.

Table 1. Soil chemical and physical analysis of the experiment areas in Brazil[1].

Soil depth	pH ($CaCl_2$)	OM	P	S	K	Ca	Mg	Al	H+Al	CEC	SB	V	m	Sand	Silt	Clay
cm		*g dm^{-3}*	----*mg dm^{-3}*-----		-------------------*mmol$_c$ dm^{-3}*-------------------					*cmol$_c$ kg^{-1}*	----------%-----------			------------*g kg^{-1}*-----------		
								Site 1								
0-25	5.0	23.0	8.0	9.0	2.0	34	8.0	0.0	38	82.0	44.0	54	2	118	173	709
25-50	4.7	26.0	6.0	14.0	1.5	26	9.0	2.0	42	78.5	36.5	46	5	113	172	715
								Site 2								
0-25	4.6	13.0	8.0	3.0	1.8	10	3.0	1.0	28	42.8	14.8	35	5	750	50	200
25-50	4.5	12.0	6.0	5.0	0.9	6	2.0	1.0	33	38.7	9.5	25	7	726	45	229
								Site 3								
0-25	4.8	14.0	5.0	7.0	1.3	10	7.0	1.0	34	52.3	18.3	35	0	724	23	253
25-50	4.5	12.0	0.3	5.0	0.6	5	4.0	2.0	42	51.6	9.6	19	17	676	21	303

[1]pH in $CaCl_2$ (0.01 mol L^{-1}); OM, soil organic matter by Walkley-Black; P, K, Ca, Mg by the exchangeable resin method; sulfur (S) by calcium phosphate extraction; CEC, cation exchange capacity; SB, sum of bases; V, base saturation; m, aluminum saturation.

at the upper soil level (0-25 cm). Soil K contents were classified as low to medium (0.7-3.0 $mmol_c$ dm^{-3}), according to van Raij *et al.* (1997).

The experiments were laid out in a randomized block design with five K rates (0, 60, 120, 180 and 240 kg K_2O ha^{-1}) applied through potassium chloride (KCl) directly into the furrow at planting (B) in four replications. Other treatments were carried out to evaluate six different combinations of B and TD K applied at a constant rate of 120 kg K_2O ha^{-1}: 0+120; 20+100; 40+80; 60+60; 80+40; and 100+20 kg K_2O ha^{-1}, respectively. TD was performed between 60 and 90 days after planting, following usual practices adopted by sugarcane growers. There was a total of 11 treatments comprising 44 experiment units; each experiment unit consisted of six sugarcane furrows, spaced 1.5 m apart and 15 m long.

Sugarcane (CTC4 variety) was planted using conventional soil tillage operations (disking or chiseling) in 2016. Lime was applied and incorporated (0.25 m deep) to increase the base saturation to 70% in all sites. After lime incorporation, furrows were opened, and applied with 150 kg phosphorus pentoxide (P_2O_5) ha^{-1} as mono-ammonium phosphate (11% N and 52% P_2O_5). Sugarcane was cultivated following usual agronomic practices of the sugarcane mills, including weed and disease control methods. In all sites, N and K were applied after the first harvest at a ratio of 1:1 kg Mg^{-1} biomass produced, and the residual effects were evaluated after the first ratoon.

Measurements and analysis

Evaluation of tiller density was performed 120 days after planting (DAP), by counting the number of tillers in the four central lines of each plot. Sugarcane yield (Mg ha^{-1} of stalk) was determined by mechanical harvesting of the four central rows of each plot, and after weighing the stalks in a truck equipped with a scale. Ten plants were collected per plot and the RTSC was analyzed according to Fernandes (2011).

Data were submitted for analysis of variance based on the F-test ($p<0.05$). When the F test showed significance, the effect of K rates was compared by regression analysis ($p<0.1$), while the effect of split application was compared using the LSD test ($p<0.1$).

Results and discussion

Effect of K rates

Significant differences in sugarcane performance occurred between the three experiment sites (Table 2). Tiller density and stalk yield of the plant cane cycle differed significantly in the order of site 1 (Chavantes) > site 2 (Valentim) > site 3 (Ivinhema). However, this order changed dramatically at the first ratoon harvest, where Ivinhema became the leading site. There was a significant positive relationship between tiller density and stalk yield ($p<0.005$), demonstrating that tiller density is a major factor in determining sugarcane yield. Nevertheless, these two parameters failed to predict the RTSC and the consequent sugar yield. Sugarcane ripening and sugar production are very sensitive to weather conditions and were possibly promoted by the drier conditions at Valentim compared to the other two sites. Potassium rates did not affect tiller density and RTSC at all sites and seasons, and a mean value of 15.8 tillers m^{-1} and 150.9 kg

Table 2. Sugarcane performance at the three experiment sites (site 1: Chavantes; site 2: Valetim Gentil; and site 3: Ivinhema) during the plant cane and first ratoon production cycles. Values show the average yield parameters for all K doses. Similar letters indicate no significant differences ($p<0.01$) between sites within a cycle.

	Plant cane			Ratoon		
	Site 1	Site 2	Site 3	Site 1	Site 2	Site 3
Tiller density (tillers m^{-1})	16.0a	14.1b	11.7c	15.8c	18.1b	19.6a
Stalk yield (Mg ha^{-1})	118.4a	104.5b	101.1c	107.5b	85.3c	120.5a
RTSC (kg sugar Mg^{-1} stalks)	131.7c	163.1a	143.9b	164.6	-	162.4
Sugar yield (Mg ha^{-1})	15.6	17.05	14.55	17.71	-	19.57

Mg^{-1} was achieved, respectively. The lack of tiller density response to K rate may indicate that the high-salinity effect anticipated from B KCl applications was not severe enough to reduce tiller density and sugarcane yield, at least in the sites evaluated herein. Alleoni and Beaclair (1995) also found no relationship between K rates and tillering in their study. In contrast, Otto *et al.* (2010) reported that tiller density was reduced where B applied K rates exceeded 130 kg K_2O ha^{-1}.

Rising K application doses from 0 to 240 kg K_2O ha^{-1} resulted in significant increases in stalk yield on the clay soil of Chavantes (site 1), which was accompanied by a significant rise in sugar yields (calculated). On the two other sites, stalk and sugar yields fluctuated randomly with no observable influence of K rates (Fig. 5). Nevertheless, even where a significant yield increase was identified, the contribution of K fertilizer was very low – less than 50 kg stalks, and 6-10 kg sugar per one kg K_2O applied. It is worth noting that the yield values obtained can be considered within the top range of worldwide sugarcane yields (FAOSTAT, 2017). It appears, therefore, that at all three sites, sugarcane performance was a function of the soil fertility during each cycle rather than the current K application dose. A consequent question would therefore regard the fate of the applied K.

All chemical interactions between plant and soil occur in the liquid soil phase, which maintains durable ion exchange with the soil particle surface. The greater the particle's specific surface area (SSA) the larger capacity it harbors for ion exchange. Therefore, soil texture, namely the ratio between clay, silt and sand, is a key determinant of soil fertility. Sand particles are considered inert due to their extremely low SSA, and hence, poor CEC. In contrast, clay minerals comprise the tiniest soil particles that consequently possess immense SSA with correspondingly high CEC. Therefore, clay minerals, and to a much lesser extent silt, are considered the most chemically active soil fractions.

When a soluble K fertilizer is applied and the soil wetted, the liquid soil phase is enriched with K^+ ions. The greater the sand soil fraction, the higher the risk of K leaching and loss, which was probably the case at Valetim Gentil and Ivinhema

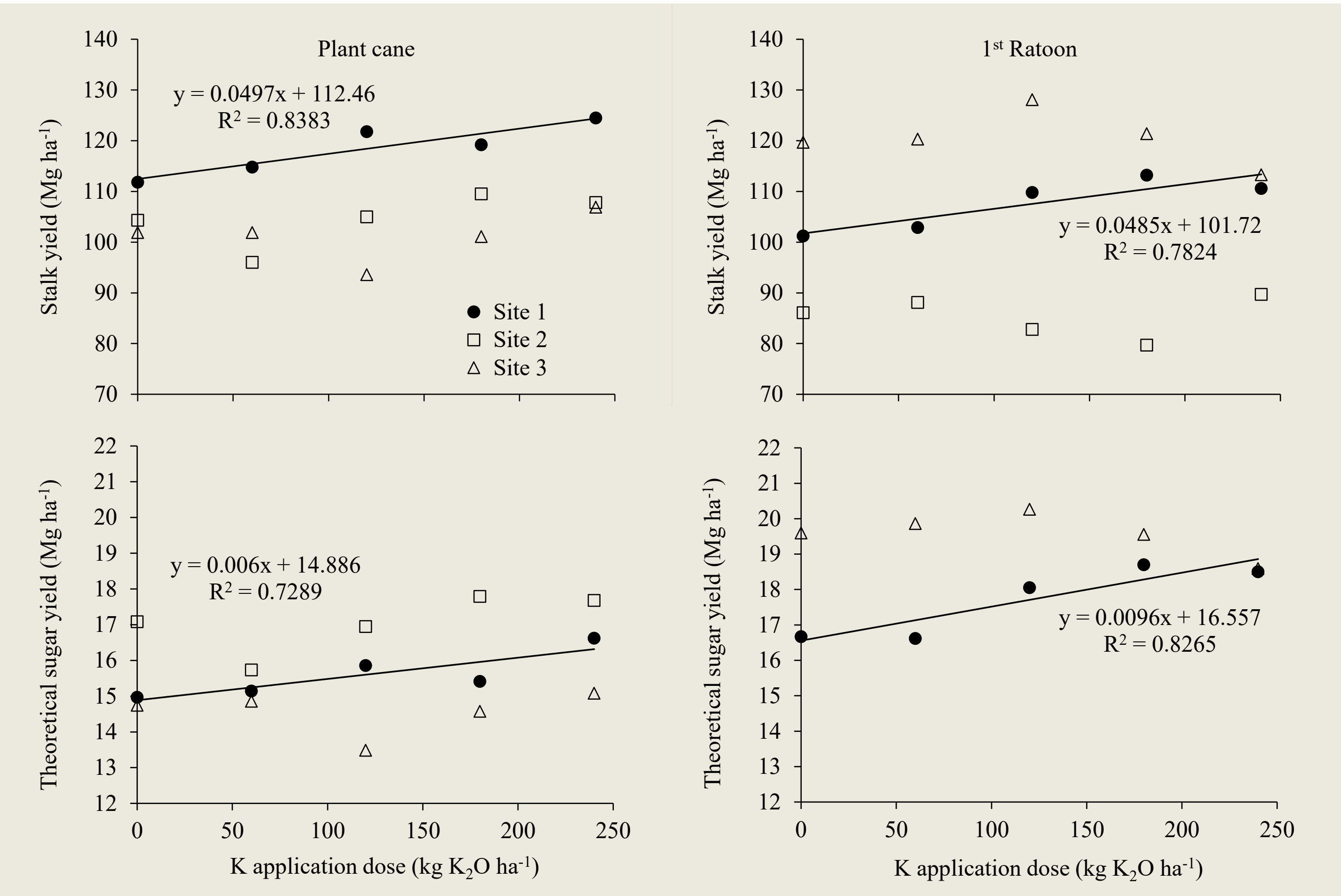

Fig. 5. Effects of K application dose on the stalk (upper figures) and on the theoretical sugar (lower figures) yields in two successive seasons (plant cane and first ratoon of sugarcane crops at three experiment sites in Brazil (site 1: Chavantes; site 2: Valetim Gentil; and site 3: Ivinhema). Significant correlation curves could be obtained for site 1 only.

experiment sites. However, the clay and silt fractions at these sites still seemed to bear considerable capacity to support an acceptable sugarcane performance, including the significant residual effect demonstrated at the first ratoon.

In addition to the vast on-surface chemical activity, clay particles retain significant long-term ion exchange capacity between external and internal mineral layers. This aspect of soil fertility largely depends on the mineral composition, spatial structure, and the history of the clay fraction of a given soil and its location (Zörb *et al.*, 2014). Generally, where a positive K balance has been maintained in the long-term, it may be assumed that the clay fraction is K-saturated, harboring significant K-residual potency. However, similar soil types that have experienced long periods of a negative K balance often display a considerable tendency to adhere K^+ ions in internal mineral layers, and hence reduce K availability to plant roots. This was more likely the situation at Chavantes (site 1), which may explain the unsatisfactory sugarcane response to the rising K application dose (Fig. 5).

Split K application

Splitting the K application dose may offer solutions for K losses through leaching on sandy soils or fixation on K-poor clay soils. Nevertheless, the splitting treatments, as carried out in the present study, failed to enhance sugarcane performance. The average yield parameters obtained from the splitting treatment (Table 3) did not differ from those of the B applied K experiment (Table 2), with similar significant differences between the three locations. Ivinhema (site 3) was the sole location at which a significant and consistent effect was observed as a result of the split combinations on sugarcane performance (Fig. 6).

At the Ivinhema site, the extreme treatment of applying the complete seasonal K dose through the B or TD application, gave rise to the lowest stalk yields. In contrast, the combination of 40 and 80 kg K_2O ha^{-1} as the B and TD application, respectively, resulted in the highest stalk yield (Fig. 6). Furthermore, there was a clear yield increase with the rise of the TD rate from 0-80 kg K_2O ha^{-1}; yet, the stalk yields started to decline once the B rate dropped below 40 kg K_2O ha^{-1} (Fig. 6). These results weakly support the split K application principle, however, the maximum yield increase did not exceed 10-15% – much less than expected and needed economically – and more importantly, the results were insufficiently consistent. Previous studies have shown that splitting the K dose into two applications on sandy soils could raise sugarcane stalk yields by 10-15 Mg ha^{-1} (Casagrande *et al.*, 1983; Lana *et al.*, 2004), but will fail to contribute on clay soils (Casagrande *et al.*, 1983).

Overall, based on the results shown here, it would be too difficult to recommend any specific K dose or practice to conclusively enhance sugarcane yields. A more careful analysis of the present study's circumstances may suggest directions for further evaluation of the split dose approach.

On sandy soils under humid tropical conditions, plant roots have an extremely narrow window of time to take up soil K – from the time of application to the impending rains – before it is leached away from the rhizosphere. Leaching could occur for any application of soluble fertilizer, the rate of which exceeds the uptake capacity during a given opportunity. Therefore, splitting the seasonal K dose into two applications is

Table 3. Sugarcane performance under split K application at the three experiment sites (site 1: Chavantes; site 2: Valetim Gentil; and site 3: Ivinhema) during the plant cane cycle. The average yield parameter values are provided for all split combinations within each site. Similar letters indicate no significant differences (p<0.01) between sites.

	Plant cane			
	Site 1	Site 2	Site 3	Mean
Tiller density (tillers m^{-1})	16.4a	14.2b	11.9c	13.4
Stalk yield (Mg ha^{-1})	120.1a	100.7b	100.2c	100.7
RTSC (kg sugar Mg^{-1} stalks)	131.0c	165.4a	144.1b	146.9
Sugar yield (Mg ha^{-1})	15.73	16.66	14.44	15.72

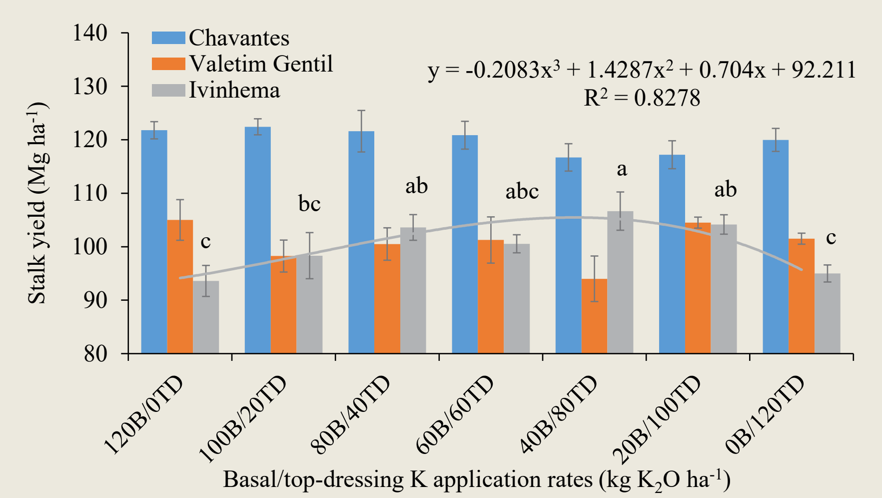

Fig. 6. Effect of seven combinations of split K application (totaling 120 kg K_2O ha^{-1} per treatment) at B and a single TD application, 60-90 days after planting on sugarcane stalk yields at three experiment sites in Brazil (site 1: Chavantes; site 2: Valetim Gentil; and site 3: Ivinhema). Bars indicate ± standard error. Similar letters indicate no significant differences (p<0.05) between combinations within Ivinhema site.

probably just a very small step forward, as indicated by the results of the present study. On the other hand, splitting the seasonal dose into many applications might significantly expand the number of opportunities for nutrient uptake during a crop cycle, boost K use efficiency, and lead to enhanced sugarcane performance. This approach is technically feasible in various ways, from hand application to fertigation, and the economic balance of each should be carefully considered.

An alternative approach may be the introduction of polyhalite, which beyond a relatively slower K release, is comprised of nutrients other than just K (Mg, Ca, and S), with the potential to deliver substantial benefits to poor acidic soils in Central-South Brazil (Vale and Sério, 2017; Bernardi *et al.*, 2018). Any alternative solution selected must include serious attempts to reduce soil acidity, as the soil pH values at the experiment sites were too low (Table 1). Low pH significantly confines K^+ access to soil particle surface, thus reducing short- and long-term interactions between the nutrient and the soil, and subsequently leading to declined soil fertility.

Conclusions

Generally, sugarcane performance and yields at all three experiment sites of the present study were reasonably high (100-120 Mg stalks ha^{-1}), above the recent yearly average in Brazil (75 Mg stalks ha^{-1}), and within the top range of worldwide yields. However, crop performance hardly responded to the K application dose, suggesting a reliance on residual soil resources rather than on current K supply. Moreover, crop response to split K dose into two applications (basal and a later top-dressing) was statistically significant only in one of the three locations.

On clay soils, careful pre-planting attention must be paid to the composition of the clay minerals and to the determination of both total and available K. Determining these parameters is necessary to calculate current soil K resources – both residual and exchangeable. Consequently, the seasonal K dose should be defined according to crop requirements upon a predetermined target yield, plus the K amount required to maintain or recuperate soil K reserves. Nutrient leaching is less critical on clay soils, and hence split application would be useful only where salinity problems might occur.

Sandy loam soils are more complex; the very low CEC, in addition to the rapid drainage imposed by the dominant sand fraction significantly curtail the opportunity of roots to take up nutrients. Still, the smaller clay fraction may harbor considerable nutrient stores. On sandy loam soils, splitting the K dose has great potential not only in expanding nutrient uptake opportunities during the crop cycle, but also in replenishing soil K reserves in the long-term. Nevertheless, further investigation is required to verify the intensity of splitting for maximum impact.

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