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Vinasse for sugarcane crop nutrition: accumulation and efficiency in the use of nutrients

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Abstract

The use of agro-industrial by-products such as biofertilizers hinders polluting discharges and allows savings commercial fertilizers. The application of vinasse (a by-product of ethanol manufacture) in sugarcane (*Saccharum officinarum*) production was evaluated in two soils of Uruguay (L1 and LB2). In a first ratoon crop, 150 and 300 m^3 ha^{-1} of vinasse were applied (V150 and V300) and compared with the application of fertilizer (F) and a Control (C) with no application. Then, production and the plant's N, P, K, Ca and Mg contents were determined. Vinasse and fertilizer applications increased sugarcane growth, as compared to C. However, there were no differences between vinasse dosses. The L1 fertilization treatment produced higher stem yield than vinasse application, whereas LB2 caused no differences. The application of vinasse at LB2 and L1 increased K uptake, exceeding the control, by 151 and 133 kg ha^{-1} of K, respectively, indicating that it could substitute fertilizer, while supplemental nitrogen fertilization would be required for maximum yield. The low use-efficiency of potassium (K) in vinasse treatments suggests that there was excessive consumption. Although vinasse increased soil exchangeable K, its residual effect would be insufficient for the second ratoon harvest, requiring annual applications.

Keywords: Saccharum, byproduct of ethanol production, biofertilizer, potassium, Uruguay.
Abbreviations: BS_ Base saturation at pH 7; C_ Control treatment; Ca_ calcium; CEC pH7_ cation exchange capacity measured at pH 7; DM_ dry matter; F_ Fertilizer treatment; K_ potassium; Mg_ magnesium; N_ nitrogen; Na_ sodium; P_ phosphorus; pH (H_2O)_ hydrogen potential of soil measured in water; SOC_ soil organic carbon; V150_ Vinasse dose of 150 m^3 ha^{-1} treatment; V300_ Vinasse dose of 300 m^3 ha^{-1} treatment

Introduction

Generation of energy is one of the most important challenges worldwide. In this context, the production of ethanol from sugarcane (*Saccharum officinarum*) has increased in South America, mainly because of Brazil high production (Walter et al., 2014), but also other countries in this region are increasingly adopting and adapting this technology to their environmental conditions. In Uruguay, ethanol is produced from sugarcane in the north of the country, where the temperature conditions are more suitable for this crop.

Sugarcane allows several harvests, each followed by a re-growth. Hence, it is considered a semi-perennial crop. This crop has a great capacity to absorb nutrients due to its extensive root system, which can remain active even after being cut (Smith et al., 2005). In Uruguay the crop is harvested from late autumn (May/June) to early spring (October), reaching mean yields of 55 Mg ha^{-1} of stem, that can be destined for sugar or ethanol production. The crop is fertilized at sowing and after each harvest, adding N, P and K during the dynamic growth stage in the spring when extraction is more efficient (Butler et al., 2002; Gopalasundaram et al., 2012). The doses of fertilizers applied are generally high compared to other extensive crops in the country, based on the sugarcane's extraction of those nutrients.

Given its great growth potential, sugarcane has high nutrient requirements, especially N and K (Coale et al., 1993; Freitas et al., 2018). Since most of the plant is harvested, a high proportion of the nutrients are extracted from the site along with the product (Oliveira et al., 2010; Leite et al., 2016) and they must be replenished to ensure the sustainability of the system. In Florida (USA), Coale et al. (1993) observed that in sugarcane crops 55%, 63%, 64%, 25% and 38% of the total accumulated N, P, K, Ca, and Mg, respectively, are removed from the soil with the product, thus indicating that nutrient extraction should be considered in crop fertilization programs. However, a significant volume of residue (leaves and cuttings) remains on the field after harvest, contributing nutrients for the regrowth and reducing the risks of erosion (Carvalho et al., 2017).

The production of ethanol generates vinasse as a liquid waste, with the ALUR-Bella Unión plant producing approximately 7 L of vinasse per L of ethanol. On the other hand, Uruguay promotes the use of agro-industrial waste and byproducts, including the use of vinasse as biofertilizers. In addition to minimizing negative environmental effects compared to other forms of waste disposal, it enables to reduce the application of fertilizers, making it an attractive prospect (Smeets et al., 2008). However, difficulties usually arise in the management of this byproduct, mainly due to its heterogeneous composition and relatively low concentration of nutrients. Therefore, it is necessary to know the behavior of vinasse in the soil to improve the dosage to make efficient use and to identify potential disproportions in nutrient supply.

Brazil is one of the largest producers of ethanol in the world. Vinasse has been widely used to substitute or complement fertilization in sugarcane crops (Smeets et al., 2008; Walter et al., 2014). Since the most abundant nutrient in vinasse is K, the dosage is often based on this nutrient (de Oliveira et al., 2017). The application of vinasse not only contributes nutrients to the crop (Paulino et al., 2002; Gallego Blanco et al., 2012; Soobadar and Ng Kee Kwong, 2012; de Mello Prado et al., 2013), but also improves soil properties in the long term (Canellas et al., 2003; Su et al., 2012; de Mello et al., 2016). The potential of soil degradation is usually represented by the continuous cropping (Torres et al., 2016). Although vinasse organic matter content is low, it could contribute to prevent further decline in this parameter (Canellas et al., 2003). In addition, the use of vinasse provides secondary and micronutrients (da Silva et al., 2014), which are not generally considered in fertilization programs. In a laboratory experiment, del Pino et al. (2017) characterized the vinasse produced by ALUR (Uruguay), determining a significant potential contribution of N, P and cations (Ca, Mg and K) observing that most of these nutrients were present in rapidly available forms for the plants. However, the effects of vinasse on nutrient availability, as well as on soil properties, depend largely on the characteristics of the soils involved and the production technology (Cherubin et al., 2015), which reaffirms the importance of evaluating its application in specific field studies.

Since vinasse is liquid, which makes it difficult to transport, its application in sugarcane crops near industrial facilities is recommended (Christofoletti et al., 2013). In Uruguay, although the crop is irrigated during the summer, priority is given to the application of pure vinasse by spraying after harvest (winter and spring), when the crop is not irrigated. This management avoids the long-term storing of vinasse, increasing nutrient availability prior to reaching the highest growth rate (Coale et al., 1993). Consequently, it is necessary to have information on the pattern of nutrient accumulation throughout the annual cycle and to evaluate its effectiveness for sugarcane nutrition.

The objectives of this work were: i) to characterize the effect of vinasse application on sugarcane production and nutrient uptake by the crop in northern Uruguayan soils; ii) to evaluate the residual effect of vinasse application, particularly in terms of available soil K for the next production cycle.

Results

Sugarcane aerial biomass production

Comparing the aerial biomass production of sugarcane 6 months after the regrowth and at harvest, we observed that most of the growth occurred in the second stage (Fig. 1). During the first 6 months of growth, biomass production at LB2 reached a mean of 4.5 Mg ha^{-1} of dry matter (DM), whereas it was lower at L1 (3.9 Mg ha^{-1} of DM). While there were no differences between the treatments in early growth in LB2, the application of vinasse in L1 produced a negative effect, with significantly lower yields than C and F treatments.

At harvest, the mean total accumulated biomass was 27.8 and 29.2 Mg ha^{-1} of dry matter (DM) for the LB2 and L1 sites, respectively. According to the contrast analysis for LB2, the production of C was significantly lower than the other treatments, which did not differ from each other. At L1, the total biomass production of the vinasse treatments was significantly higher than C, but lower than the F treatment, with no differences between the two vinasse doses.

Analysis of the commercial yield as the production of stems expressed that LB2 production was higher in the vinasse and F treatments than in C treatment, but differences were not statistically significant (Table 3). At L1, the application of the V300 dose produced a significant increase in yield compared to C, while the yield in F was significantly higher than in vinasse treatments. The effect of the vinasse dose was not significant at any of the sites. No differences in the leaf to stem ratio were observed between treatments. The proportion of stems in the total harvested biomass (DM) was 69% at LB2, and 63% at L1.

Accumulation of nutrients in the aerial biomass and nutrient use efficiency

The foliage generally showed higher concentrations of nutrients two months after the application of the treatments than at harvest, especially regarding K, N and P (Table 2). In early sampling, fertilization had a positive effect on the concentration of N at both sites, and on the concentration of P at L1. None of the sites evidenced any effect of the treatments on the concentration of Ca, but the application of vinasse produced an increase in the concentration of K and a negative effect on the concentration of Mg. At harvest, vinasse treatments showed higher K concentrations in stems and leaves than C and F treatments. In the leaves, the same negative effect of vinasse on Mg concentration observed in the 6 months old foliage at harvest. There were no statistical differences between vinasse doses for any of the parameters examined.

In both sites, most of the nutrients in the aerial biomass were accumulated in the stems at harvest. The amount of total K evidenced a clear influence of its addition, either with vinasse or fertilization, especially in the stems. The amount of accumulated Mg was lower in vinasse than in the fertilized treatment. Likewise, fertilization produced higher accumulation of N and P in both fractions compared to C and vinasse treatments. There were no significant differences between vinasse doses in the amount of nutrients accumulated.

The crop at LB2 showed higher K uptake in all treatments compared to L1, especially at harvest. At LB2, the mean accumulation of K of the entire experiment was 255 kg ha^{-1}, with a mean of 310 kg ha^{-1} of K in the treatments with vinasse. At L1, the mean of the experiment was 149 kg ha^{-1}, with a mean of 203 kg ha^{-1} of K in the treatments with vinasse.

Regarding nutrient partitioning at harvest, the majority of the nutrients corresponded to the stem, except for Ca, with a higher proportion in the foliage, and N, which was equally distributed. There was no effect of the treatments on the partitioning of the nutrients and there were few differences between sites.

The amount of biomass accumulated in the first stage represented a small proportion of the total accumulated at harvest (16% and 14% on average for the LB2 and L1 sites, respectively) (Fig. 2). Regarding N, an important part of its uptake occurred in the first stage at both sites, more noticeably at LB2. In contrast, the early absorption of K in the treatments represented, on average, less than 20% of the accumulated total, while for P, Ca and Mg, approximately one third of the total uptake occurred in the first stage. At L1, the early accumulation of biomass and nutrients was higher in C compared to the other treatments.

When examining nutrient use efficiency, measured as kg of nutrient per Mg cane yield, the means of N, P, Ca and Mg were lower at LB2 than L1, but the opposite was occurred with the use efficiency of K (Table 3). The higher values of N per unit of product correspond to the F treatment at both sites, with similar results recorded for C and vinasse treatments. Control and F treatments showed the highest use efficiency of K, while the lowest was recorded for the V150 dose at both sites. There was no effect of the treatments on the efficiency indicator for Ca, Mg and P.

The addition of vinasse and fertilizer produced an increase in K and N extraction compared to C, with a mean of the two doses exceeding C by 151 and 133 kg ha^{-1} of K at LB2 and L1, respectively. Similarly, the extraction of the mean of the vinasse doses was higher by 95 and 77 kg ha^{-1} of K at LB2 and L1, respectively, compared with F. The inverse behavior was observed in the extraction of N, with means of 25 and 20 kg ha^{-1} of N at LB2 and L1, respectively, for the two doses of vinasse in relation to C, which were significantly lower than for those calculated for F (55 and 78 kg ha^{-1} of N at LB2 and L1, respectively). On average, for both sites and vinasse doses, only 21% and 15% of the added K and N, respectively, were quantified in the aerial biomass, while for F, averaging the two sites, the difference in relation to C corresponded to 73% of the added K and 48% of the added N.

Effects of vinasse application on soil parameters

In the pre-harvest soil sampling, in both sites pH showed a slight increase in the treatments with vinasse and a small decrease with the application of fertilizer (data not presented in this work). There were no differences in the contents of available P, nor in interchangeable Ca and Na (data not presented). The most important treatment effects were recorded in exchangeable K and Mg (Fig. 3). There were increases in both nutrients when vinasse was applied, with little difference between doses. The effects of vinasse were statistically significant, compared to C, except for Mg at the L1 site.

Discussion

The application of vinasse had a positive influence on the growth of the crop at both sites, obtaining yields close to those obtained with conventional fertilization. At the LB2 site, although the commercial yield of C was lower than the vinasse treatments, these differences were not statistically significant, probably due to a higher variability (the coefficient of variation of stem production for LB2 was 25%, compared to 12 % for L1). This fact was unexpected, since at first sight the crop did not present evidence of heterogeneity in its population or its growth. At L1, the increase in aerial biomass and yield produced by the application of vinasse is contradicted with the negative effect observed in the first stage. Given the light texture of the soil, the application of vinasse might have produced an increase in the salinity of the soil solution that hampered growth, later reversing this behavior.

Although the accumulation of nutrients by the plants generally precedes the accumulation of biomass, it was prominent in the case of N and, to a lesser extent, Ca, Mg and P, as reported by Coale et al. 1993, but it was not clear for K. The higher absorption of K in the second period can be related to the higher temperature and availability of water that promote diffusion and the late absorption of K (Wood and Meyer, 1986; Donaldson et al., 1990). In turn, the application of vinasse promoted a luxury consumption of K in later stages, probably due to its great abundance. In contrast C showed a higher proportion of nutrient absorption in the first stage, suggesting that the crop suffered nutritional restrictions in the second stage of rapid growth.

The extraction of nutrients, especially K, was substantially increased with the application of vinasse, recording extraction rates more than twice as those of C at both sites. In a study conducted in Venezuela, Rengel et al. (2011) reported a total aerial biomass of sugarcane of 43 Mg ha^{-1} and nutrient extraction rates of 201.4, 43.2, 112.7 and 71.1 kg ha^{-1} of N, P, Ca and Mg, respectively, which are above the values obtained in this study. However, these authors presented a K extraction of 149 kg ha^{-1}, lower than that of all the treatments at the LB2 site, and intermediate at the L1 site.

The higher K use efficiency observed at L1 is probably due to the lower initial level of soil exchangeable K, which was below the critical level proposed by Barbazán et al. (2012) for the fertilization of extensive crops in Uruguay (0.34 cmol$_c$ kg^{-1}) and the critical levels used in South Africa and Australia (Ridge, 2013).

The crop from the L1 site made a more efficient use of K, even with vinasse applications, while at LB2 all treatments (particularly those with vinasse) had lower K use efficiency. The high level of K in stems is not desirable, because it produces a high proportion of ash during cane industrialization (Korndorfer, 2009). Oliveira et al. (2010) compared 11 sugarcane varieties in Pernambuco, Brazil, and obtained higher K use efficiencies (a mean of 1.71 kg Mg^{-1}, for mean yields of 195 Mg ha^{-1}). It should be clarified, that this experiment was conducted under ideal conditions of humidity, temperature and radiation that produced high yields and maximized nutrient use, which are not possible to achieve in Uruguay. Also in Brazil, Leite et al., (2016), obtained an efficiency of 2.4 kg Mg^{-1} for yields lower than 80 Mg ha^{-1} (closer to those of our study, slightly lower than the mean recorded at L1 in crops

Table 1. Stem (cane) yield and leaf to stem ratio (fresh basis). Different letters indicate the difference between treatments for each site (P<0.05).

	Yield	leaf : stem
LB2 Site	(Mg ha^{-1})	
C	57.3 ^{a}	0.30 ^{a}
V150	74.8 ^{a}	0.26 ^{a}
V300	80.4 ^{a}	0.26 ^{a}
F	82.8 ^{a}	0.29 ^{a}
Mean	73.8	0.27
L1 Site		
C	57.2 ^{c}	0.36 ^{a}
V150	63.4 ^{bc}	0.39 ^{a}
V300	64.2 ^{b}	0.36 ^{a}
F	78.8 ^{a}	0.39 ^{a}
Mean	65.9	0.38

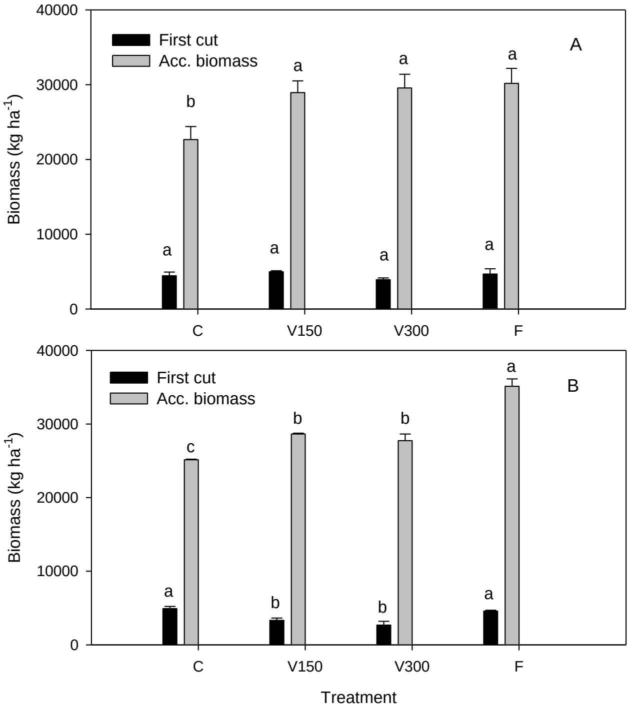

Fig 1. Aerial biomass accumulation of sugarcane in two moments of the cycle (first cut at 6 months and total accumulated at harvest) in the control (C), 150 and 300 m^{3} ha^{-1} vinasse applications (V150 and V300), and fertilization (F) treatments in sites LB2 (A) and L1 (B). Vertical bars indicate the standard error. For each cut and site, means with the same letter do not differ at P<0.05.

Table 2. Nutrient concentration and amount of accumulated nutrients in the aerial biomass of sugarcane Different letters indicate the difference between treatments for each site, sampling and harvested fraction (P<0.05).

		N	P	K	Ca	Mg	N	P	K	Ca	Mg
LB2 Site		(g kg^{-1})					(kg ha^{-1})				
Foliage 12/2013	C	7.9^{b}	1.2ª	6.3^{b}	2.4ª	1.6ª	35,5ª	5.5ª	30.5^{b}	10.5ª	7.0^{a}
	V150	10.0^{ab}	1.1ª	14.7^{a}	2.1ª	1.2^{b}	49,0^{a}	5.7ª	74.0^{a}	10.2ª	6.1ª
	V300	10.4^{ab}	1.1ª	15.5^{a}	2.3ª	1.3^{b}	40,1ª	4.4ª	60.4^{ab}	9.0^{a}	5.0^{a}
	F	12.8ª	1.2ª	7.8^{b}	2.3ª	1.8ª	61,0^{a}	5.8ª	32.0^{b}	11.3ª	8.4ª
Stem harvest 07/2014	C	2.6^{ab}	0.7ª	8.5^{b}	0.9ª	0.9ª	36.3^{b}	10.3ª	126.4^{b}	13.1ª	13.1ª
	V150	2.1^{b}	0.6ª	12.4ª	0.7ª	0.8ª	44.0^{b}	11.9ª	260.4ª	13.8ª	15.9ª
	V300	2.4^{ab}	0.6ª	12.5ª	0.7ª	0.7ª	51.4^{ab}	13.1ª	270.8ª	15.3ª	14.8ª
	F	3.5^{a}	0.6ª	10.4^{ab}	0.8ª	0.9ª	67.9^{a}	12.4ª	202.0^{ab}	15.6^{a}	17.3ª
Leaf harvest 07/2014	C	4.5ª	0.5ª	3.6ª	2.2ª	0.9^{b}	33.2^{b}	4.0^{a}	26.3ª	16.5^{b}	6.4^{b}
	V150	5.1ª	0.5ª	5.2ª	2.3ª	0.8^{b}	45.3^{ab}	4.2ª	43.0^{a}	19.0^{ab}	6.9^{b}
	V300	5.6ª	0.6ª	5.3ª	2.5ª	0.8^{b}	47.6^{ab}	4.7ª	45.8ª	21.1^{ab}	7.0^{b}

	F	5.7ª	0.5ª	4.2ª	2.4ª	1.1ª	57.8^{a}	5.5ª	45.6ª	24.0^{a}	11.2^{a}
Harvested (%)							52	72	84	42	66
L1 Site											
Foliage 12/2013	C	10.2^{b}	1.2^{ab}	3.3^{b}	3.3ª	1.8ª	49.2^{ab}	5.7^{ab}	16.2ª	16.5ª	8.9ª
	V150	10.1^{b}	1.0^{b}	7.7^{ab}	3.0ª	1.3^{b}	33.6^{b}	3.5^{b}	27.8ª	9.6ª	4.4ª
	V300	11.4^{ab}	1.0^{b}	10.8ª	2.1ª	1.5^{ab}	29.4^{b}	2.5^{b}	31.1ª	7.9ª	4.2ª
	F	12.8ª	1.6^{a}	4.8^{ab}	3.5ª	1.8ª	61.3ª	7.8ª	23.0^{a}	17.1ª	8.6ª
Stem harvest 07/2014	C	2.7ª	0.6ª	2.8^{b}	1.3ª	1.0^{a}	42.4^{b}	9.5^{b}	43.8^{b}	20.2ª	14.8ª
	V150	3.1ª	0.6ª	9.4ª	1.3ª	0.9ª	52.7^{b}	10.6^{ab}	159.2ª	20.5ª	14.5ª
	V300	3.1ª	0.6ª	9.0^{a}	1.4ª	0.8ª	55.2^{b}	10.9^{ab}	162.4ª	24.7ª	14.3ª
	F	3.9ª	0.6ª	4.9^{b}	1.1ª	0.9ª	87.3ª	14.5ª	106.0^{b}	24.8ª	19.7ª
Leaf harvest 07/2014	C	4.9^{b}	0.6^{ab}	2.9ª	3.2^{ab}	1.1^{a}	45.5^{b}	5.5^{b}	24.9ª	26.0^{b}	8.6ª
	V150	4.9^{b}	0.5^{b}	3.7ª	2.7^{b}	0.7^{b}	56.2^{b}	6.2^{b}	45.1ª	30.8^{b}	7.6ª
	V300	5.3^{ab}	0.5^{b}	4.2ª	2.9^{ab}	0.8^{b}	52.2^{b}	5.2^{b}	39.0^{a}	29.0^{b}	8.4ª
	F	6.4^{a}	0.7^{a}	3.3ª	3.5ª	1.2^{a}	78.3ª	8.6ª	35.6ª	40.1ª	13.7ª
Harvested (%)							50	64	74	41	61

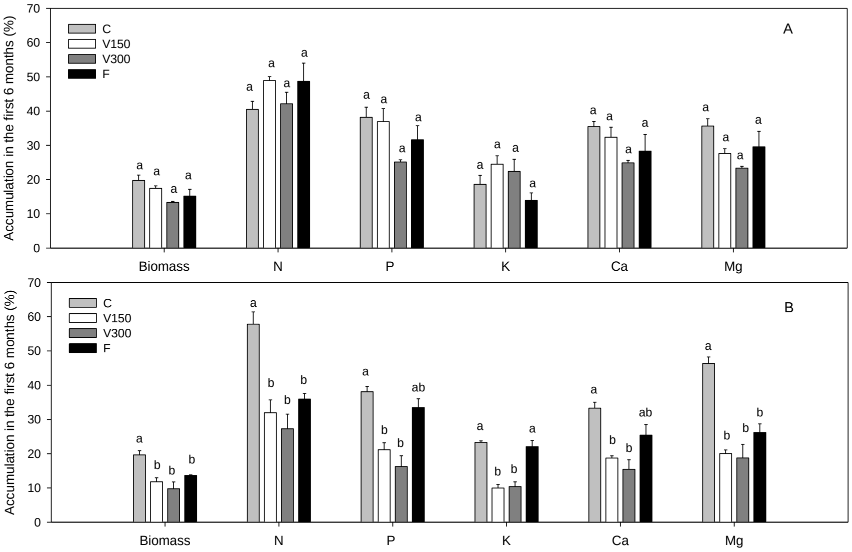

Fig 2. Accumulation of biomass and nutrients in the first 6 months of growth of the sugarcane crop as a proportion of the total amount accumulated at harvest in sites LB2 (A) and L1 (B). The vertical bars indicate the standard error. For each site and nutrient means with the same letter do not differ at P<0.05.

Table 3. Nutrient extraction per unit of sugarcane product. Different letters indicate the difference between treatments for each site (P<0.05).

	N	P	K	Ca	Mg
LB2 Site	(Kg Mg^{-1})				
C	1.23ª	0.25ª	2.67ª	0.52ª	0.34ª
V150	1.21ª	0.22ª	4.06ª	0.44ª	0.30ª
V300	1.23ª	0.22ª	3.94ª	0.45ª	0.27ª
F	1.52ª	0.22ª	2.99ª	0.48ª	0.34ª
Mean	1.30	0.23	3.41	0.47	0.32
L1 Site					
C	1.54^{b}	0.26ª	1.21^{b}	0.88ª	0.44ª
V150	1.72^{b}	0.27ª	3.19ª	0.82ª	0.35ª
V300	1.67^{b}	0.25ª	3.17ª	0.83ª	0.35ª
F	2.10ª	0.29ª	1.86^{b}	0.87ª	0.44ª
Mean	1.64	0.26	2.53	0.84	0.38

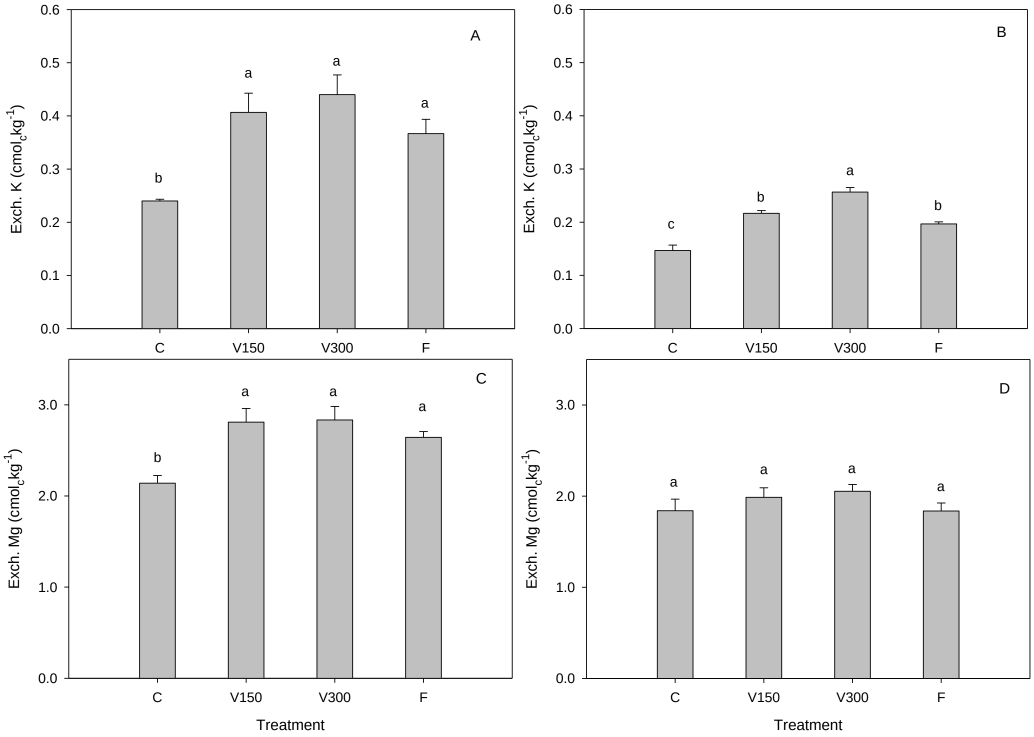

Fig 3. Effect of the application of vinasse and fertilization on soil exchangeable K and Mg (0-20 cm). Sampling performed in July 2014, prior to the sugarcane harvest. Histograms A and C correspond to LB2, and histograms B and D correspond to L1. The vertical bars indicate the standard error. For each site and nutrient, means with the same letter do not differ at P<0.05.

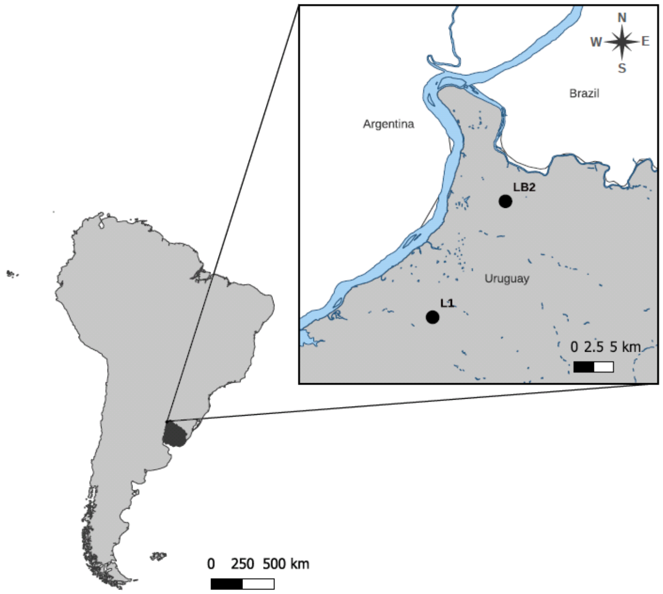

Fig. 4. Location of the experimental sites LB2 and L1.

that received moderate doses of K fertilization. At LB2, increasing the vinasse dose from V150 to V300 increased only 13 kg ha^{-1} of the absorbed K, suggesting that the crop was close to the maximum capacity of accumulation. Contrarily, a higher efficiency was achieved in the fertilization treatment, probably because a lower dose of K was applied. These results showed that if doses of approximately 150 m^3 ha^{-1} of vinasse were applied, supplementary applications of this nutrient through fertilizers would be unnecessary.

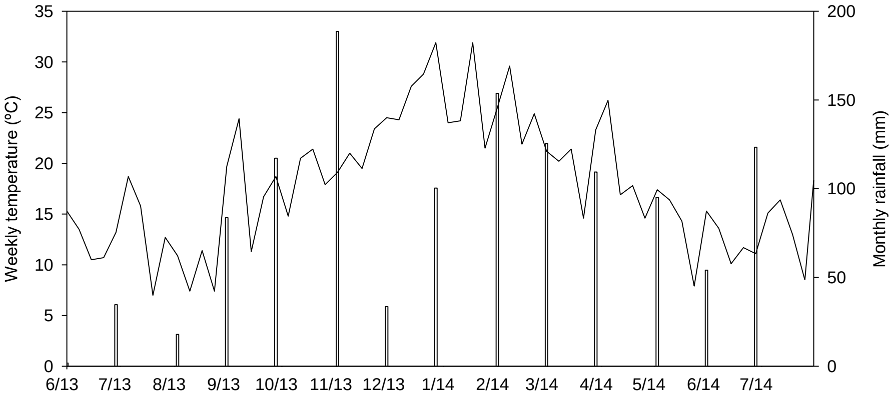

Fig 4. Mean weekly temperature (line) and accumulated monthly precipitation (bars) during the evaluation period.

In both experiments, the concentration of Mg in the plant tissue was higher in C than in the treatments with vinasse, which affirms the antagonism in the absorption and translocation of Mg and K (Wood and Meyer, 1986; Rhodes et al., 2018). At 6 months, the concentration of both nutrients in the foliage showed a negative correlation (R=-0.66; P<0.05). It is not possible to verify whether this affected growth, but the concentration of Mg at both sites and in all treatments was above 0.08%, which is the critical level reported in South Africa for leaves at that stage of growth (Miles and Rhodes, 2013). It should be noted that larger amounts of Mg were added with the vinasse than those absorbed by the crop. Therefore, there would be no reason to fertilize with Mg.

Although the application of vinasse promoted higher N absorption, the difference with C was not significant. Franco et al. (2008) evaluated the application of vinasse together with sewage sludge in Brazil, observing that the latter complemented the N contribution of the vinasse to achieve higher yields. The L1 site showed a lower efficiency than LB2, but these values (1.64 and 1.30 kg Mg^{-1} means for L1 and LB2, respectively) are well above the rate obtained by Oliveira et al. (2010) in Brazil (0.91 kg Mg^{-1}), probably for the reasons previously discussed. The higher use efficiency of N in the treatments with vinasse, suggests that the crop had a shortage of this nutrient. In addition, the difference in N uptake between the treatments with vinasse and C, compared to the fertilized crop, showing a low availability of N applied with vinasse. Consequently, vinasse application could be valuable to maintain the balance of N within the system, although a N fertilization supplement would be needed to reach the highest yields.

The high proportion of stems in the total harvested biomass is consistent with the reports of Rengel et al. (2011), who observed that 300 days after the cut they represented 75% of the biomass. Knowing the quantities of the different nutrients exported with stems is important to determine the potentially recyclable amount for the subsequent regrowth of the crop. Thus, approximately 60% of the Ca, 50% of the N, between 30% and 40% of the P and Mg, and between 15% and 20% of the extracted K could be reused, when there is a suitable management of the residues (Digonzelli et al, 2013). Rengel et al. (2011) highlighted the low proportion of nutrients in leaves, except for Ca, which remained in high proportion at the end of the cycle. Oliveira et al. (2010) studied the mean of 11 varieties and found exports of 83%, 51%, 60%, 76% and 58% in Ca, N, P, Mg and K, respectively. These values are similar to our results for N, P and Mg, but differ in the case of Ca and K. Since K is a mobile nutrient in the plant, there was probably a large translocation from the senescent leaves to the stems, which resulted in a low potential for reuse of K absorbed by the crop. On the other hand, Kingston et al. (2009) in Australia, observed stems contained between 52% and 63% of the crop's total K at one site and between 45% and 72% at another, with a recycling potential of 53 to 68 kg ha^{-1} of K, which is larger than the accumulated amount in leaves and stems in our study.

The lack of effect of vinasse application on soil pH and exchangeable cation content observed at both sites is contradicted by the increases reported by de Resende et al. (2006) and da Silva et al. (2014). A possible cause of this discrepancy is that in our work only one application of vinasse was made, but it is likely to produce a cumulative effect over the years.

The increases in the exchangeable K were rather low in the treatments with vinasse (0.06 and 0.08 $cmol_c$ kg^{-1} in LB2 and L1, respectively), despite the high doses applied (517 and 1034 kg ha^{-1} of K for V150 and V300, respectively). The availability of nutrients at harvest is important, since this value integrates the extraction of the crop and quantifies the soil's reserve of nutrients for the regrowth of the cane, or the sow of the new crop. Although transition to non-exchangeable K forms, especially in the L1 soil where the initial level was lower, is expected, the extraction by the crop becomes relevant for the balance. In these soils, K leaching in the profile is not to be expected, due to its slow infiltration and medium to high CEC. Interestingly in both soils, treatment C showed exchangeable K contents below the initial ones and below the critical levels mentioned, which reaffirms the need to add K to the crop on an annual basis.

Although excess K caused by the application of vinasse or fertilizers is not easy to detect, Korndorfer (2009) recommends that K should not exceed 5% of the total of the exchangeable bases. At harvest, the exchangeable K in vinasse treatments represented approximately 3% and 2% of the total bases at LB2 and L1, respectively, indicating that the application of vinasse did not cause an imbalance of the exchangeable bases in these soils.

Materials and methods

Sites

For this study, two representative soils of the sugarcane production area were selected in the local Soil Catalogue as LB2 and L1 and classified as "Fine, Mixed, Superactive Thermic Pachic Argiudoll" and "Fine, Mixed, Superactive Thermic Typic Argiudoll", respectively (Soil Survey Staff, 2014). Sites are referred as LB2 and L1. The parent material of LB2 soil is sediment derived from basalt alteration, whereas L1 derives from Quaternary age mudstones. The textures of Horizon A correspond to silt loam at LB2 (240, 500 and 260 g kg^{-1} of clay, silt and sand, respectively) and sandy loam at L1 (190, 290 and 520 g kg^{-1} of clay, silt and sand, respectively). The coordinates of LB2 are 30°19' S and 57°33' W, while those of L1 are 30° 26' S and 57° 39' W (Fig. 4). The soil's physicochemical properties are presented in Table 1 of the Supplementary Data.

The experiments were conducted in two commercial plantations, approximately 30 km apart. Each experimental site complied with the following conditions: where the site did not receive vinasse previously, and not been fertilized for one year, and not shown signs of erosion and it was a first ratoon crop (regrowth after the first harvest). The variety was TUC77-42.

The climate of the Bella Unión area is classified as humid subtropical climate (Cfa), with a mean annual rainfall of 1268 mm and a mean annual temperature of 19.8°C (Fig. 5).

Treatment and application of vinasse

The treatments were: (1) a Control treatment without the addition of vinasse or fertilizer (symbolized as C); (2) a vinasse dose of 150 m^3 ha^{-1} (symbolized as V150); (3) a vinasse dose of 300 m^3 ha^{-1} (symbolized as V300); and (4) a treatment with a commercial fertilizer (symbolized as F), without the application of vinasse. The amount of fertilizer used (140 kg ha^{-1} of N plus 140 kg ha^{-1} of K_2O) is the recommended dose for local farms. Table 2 of the Supplementary Data shows the composition of the vinasse and the doses of nutrients applied with vinasse and fertilizer.

The treatments were applied to plots arranged in random blocks (3 replications), each plot consisting of 10 rows of sugarcane planted at 1.20 m distance, and 20 m long. Undiluted vinasse was sprayed on October 30, 2013, when the foliage was poorly developed (less than 30 cm high). A previous test determined that, to prevent runoff, the V150 treatment required 3 consecutive irrigations, whereas the V300 treatment required 6. The management of the crop, especially summer irrigation (November-March), was based on the technical recommendations for each farm, thus the experimental area did not have a differential management.

Soil and plant sampling and analysis

The 4 central rows of each plot were selected for crop evaluation. The first cut of aerial biomass was made two months after applying vinasse (December 20, 2013), when the crop was approximately 6 months old. One linear meter per plot (1.2 m^2) was cut at 5 cm, weighing it in the field and taking a sub-sample, which was dried at 60 ºC and ground for analysis (<0.5 mm). The crop's commercial harvest was carried out on July 24, 2014, approximately 9 months after applying the vinasse and one year after the previous cut. Two linear meters per plot (2.4 m^2) were cut and weighed in the field. Five canes in which the stems were separated from the leaves (including sprouts) were sampled. The stem and leaf fractions were dried and ground as explained above.

In the plant samples, total N content was analyzed according to the Kjeldahl method, mineralizing the material with H_2SO_4 at 350 ºC. The samples were calcined for 5 hours at 550 ºC and the ashes were dissolved with hydrochloric acid, determining P content by colorimetry; Ca, Mg and K were determined from the same extract by atomic absorption (Ca and Mg) and emission (K) spectrometry.

The harvest composite soil samples (20 cores, 0-20 cm) were taken from each plot. The samples were dried at 40 ºC and ground (<2 mm). In the soil samples, the pH in water (1:1 ratio), available P content (Bray 1) and exchange cations (Ca, Mg, K and Na) were determined, extracting the latter with neutral ammonium acetate, and were determined as explained above.

Calculations and data analysis

In the first cut, the amount of accumulated aerial biomass was calculated based on the weight and dry-matter content of the foliage. At harvest, the proportion of stems and leaves from the 5 canes sub-sample was used to calculate the yield (expressed on a fresh weight basis) and amount of biomass (dry basis) of each fraction. The accumulated amount of nutrients in stem and leaf was calculated based on biomass production and the concentration of nutrients. The proportion of biomass and nutrients in the first cut was calculated as a percentage, based on the aerial biomass of each cut and the amount of nutrients accumulated. To estimate nutrient-use efficiency the extraction of nutrients by the crop per unit of cane production (kg Mg^{-1}) was calculated.

In each experiment, the effect of the treatments was statistically analyzed according to a randomized complete block design, with the subsequent separation of means according to Tukey. In addition, by means of contrast analysis, (1) the effect of the addition of vinasse and fertilizer was compared to the C treatment, (2) the effect of the vinasse was compared to that of the F treatment, and (3) the effects of the different doses of vinasse were compared with each other. The SAS 9.3 program (SAS Institute, 2011) was used for the statistical analyses.

Conclusions

At both sites, the application of vinasse had a positive effect on the accumulation of crop biomass. An increased absorption of K was the most important nutrient contribution from the vinasse, allowing producers to dispense with potassium fertilization if they apply doses of vinasse similar to the lowest one used in this experiment (150 m^3 ha^{-1}). In contrast, the comparison with the fertilized treatment suggests that N was limiting when vinasse was applied, requiring a nitrogen fertilization supplement.

The effects of vinasse application on soil K levels were minimal, producing an increase of exchangeable K of 0.06 and 0.08 cmol$_c$ kg^{-1} in LB2 and L1 soils, respectively, in pre-harvest sampling. This finding highlights the necessity of annual K applications for this crop that could be provided by vinasse application.

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