Revista Brasileira de Ciência do Solo

Division - Soil Use and Management | Commission - Soil Fertility and Plant Nutrition

Corrective and maintenance P fertilization on sugarcane yield in multi-sites of south-central Brazil

Rafael Otto[(1)*], Gabriel Pinheiro Silva[(1)], Johnny Rodrigues Soares[(1)], Sarah Mello Leite Moretti[(1)], Lucas Miguel Altarugio[(1)], Gerson José Marquesi de Souza Netto[(1)], Marcelo Grijalva Carneiro Barros[(1)] and Estêvão Vicari Mellis[(2)]

[(1)] Universidade de São Paulo, Escola Superior de Agricultura "Luiz de Queiroz", Departamento de Ciência do Solo, Piracicaba, São Paulo, Brasil.

[(2)] Instituto Agronômico de Campinas, Centro de Solos e Pesquisas de Fertilizantes, Campinas, São Paulo, Brasil.

*** Corresponding author:**
E-mail: rotto@usp.br

Received: June 30, 2024

Approved: December 29, 2024

How to cite: Otto R, Silva GP, Soares JR, Moretti SML, Altarugio LM, Souza Netto GJM, Barros MGC, Mellis EV. Corrective and maintenance P fertilization on sugarcane yield in multi-sites of south-central Brazil. Rev Bras Cienc Solo. 2025;49nspe1:e0240131.
https://doi.org/10.36783/18069657rbcs20240131

Editors: Tales Tiecher, Luciano Colpo Gatiboni and Jimmy Walter Rasche Alvarez.

ABSTRACT: Corrective phosphate is a usual practice in poor soils to improve P levels and yield potential. However, the broadcast P application in soils with high P fixing capacity may have low efficiency. This study evaluated sugarcane yield response to corrective phosphate (broadcast application and incorporated) and in planting maintenance phosphate application in four sugarcane sites during three crop cycles in South-Central Brazil. The experimental design was a factorial 2 × 5: presence or absence of corrective phosphate and five rates of P_2O_5 as maintenance , with four repetitions. A reactive phosphate rock (Bayovar, 29 % of total P_2O_5, 14 % soluble in citric acid 2 %) was broadcast applied at a rate of 150 kg ha^{-1} P_2O_5, while monoammonium phosphate was used in planting furrow in rates varying from 0 to 200 kg ha^{-1} P_2O_5. Sugarcane stalk yield, total recoverable sugar, and sugar yield were evaluated in each site for three consecutive harvests with no re-application of P. Corrective phosphate fertilization combined with maintenance P statistically improved sugarcane yields in 4 of 12 sites-years, showing a yield gain of 4.2 Mg ha^{-1} compared to control. On the average of the literature review, corrective phosphate combined with maintenance P improved sugarcane yield of 7.8 Mg ha^{-1}. In addition, the corrective P had a positive isolated effect in the other two ratoon cycles and a negative in one. maintenance P application isolated (rates of 100-200 kg ha^{-1} P_2O_5) improved sugarcane stalk yield in an average of three harvest, with a mean yield gain of 6.5 Mg ha^{-1}. On average, of all cycles, the CP combined with maintenance P or the isolated practices (at the same rate) increased sugarcane yield from 92 Mg ha^{-1} of control to 97-98 Mg ha^{-1}. Phosphorus fertilization slightly improved total recoverable sugar, so sugar yield improvement was most associated with yield enhancement. Corrective P combined with maintenance P can be a strategy for improving the sustainability of P usage in sugarcane production, including a potential reduction in P input in the cane-plant cycle, aligned to a positive residual effect on the ratoons.

Keywords: corrective fertilization, maintenance P, P use efficiency, residual effect, Saccharum spp.

INTRODUCTION

Sugarcane is one of the most significant crops in Brazil. The cultivated area of sugarcane in Brazil is 9 million hectares, and the country is the largest sugarcane producer in the world (Faostat, 2021). In the last season (2023/2024), sugarcane production totaled 677 million tons of processed sugar (60 %) or ethanol (40 %) production (Conab, 2023). Beyond economic considerations (Heinrichs et al., 2017), sugarcane plays a pivotal role in mitigating climate change, particularly through the increasing adoption of biofuels. Brazil stands as the global leader in sugarcane ethanol production (Bordonal et al., 2018).

Phosphorus is an essential nutrient for plants, and the demand for this element is escalating due to population growth, dietary changes, and the expansion of biofuel usage (de Boer et al., 2018). However, it is acknowledged that P sources are limited and non-renewable (Cordell and White, 2014), necessitating the utmost efficiency in its agricultural production to minimize the depletion of phosphate rock reserves, environmental issues, and production costs (Coelho et al., 2019).

Nutritional management of sugarcane is fundamental for achieving high yields and the longevity of the sugarcane plantation, allowing for increased cutting cycles without the need for renewal. Among the key nutrients for sugarcane cultivation, P is relevant for establishing the sugarcane field, plant tillering, and particularly for the regrowth of ratoons (Zambrosi et al., 2017).

Most soils in Brazil are composed of iron and aluminum oxides, along with kaolinite, which are the main constituents of the clay fraction (Camargo et al., 2013). Reactions leading to the immobilization of applied P as fertilizer involve varying energy levels, including precipitation reactions in solution or specific sorption to clay mineral fractions (Penn and Camberato, 2019) (Liu et al., 2019). This results in the accumulation of a significant amount of P from fertilization in compartments that are of very low availability to plants, creating a compartment known as “legacy P” (Menezes-Blackburn et al., 2018; Pavinato et al., 2020).

Usual P recommendation for sugarcane fields in Brazil includes a broadcast P application in soils with low P levels, maintenance P application in the planting with rates as high as 180-200 kg ha^{-1} P_2O_5, and P application to sequential ratoon varying from 20 to 60 kg ha^{-1} P_2O_5 per year (Cantarella et al., 2022). Corrective phosphate is usually recommended in soils with low P levels, with broadcast application of soluble or partially soluble P sources and incorporated into surface layers. This practice is used to build P-levels (Rein et al., 2015) and generate a residual effect for the ratoons.

Several studies have been conducted to evaluate methods of application, rates, and sources of corrective phosphate with contrasting results (Freiling et al., 2022). However, studies assessing the long-term effects of corrective phosphate under tropical conditions in highly weatherized soils with high levels of iron and aluminum oxides and different textures for sugarcane cultivation are scarce, leading to discussions about its efficiency (Lu et al., 2019; Oliveira et al., 2020; Rein et al., 2021; Freiling et al., 2022). The successful use of corrective phosphate management practice involves the need to build up soil P levels and crop yields, in contrast to the high P fixation capacity of tropical soils and a broadcast P application that allows the contact of inorganic P to soil colloids.

The hypothesis of this study is that broadcast P application as corrective soil fertilization should be gradually replaced by better strategies of P usage in sugarcane fields, including localized P application to planting furrow. This study aimed to assess the sugarcane response to corrective phosphate in association with maintenance P application in sugarcane cultivation in different cycles and sites in South Central Brazil.

MATERIALS AND METHODS

Description of experimental areas

four experimental sites from commercial sugarcane mills in the Center-South region of Brazil – Ivinhema/MS (Site 1), São Pedro do Turvo/SP (Site 2), Chavantes/SP (Site 3), and Suzanápolis/SP (Site 4) (Figure 1) with diverse edaphoclimatic conditions (Alvares et al., 2013; Soil Survey Staff, 2022) were cultivated over three sugarcane cycles (plant cane, first and second ratoon) (Supplementary Data). All experimental areas were subjected to conventional planting practices (plowing and/or harrowing). During the plant cane cycle, soil fertility correction was performed by Cantarella et al. (2022).

Before the trials planting, ten soil subsamples were collected to compose soil samples from each experimental site at depths of 0.00-0.25 and 0.25-0.50 m for chemical characterization following the methodology outlined by van Raij et al. (2001). Additionally, granulometric analysis was conducted following the protocols outlined by Gee and Bauder (2018) (Table 1). All soils had low (7 - 15 mg dm^{-3}) or very low (<7 mg dm^{-3}) P content (Cantarella et al., 2022).

Experimental design and treatments

Following selecting experimental sites with different textures, four field experiments were implemented in a randomized complete block design in a 2 × 5 factorial arrangement with four replications. The first factor comprised the presence or absence of Corrective Phosphate (CP) application, using reactive natural phosphate Bayóvar (30 % total P_2O_5 and 15.5 % P_2O_5 soluble in citric acid 2 %) at a rate of 150 kg P_2O_5 ha^{-1}. The second factor involved five P rates (0, 50, 100, 150, and 200 kg ha^{-1} of P_2O_5 or 0, 22, 44, 66, and 88 kg ha^{-1} of P) applied using monoammonium phosphate (MAP – 50 % P_2O_5). Monoammonium phosphate was applied manually to the bottom of the planting furrow at a depth of approximately 0.15 m, with no further applications during the ratoon stages. In the presence of CP, the fertilizer was broadcast applied and incorporated with a leveling harrow to a depth of 0.15 m, one month before the sugarcane planting, following liming and gypsum application. Each experimental unit consisted of six sugarcane rows spaced at 1.5 m with a length of 15 m each. Ammonium nitrate (32 % N) was used for nitrogen fertilization, discounting the nitrogen already applied via MAP to reach a rate of 80 kg ha^{-1} of N. Potassium fertilization was realized with potassium chloride (60 % K_2O) at a dose of 120 kg ha^{-1} of K_2O. At the ratoons cycle, the nitrogen and potassium were reapplied at the same rates. Phosphorus was not reapplied in subsequent ratoons but only in the plant cane cycle. In ratoon cycles, all fertilizers were applied in the line at the soil surface without incorporation.

Evaluations

Mechanical harvesting of the central four rows of each experimental unit was conducted after 12, 24, and 36 months (plant cane, first and second ratoon), and the weight of the stalks was measured using a load cell coupled to the harvester. Sugarcane yield – Tons of Stalk per Hectare - (TSH – Mg ha^{-1}) was extrapolated to Mg ha^{-1} based on fresh weight. Before harvest, ten stalks were collected from each experimental unit, dried, and sent to each mill's laboratory to determine the Total Recoverable Sugar (TRS – kg Mg^{-1}) according to the methodology proposed by Fernandes (2011). Sugar yield (SY – Mg ha^{-1}) was quantified based on TSH and TRS.

Statistical analysis

After normality and variance homogeneity analyses, the data underwent two-way ANOVA to assess the effects of corrective phosphate and maintenance P rates and the interaction between these two factors on TSH, TRS, and SY variables at each experimental site and across the three sugarcane production cycles. The means comparisons were conducted using the LSD test at 10 %. Regression analysis ($p<0.10$) was performed for isolated effects of maintenance P rates using linear and quadratic functions. All statistical analyses and graphics were conducted using the R software (R Development Core Team, 2022) using ExpDes.pt (Ferreira et al., 2021) and ggplot2 (Wickham, 2016) R packages.

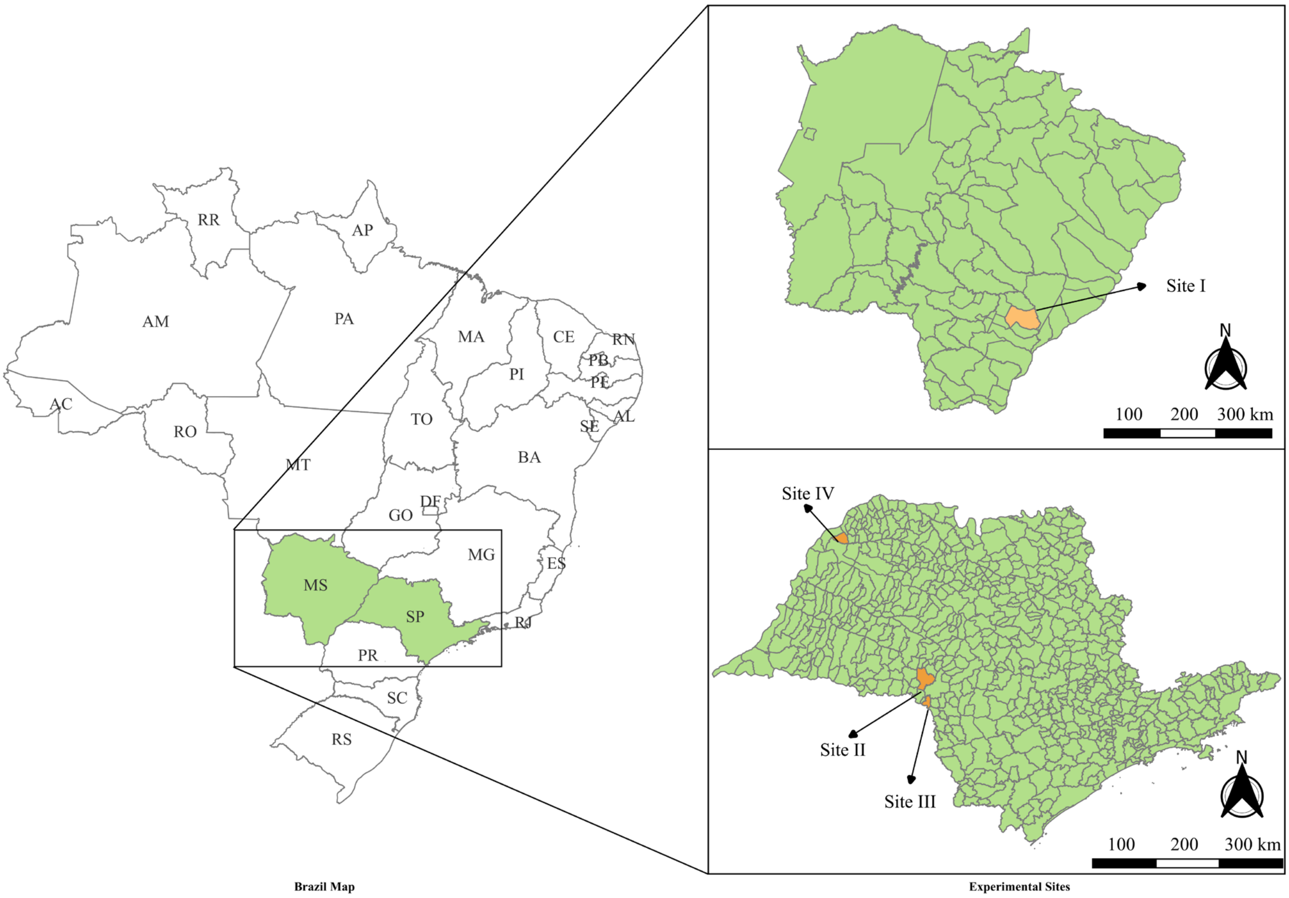

Figure 1. Geographical location of experimental areas.

Table 1. Soil chemical and granulometric characterization at each experimental site

Site/Location	Soil layer	pH	P	S	K^+	Ca^{2+}	Mg^{2+}	Al^{3+}	H+Al	CEC	BS	m	Sand	Silt	Clay
	m		– mg dm^{-3} –		——— mmol$_c$ dm^{-3} ———						—— % ——		——— g kg^{-1} ———		
1. Ivinhema/MS	0.00-0.25 0.25-0.50	4.8 4.5	5.0 0.3	7.0 5.0	1.3 0.6	10.0 5.0	7.0 4.0	0.0 2.0	34.0 42.0	52.3 51.6	35 19	0 17	724 676	23 21	253 303
2. São Pedro do Turvo/SP	0.00-0.25 0.25-0.50	5.1 4.6	6.0 8.0	34 12	0.7 0.6	24.0 11.0	3.0 0.5	0.0 2.0	20.0 28.0	47.7 40.6	58 31	0 14	802 779	24 20	175 201
3. Chavantes/SP	0.00-0.25 0.25-0.50	4.6 4.7	7.0 5.0	12 23	1.9 1.1	18.0 14.0	9.0 6.0	0.0 0.0	38.0 42.0	66.9 63.1	43 33	0 0	143 128	179 156	677 716
4. Ilha Solteira/SP	0.00-0.25 0.25-0.50	6.5 5.8	13.0 4.0	6.0 4.0	2.1 1.6	14.0 8.0	9.0 5.0	0.0 0.0	11.0 20.0	36.1 34.6	70 42	0 0	803 770	21 29	176 201

Contents of P, K, Ca, and Mg were extracted using an ion exchange resin method. Sulfur (Calcium phosphate 0.01 mol L^{-1}); pH in $CaCl_2$ 1:2.5 (solution 0.01 mol L^{-1}). Soil chemical analyses were performed according to van Raij et al. (2001); and soil particle size by Gee and Bauder (1986).

RESULTS

Sugarcane yield

Sugarcane stalk yield was assessed at four distinct sites over three cultivation cycles. Significant differences in sugarcane yield were observed across the sites in all three cycles, with interactions between CP and maintenance P rates (Table S3). The interaction of CP and MAP maintenance P rates was further analyzed within each site, and when there were no significant effects, the isolated effects of corrective P or maintenance P were accessed.

Site 1

At Site 1, the interaction effect was significant (p-value<0.10) for both the first and second ratoon crops. During the first ratoon, the CP combined with maintenance Prates of 50, 150, and 200 kg ha^{-1} of P_2O_5 resulted in yields of 124, 128, and 131 Mg ha^{-1}, respectively. In contrast, yields without CP were 110, 108, and 110 Mg ha^{-1}, reflecting yield increases of 12.7, 18.5, and 19.1 %, respectively (Figure 2). For the second ratoon, the CP had negative effect at maintenance Prates of 100 and 150 kg ha^{-1} of P_2O_5, with yields of 94 and 91 Mg ha^{-1} without CP compared to 84 and 85 Mg ha^{-1} with CP, corresponding to yield increases of 11 and 7 %, respectively (Figure 2).

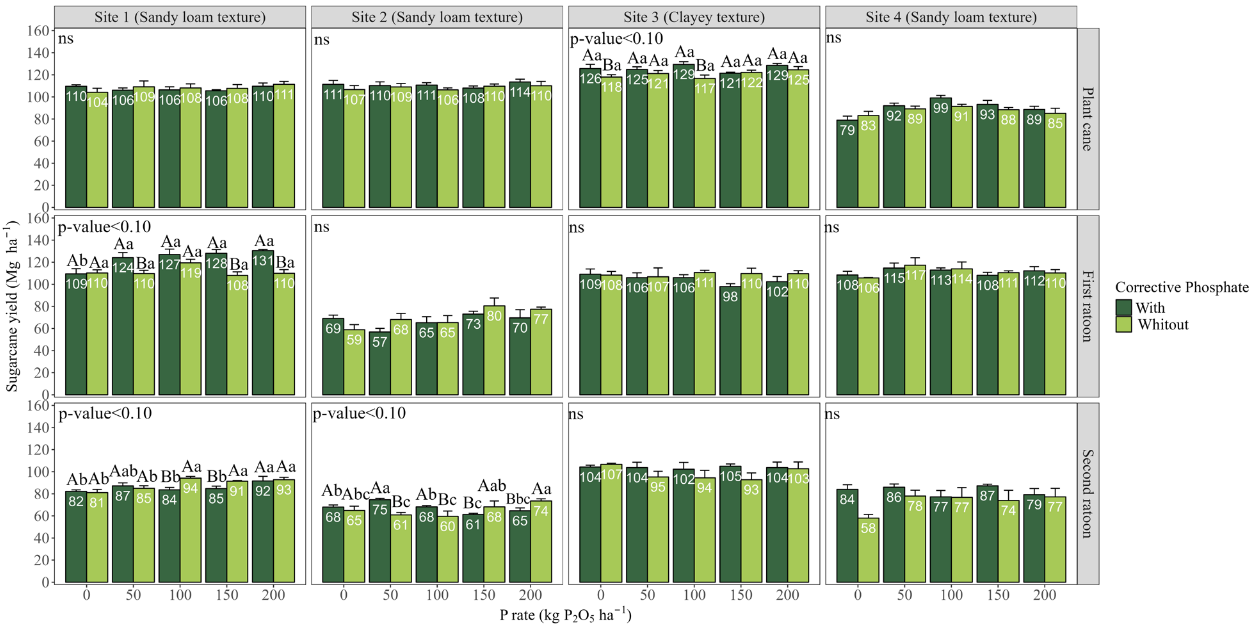

Figure 2. Sugarcane stalk yield as a function of P_2O_5 rates (as MAP) at planting furrow or corrective P fertilization (150 kg P_2O_5 ha^{-1} as reactive rock phosphate) at each site during the cane plant, first ratoon, and second ratoon. Uppercase letters indicate differences between the presence or absence of corrective phosphate. Lowercase letters indicate differences between rates of P_2O_5 in the presence or absence of corrective phosphate. ns: no significant at 10 %. Bars represent standard deviation (n = 4).

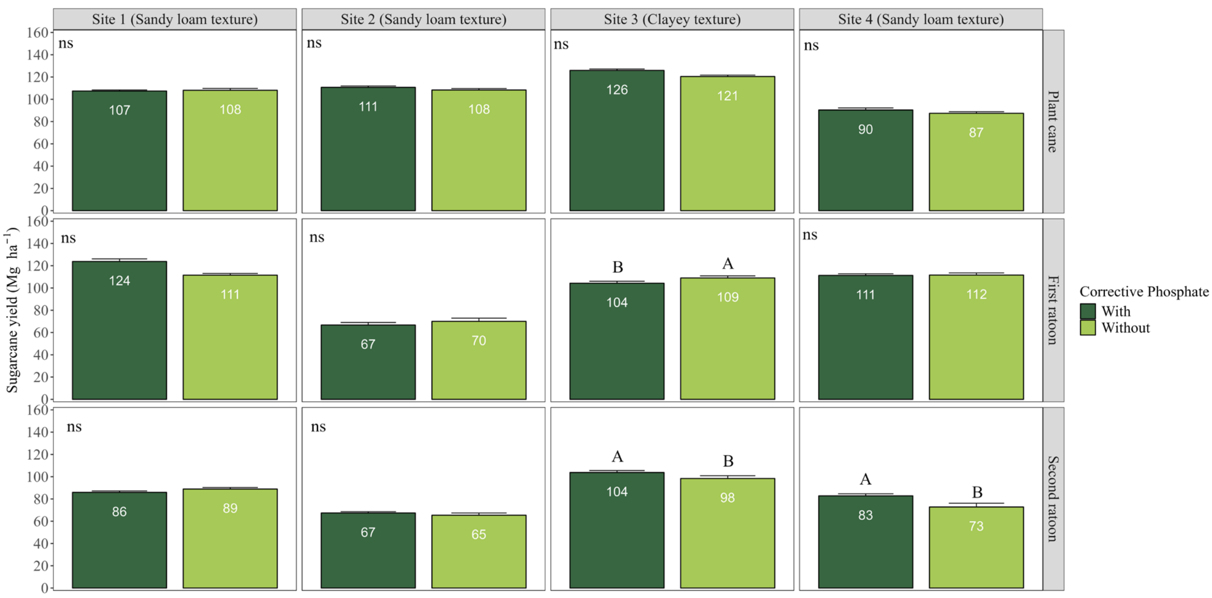

Figure 3. Sugarcane stalk yield as a function of corrective P fertilization (150 kg ha^{-1} of P_2O_5 as reactive phosphate rock) at each site during the cane plant, first ratoon, and second ratoon, on the average of P_2O_5 rates applied at planting furrow. Letters indicate differences between the presence or absence of corrective P. ns: no significant at 10 %. Bars represent standard deviation (n = 4).

Site 2

At Site 2, yield responses were observed in the first and second ratoons. In the first ratoon, an isolated response to P rates in the furrow showed a quadratic adjust, with maximum efficiency achieved at 185 kg ha^{-1} of P_2O_5 , resulting in a yield of 72.7 Mg ha^{-1} compared to 62.5 Mg ha^{-1} at 0 kg ha^{-1} of P_2O_5 (Figure 4). In the second ratoon, the interaction was significant, with positive CP responses at maintenance P rates of 50 and 100 kg ha^{-1} of P_2O_5, yielding 75 and 68 Mg ha^{-1}, corresponding to increases of 14 and 8 Mg ha^{-1} compared to without CP, respectively. However, the CP resulted in a negative effect at higher maintenance P rates, with yields of 61 and 65 Mg ha^{-1}, reducing 7 and 9 Mg ha^{-1} at 150 and 200 kg ha^{-1} of P_2O_5, respectively (Figure 2).

Site 3

At Site 3, significant yield responses were observed in all three cycles. In the plant cane cycle, the interaction between factors was significant at maintenance P rates of 0 and 100 kg P_2O_5 ha^{-1}. The CP resulted in higher stalk yields of 126 and 129 Mg ha^{-1}, compared to 118 and 117 Mg ha^{-1} without CP, corresponding to increases of 8 and 12 Mg ha^{-1}, respectively (Figure 2). During the first ratoon, the CP had a negative effect, in which without CP yielded 109 Mg ha^{-1} compared to 104 Mg ha^{-1} with CP (Figure 3). In the second ratoon, positive responses to CP were observed, with the CP yielding 104 Mg ha^{-1} compared to 98 Mg ha^{-1} without CP (Figure 3).

Site 4

At Site 4, significant yield responses were observed across all three cycles. In the plant cane cycle, an isolated effect of maintenance P rates showed a quadratic response, with maximum efficiency at 114.8 kg ha^{-1} of P_2O_5, resulting in a yield of 94.6 Mg ha^{-1} compared to 81.4 Mg ha^{-1} at 0 kg ha^{-1} of P_2O_5 (Figure 4). In the first ratoon, an isolated effect of P rates was observed, with a quadratic response and maximum efficiency at 114.9 kg ha^{-1} of P_2O_5. In the second ratoon, positive responses to CP were observed, with the CP yielding 83 Mg ha^{-1} compared to 73 Mg ha^{-1} without CP (Figure 3).

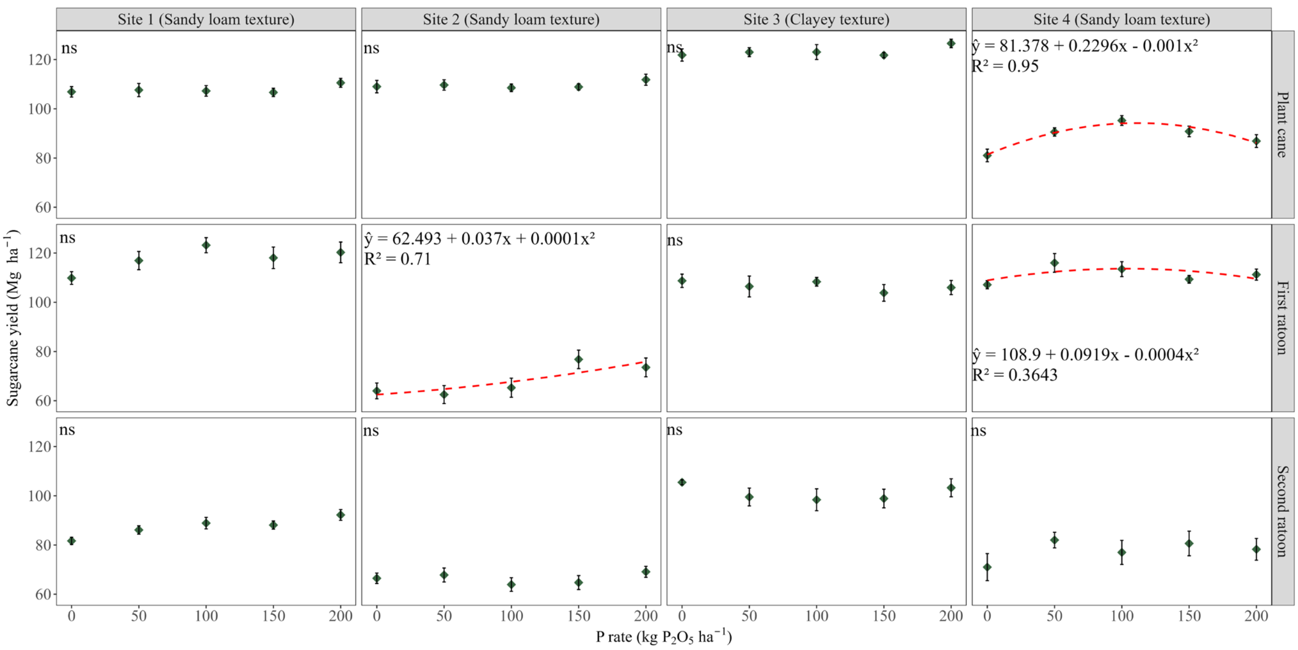

Figure 4. Sugarcane stalk yield as a function of rates of P_2O_5 (as MAP) applied at planting furrow at each site during the cane plant, first ratoon, and second ratoon, on the average of corrective P fertilization or not. ns: no significant at 10 %. Bars represent standard deviation (n = 4).

On average, in the three harvests, significant responses of maintenance P rates were observed at three of the four sites. Sites 1 and 4 exhibited a quadratic response to maintenance P rates, with maximum yields of 106.2 Mg ha^{-1} at 177.2 kg ha^{-1} of P_2O_5 and 95.7 Mg ha^{-1} at 107.4 kg ha^{-1} of P_2O_5, respectively. Site 2 showed a linear response to maintenance P rates (Figure 5).

Total recoverable sugar

For total recoverable sugar, there was an interaction between the factors maintenance P rates and CP that occurred at site 1 – Plant cane and first ratoon; site 4 – second ratoon. The results varied regarding maintenance P rates, where there were superior results for both the presence and absence of CP (Figure 6). The isolated effect of CP had a significant result only at site 2 in the second ratoon cycle, with the predominance of CP (166.8 kg Mg^{-1}) due to the absence of CP (159.9 kg Mg^{-1}) (Supplementary Material). For the effect of dose, only the cane plant cycle was affected in sites 2 and 4, both with quadratic response (Figure 7).

Sugar yield

Site 1

At Site 1, sugar yield responses were significant (p-value<0.10) in both the first and second ratoons. In the first ratoon, the isolated effect of CP resulted in higher yields, with 20.6 Mg ha^{-1} with CP compared to 18.3 Mg ha^{-1} without CP (Figure 9). Additionally, maintenance P rates showed a quadratic response, with maximum efficiency achieved at 101.2 kg ha^{-1} of P_2O_5, yielding 19.8 Mg ha^{-1} compared to 17.8 Mg ha^{-1} from no P in the furrow (Figure 10). For the second ratoon, the interaction effect was significant, with maintenance P rates of 100 and 150 kg ha^{-1} of P_2O_5 resulting in superior yields without CP, showing gains of 2.1 and 1.9 Mg ha^{-1}, respectively, compared to yields with CP (Figure 8).

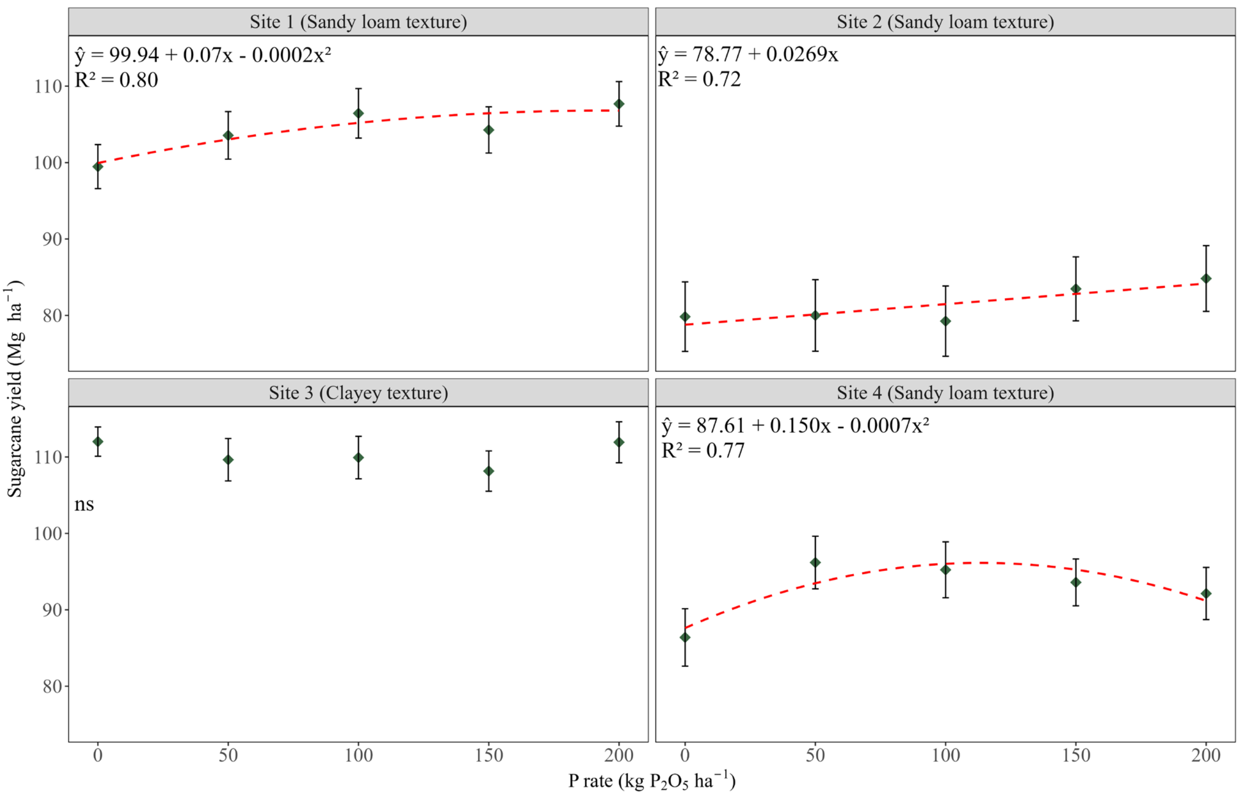

Figure 5. Average of sugarcane stalk yield (three harvest) as a function of rates of P_2O_5 (as MAP) applied at planting furrow at each site, on the average of corrective P fertilization or not. ns: no significant at 10 %. Bars represent standard deviation (n = 4).

Site 2

At Site 2, during the first ratoon, the isolated effect of maintenance P rates responded significantly, with a linear adjustment observed at higher P_2O_5 rates in the planting furrow (Figure 10). In the second ratoon, maintenance P rates of 50 and 100 kg ha^{-1} of P_2O_5 resulted in higher sugar yields with CP, with yields of 12.4 and 11.4 Mg ha^{-1}, representing increases of 2.6 and 1.6 Mg ha^{-1}, respectively (Figure 8).

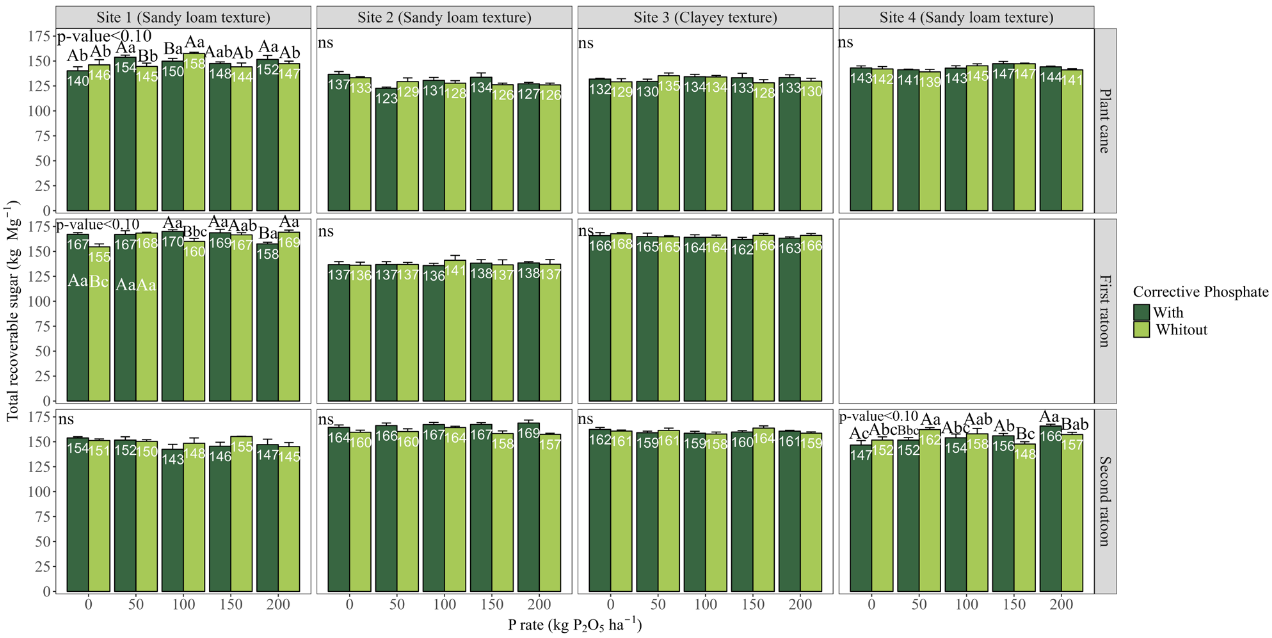

Figure 6. Total recoverable sugar as a function of P_2O_5 rates (as MAP) at planting furrow or corrective P fertilization (150 kg ha^{-1} of P_2O_5 as reactive rock phosphate) at each site during the cane plant, first ratoon, and second ratoon. Uppercase letters indicate differences between the presence or absence of corrective phosphate. Lowercase letters indicate differences between rates of P_2O_5 in the presence or absence of corrective phosphate. ns: no significant at 10 %. Bars represent standard deviation (n = 4).

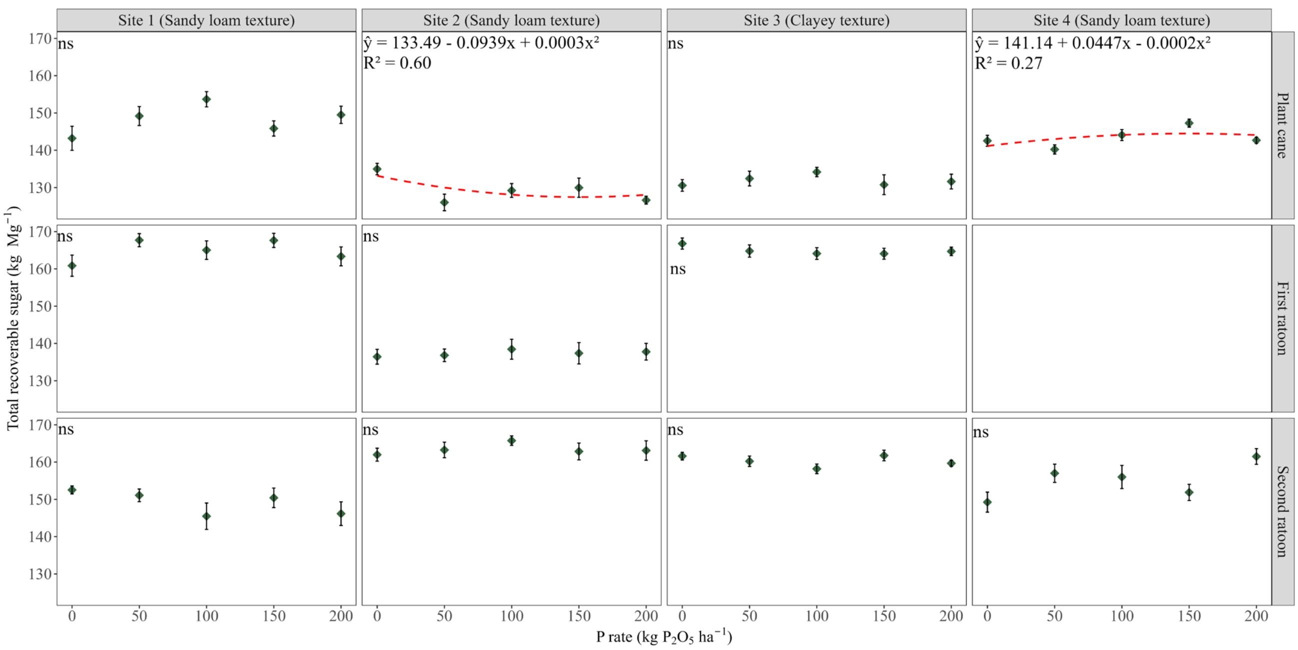

Figure 7. Total recoverable sugar as a function of rates of P_2O_5 (as MAP) applied at planting furrow at each site during the cane plant, first ratoon, and second ratoon, on the average of corrective application fertilization or not. ns: no significant at 10 %. Bars represent standard deviation (n = 4).

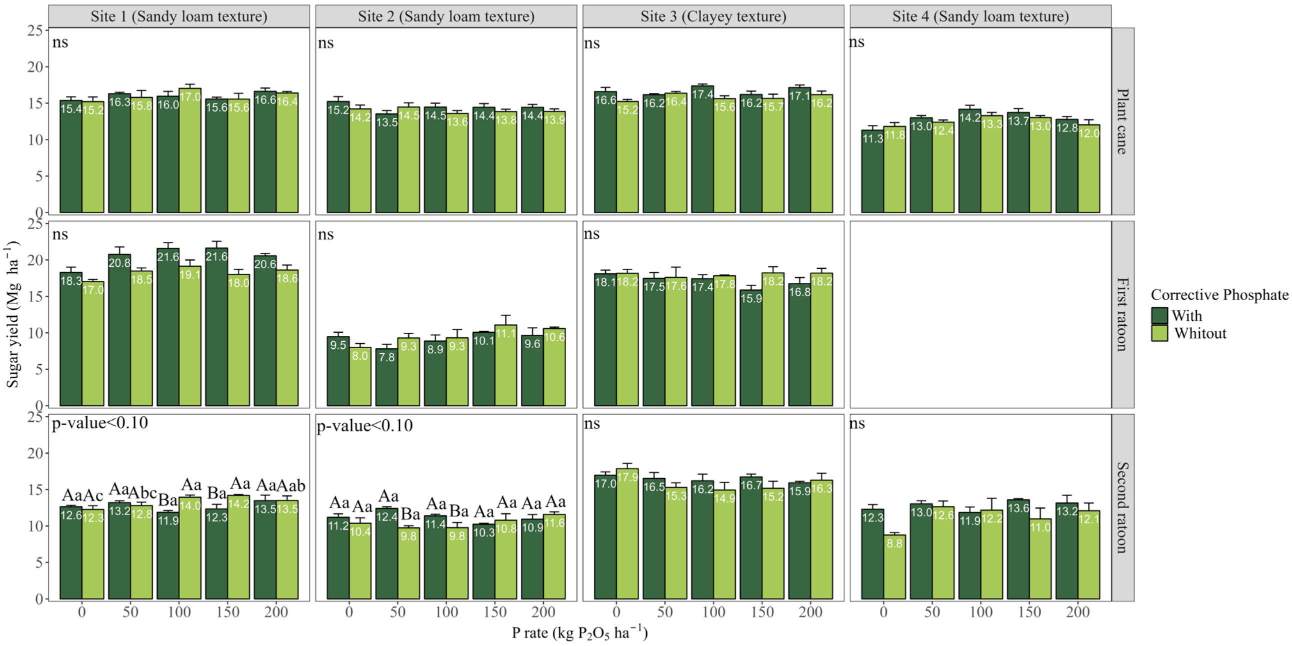

Figure 8. Sugar yield as a function of P_2O_5 rates (as MAP) at planting furrow or corrective fertilization (150 kg ha^{-1} of P_2O_5 as reactive rock phosphate) at each site during the cane plant, first ratoon, and second ratoon. Uppercase letters indicate differences between the presence or absence of corrective phosphate. Lowercase letters indicate differences between rates of P_2O_5 in the presence or absence of corrective phosphate. ns: no significant at 10 %. Bars represent standard deviation (n = 4).

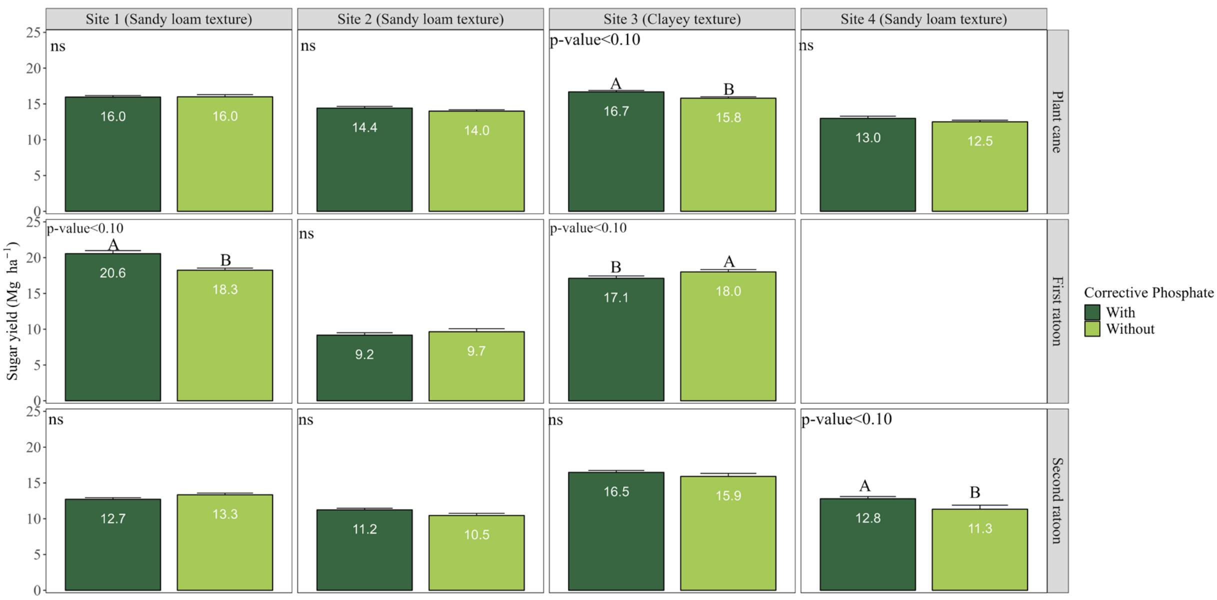

Figure 9. Sugar yield as a function of corrective P fertilization (150 kg ha^{-1} of P_2O_5 as reactive phosphate rock) at each site during the cane plant, first ratoon, and second ratoon, on the average of P_2O_5 rates applied at planting furrow. Letters indicate differences between the presence or absence of corrective phosphate. ns, no significant at 10 %. Bars represent standard deviation (n = 4).

Site 3

At Site 3, significant responses were observed in both the cane plant and first ratoon cycles. In the cane plant cycle, the isolated effect of CP was significant, with a yield of 16.7 Mg ha^{-1} with CP compared to 15.8 Mg ha^{-1} without CP. During the first ratoon, however, the CP had a negative response, with yields of 17.1 Mg ha^{-1} compared to 18 Mg ha^{-1} without CP (Figure 9).

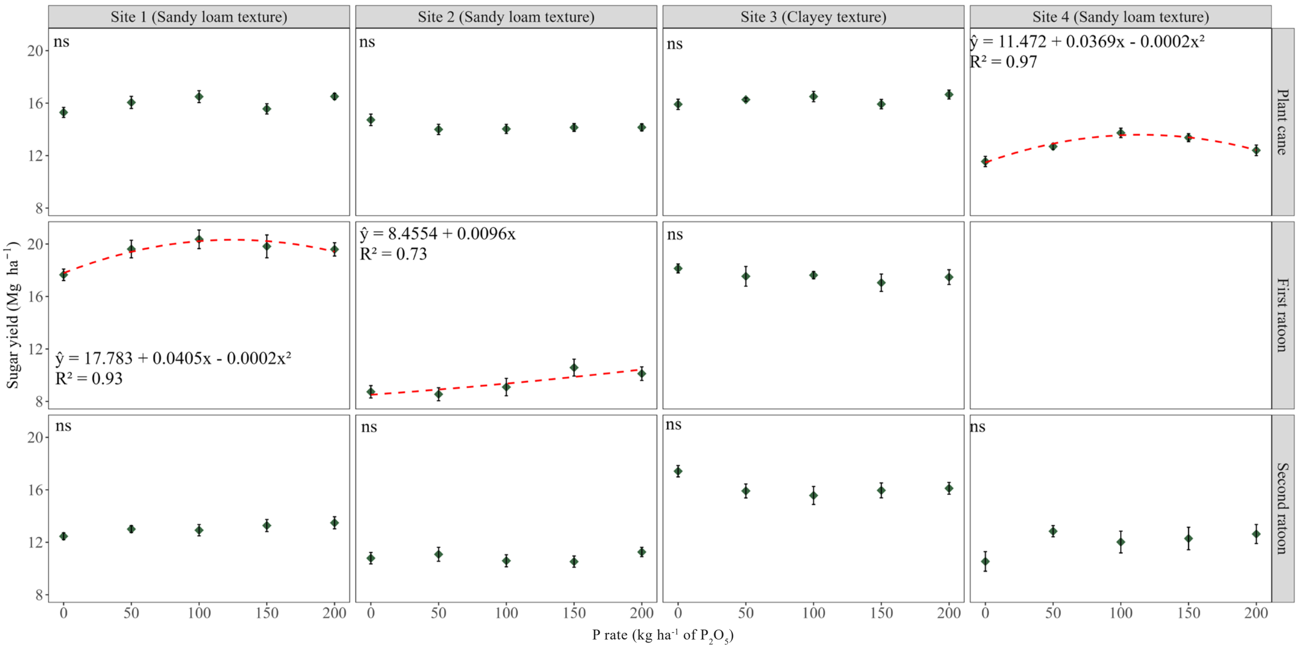

Figure 10. Sugar yield as a function of rates of P_2O_5 (as MAP) applied at planting furrow at each site during the cane plant, first ratoon, and second ratoon, on the average of corrective fertilization or not. ns: no significant at 10 %. Bars represent standard deviation (n = 4).

Site 4

At Site 4, the only significant response was observed in the isolated effect of CP during the second ratoon, where higher yields were achieved with CP, resulting in 12.8 Mg ha^{-1} compared to 11.3 Mg ha^{-1} of sugar without CP (Figure 8).

DISCUSSION

In the present study, the CP was broadcast applied, and the MAP fertilizer was applied in the furrow. The phosphate application method affects crop utilization of P (Freiling et al., 2022) and is the subject of numerous debates aiming for greater efficiency. The broadcast application of P is criticized as a low-efficiency method, yet it boasts a high operational production. For sugarcane cultivation, it is a widely practiced method, even recommended by Brazilian fertilizer guides (Sousa and Lobato, 2004; Cantarella et al., 2022). To buildup P levels, corrective phosphate aims to occupy positive charges on clay particles with less soluble P sources. Over time, the fixation of phosphate ions into soil particles will eventually reach a saturation point. Once this point is reached, it should no longer be necessary to supply more phosphate than what was removed in the previous year, as soil particles are not infinite sinks for phosphate (Barrow, 2015). This effect suggests that, after a certain period, the soil capacity to adsorb additional phosphate decreases, reducing the need for excessive fertilizer applications. Afterward, subsequent P applications become more efficient due to reduced phosphate interaction with clay.

Our findings revealed a slight but favorable response of CP associated with maintenance P application in sugarcane yield in four different cycles (cane plant, first and second ratoon) and different sites (1, 2, and 3), that have sandy loam (sites 1, and 2) and clay soil texture (site 3). The corrective P had a positive isolated effect in the other two cycles (second ratoon in sites 3 and 4) and a negative effect in one cycle (first ratoon in site 3). Maintenance P application resulted in a positive isolated effect on three sites (cane plant in site 4 and first ratoons in sites 2 and 4).

With increased P utilization by sugarcane using maintenance P has led to higher sugarcane and sugar yields per hectare (average for three harvesters). This outcome can be explained by the concentration of the root system in soil areas with higher P concentrations, potentially promoting root growth (Gao et al., 2019) and expanding the root exploration area. Robust roots can enhance water and nutrients absorption. Additionally, with CP, the residual effect of less soluble sources favors maintaining adequate P levels in subsequent cycles (Sousa et al., 2015). Another aspect to consider is the stress conditions that sugarcane may undergo during various cultivation cycles. Silva et al. (2019) concluded that the application of corrective phosphate at a dose of 150 kg ha^{-1} reduced the activity of the enzymes superoxide dismutase (SOD), catalase (CAT), and ascorbate peroxidase (APX), which are responsible for managing oxidative stress. This reduction in enzyme activity indicates that with an adequate supply of phosphorus, the plants were not under stress, thereby decreasing the need for these stress-mitigating enzymes.

Despite sugarcane exporting 15 kg ha^{-1} of P in a production of 100 Mg ha^{-1} (Cantarella et al., 2022), the fertilizer recommendation for the crop is much higher than the plant needs. This excess arises from sorption and precipitation interactions of phosphate ions with soil colloids. In light of this, corrective phosphate becomes an important practice in soils with very low P levels (<7 mg dm^{-3}) and high clay content (>350 g kg^{-1}) to provide more than the plant requires. However, in our study, only site 4 did not observe a response to CP associated with maintenance P rates, while sites 1, 2, and 3 had a response (Figure 2). The soils at sites 1, 2, and 3 had P content <7 mg dm^{-3}, while site 4 had 13 mg dm^{-3} at 0.00-0.25 m soil layer. Therefore, it is likely that the lack of positive effect from CP combined with maintenance P on site 4 was related to a higher P content in soil and the sugarcane variety (RB92579), which was different from the other three sites (CTC 4). On the other hand, the second ratoon in site 4 showed a positive effect of the isolated CP application.

Small responses (3 out of 12 sites-years) were observed for total recoverable sugar from applying P in the planting furrow, corrective phosphate, or the combination of these fertilization practices. This outcome was anticipated, as other nutrients were adequately supplied throughout all cycles, and P does not directly influence the transport of sugars to the stalks. However, Tarumoto et al. (2022) demonstrated that sugar production was higher in an experiment with two sugarcane varieties under low P conditions but with adequate supplementation through a nutrient solution. Therefore, the importance of P in sugar production is well established.

Results for sugar yield were strongly influenced by those for sugarcane stalk yield, highlighting the critical role of P in sugar productivity and the longevity of sugarcane plantations (Zambrosi et al., 2017; Rein et al., 2021). However, reducing the costs of phosphate fertilizers is crucial to enhancing production sustainability (Bordonal et al., 2018) and ensuring profitability.

Compiled results from 15 studies, including the four experimental sites in this study, regarding the effect of CP on sugarcane, showed different responses to the impact of CP in sugarcane (Table 2). Positive responses were observed in 9 out of 15 studies evaluated; however, most of them evaluated only the first harvest, making a long-term evaluation of this practice difficult. In this study, 4 cycles had positive effects of CP combined with maintenance P, and in 2 cycles of 12 harvests, the CP demonstrated isolated positive effects. These different responses are due to numerous factors involving management, such as soil texture, Fe and Al content (Campos et al., 2016), acidity (Zhao et al., 2022), use of agro-industrial wastes (Estrada-Bonilla et al., 2021; Silva et al., 2022), water regime (Allen et al., 2006) cultivar, and available P content.

Interestingly, that sugarcane had different responses to CP and/or maintenance P in each cycle and site; where the combined practices were positive in 4 cycles, the isolated CP in 2 cycles, and maintenance P in 3 cycles. However, when comparing the equivalent effect on average of isolated corrective phosphate applied at a dose of 150 kg ha^{-1} of P_2O_5 to the isolated dose of 150 kg ha^{-1} of P_2O_5 applied in the planting furrow, across the average of three harvests and four locations, the results were similar, with yields of 97 and 97 Mg ha^{-1}, respectively, compared to 92 Mg ha^{-1} from control plots. The combined application of corrective phosphate and maintenance P produced 98 Mg ha^{-1}, indicating a limited response to the combined practice and lower efficiency compared to isolated practices, given that a higher amount of P was applied.

The efficiency of P use can be calculated by comparing the amount of P entering minus the amount extracted by the crop, with the remainder counted as lost (Schröder et al., 2011). Thus, it can be assumed that, on average, using maintenance P combined with CP was less efficient than applying P only in the sugarcane furrow or CP isolated, as cane yields were similar, as the P application was higher with combined practices. In addition, in the present study, both CP and maintenance P fertilizer resulted in a positive effect in a few cycles and no effect in most of the cycles evaluated. Moreover, the solubility of reactive natural phosphates is affected by pH and particle size (Saied et al., 2022). Consequently, the effect of CP may have been reduced since lime was used before CP in all sites. In one cycle, the isolated CP resulted in a negative effect on yield, and in another two cycles, it was observed a negative effect of CP combined with a high rate of maintenance P. Probably, the higher sugarcane yield in previous cycles due to CP and/or maintenance P application had higher nutrient removal from the field, affecting the next cycle. Therefore, to increase P use efficiency, avoid environmental problems, and ensure satisfactory yields, it is worthwhile to rethink more efficient strategies for phosphate use in sugarcane cultivation, such as reducing the use of high P rates in the furrow when corrective phosphate is used.

Table 2. Average of sugarcane stalk yield as a function of corrective phosphate in different initial P content

Clay	Initial P	P_2O_5 applied		Corrective phosphate	No corrective phosphate	Yield gain	Source
		Corrective	Furrow				
g kg^{-1}	mg dm^{-3}	kg ha^{-1}		Mg ha^{-1}			
253	5.0 (R)	150	rates	105.7	102.8	2.9	This study[1]
175	6.0 (R)	150	rates	81.6	81.3	0.3	This study[1]
677	7.0 (R)	150	rates	111.3	109.3	2.0	This study[1]
176	13.0 (R)	150	rates	94.8	90.6	4.2	This study[1]
320	9.8 (R)	150	170	141.8	130.6	11.2	Rein et al. (2021)
613	30.6 (R)	150	170	130.4	121.7	8.7	Rein et al. (2021)
120	4.0 (R)	180	180	135.2	139.8	- 4.6	Santos et al. (2018)
NA	5.0 (M)	200	100	67.3	56.6	10.7	Albuquerque et al. (2016)
620	1.2 (M)	100	200	120.5	104.7	15.8	Rein and Sousa (2013)
NA	0.4 (R)	300	112	83.7	70.0	13.7	Sousa and Korndorfer (2011)[1]
429	0.2 (M)	270	150	92.2	82.1	10.1	Caione et al. (2011)
120	13.0 (M)	100/200	100/200	145.5	145.0	0.5	Tomaz (2009)
530	12.0 (M)	170	168	94.0	92.0	2.0	Gama (2007)
380	2.0 (M)	170	168	118.0	103.0	15.0	Gama (2007)
NA	2.0 (M)	100	150	123.0	98.0	25.0	Reis and Cabala-Rosand (1986)
Average				109.6	101.8	7.8	

(1) Average of three sugarcane harvests (plant cane, first and second ratoon). (R): resin ion exchange; (M): Mehlich-1 extractant method.

In addition, P reapplication in sugarcane ratoons has been considered a beneficial and more efficient practice from a productivity standpoint, with increases of up to 23.1 % compared to the absence of P reapplication, as reapplication rates are lower (Zambrosi, 2021). Another strategy that improved efficiency in P fertilization and eco-friendly production of sugarcane is the use of alternative phosphate sources, such as compost of sugarcane industry wastes, phosphate-solubilizing bacteria (Estrada-Bonilla et al., 2021; Lopes et al., 2021) and mycorrhizal fungi (Li et al., 2024). Further studies should investigate the application o CP combined with conventional P fertilizer in sugarcane yield at different sites and other sources of greater solubility. They should also include other managements to improve P use efficiency as phosphate-solubilizing microorganisms.

CONCLUSION

Residual effect of corrective phosphate combined with maintenance P contributed to increased production during the first and second ratoons, therefore can contribute to the long-term fertilization in sugarcane fields. Despite the potential average gains of up to 4.2 Mg ha^{-1} through corrective phosphate practices combined with maintenance P, positive responses compared to the absence of corrective P were observed in only 4 out of 12 cycles evaluated. In addition, the corrective P had a positive isolated effect in only 2 out of 12 site-cycles. In this way, more studies are necessary to evaluate the efficiency of corrective phosphate and maintenance P in sugarcane including other management options to improve P use efficiency.

Isolated effect of maintenance P shows a positive impact on the average of three harvests in three of four sites, with a recommended rate of 100 – 200 kg ha^{-1} of P_2O_5 according to the soil P content and soil texture. Corrective P combined with maintenance P showed positive effects in more cycles than in isolated practices. However, the average yield gains achieved with combined practices were similar to corrective phosphate and maintenance P isolated (same rate), suggesting that using only one of these P fertilization practices may be more efficient.

SUPPLEMENTARY DATA

Supplementary data to this article can be found online at https://www.rbcsjournal.org/wpcontent/uploads/articles_xml/1806-9657-rbcs-49-spe1-e0240131/1806-9657-rbcs-49-spe1-e0240131-suppl01.pdf

DATA AVAILABILITY

The data will be provided upon request.

FUNDING

The Programa Cooperativo de Experimentação e Manejo (PCEM), together with Grupo de Apoio à Pesquisa e Extensão (GAPE), thanks all the mill's collaborators: Adecoagro, São Luiz and Companhia Melhoramentos Norte do Paraná, for their funding, availability and dedication to the development of this research. R. Otto received a research productivity fellowship from the National Council for Scientific and Technological Development (CNPq), grant #309061/2020-2. GPS received a scholarship from Coordenação de Aperfeiçoamento de Pessoa de Nível Superior (CAPES), grant #88887.823838/2023-00. JRS received a scholarship from Foundation for Research and Agricultural and Forestry Studies (FEPAF), grant #1145.

AUTHOR CONTRIBUTIONS

Conceptualization: Estêvão Vicari Mellis (supporting), Gabriel Pinheiro Silva (lead) and Rafael Otto (lead).

Data Curation: Gabriel Pinheiro Silva (lead), Johnny Rodrigues Soares (supporting), Lucas Miguel Altarugio (lead) and Sarah Mello Leite Moretti (supporting).

Formal Analysis: Gabriel Pinheiro Silva (lead) and Johnny Rodrigues Soares (supporting).

Investigation: Estêvão Vicari Mellis (supporting), Gerson José Marquesi de Souza Netto (supporting), Johnny Rodrigues Soares (supporting), Lucas Miguel Altarugio (supporting), Marcelo Grijalva Carneiro Barros (supporting), Rafael Otto (lead) and Sarah Mello Leite Moretti (supporting).

Methodology: Estêvão Vicari Mellis (supporting), Gerson José Marquesi de Souza Netto (lead), Lucas Miguel Altarugio (lead) and Rafael Otto (lead).

Project Administration: Gerson José Marquesi de Souza Netto (supporting), Lucas Miguel Altarugio (supporting), Rafael Otto (lead) and Sarah Mello Leite Moretti (supporting).

Visualization: Estêvão Vicari Mellis (supporting), Gabriel Pinheiro Silva (lead) and Johnny Rodrigues Soares (supporting).

Writing – original draft: Gabriel Pinheiro Silva (lead) and Johnny Rodrigues Soares (supporting).

Writing – review & editing: Estêvão Vicari Mellis (supporting), Gerson José Marquesi de Souza Netto (supporting), Johnny Rodrigues Soares (supporting), Lucas Miguel Altarugio (supporting), Marcelo Grijalva Carneiro Barros (supporting), Rafael Otto (lead) and Sarah Mello Leite Moretti (supporting).

REFERENCES

Albuquerque AW, Sá LA, Rodrigues WAR, Moura AB, Oliveira Filho MS. Growth and yield of sugarcane as a function of phosphorus doses and forms of application. Rev Bras Eng Agr Amb. 2016;20:29-35. https://doi.org/10.1590/1807-1929/agriambi.v20n1p29-35

Allen BL, Mallarino AP, Klatt JG, Baker JL, Camara M. Soil and surface runoff phosphorus relationships for five typical USA Midwest soils. J Environ Qual. 2006;35:599-610. https://doi.org/10.2134/JEQ2005.0135

Alvares CA, Stape JL, Sentelhas PC, Gonçalves JLM, Sparovek G. Köppen's climate classification map for Brazil. Meteorol Z. 2013;22:711-28. https://doi.org/10.1127/0941-2948/2013/0507

Barrow NJ. Soil phosphate chemistry and the P-sparing effect of previous phosphate applications. Plant Soil. 2015;397:401-9. https://doi.org/10.1007/s11104-015-2514-5

de Boer MA, Wolzak L, Slootweg JC. Phosphorus: Reserves, production, and applications. In: Ohtake H, Tsuneda S, editors. Phosphorus recovery and recycling. Singapore: Springer; 2018. p. 75-100. https://doi.org/10.1007/978-981-10-8031-9_5

Bordonal RO, Carvalho JLN, Lal R, Figueiredo EB, Oliveira BG, La Scala N. Sustainability of sugarcane production in Brazil. A review. Agron Sustain Dev. 2018;38:13. https://doi.org/10.1007/S13593-018-0490-X

Caione G, Teixeira MTR, Lange A, Silva AF, Fernandes FM. Modos de aplicação e doses de fósforo em cana-de-açúcar forrageira cultivada em Latossolo Vermelho-Amarelo. Rev Cienc Agroamb. 2011;9:1-11.

Camargo LA, Marques Júnior J, Pereira GT. Mineralogy of the clay fraction of Alfisols in two slope curvatures: III - Spatial variability. Rev Bras Cienc Solo. 2013;37:295-306. https://doi.org/10.1590/S0100-06832013000200001

Campos M, Antonangelo JA, Alleoni LRF. Phosphorus sorption index in humid tropical soils. Soil Till Res. 2016;156:110-8. https://doi.org/10.1016/j.still.2015.09.020

Cantarella H, Quaggio JA, Mattos Jr D, Boaretto RM, van Raij B. Recomendações de adubação e calagem para o Estado de São Paulo. Campinas, SP: Instituto Agronômico de Campinas (IAC); 2022. (Boletim 100).

Coelho MJ, Diaz DR, Hettiarachchi GM, Hansel FD, Pavinato PS. Soil phosphorus fractions and legacy in a corn-soybean rotation on Mollisols in Kansas, USA. Geoderma R. 2019;18:e00228. https://doi.org/10.1016/j.geodrs.2019.e00228

Companhia Nacional de Abastecimento - Conab. Acompanhamento da safra brasileira de cana-de-açúcar. Brasília, DF: Conab; 2023.

Cordell D, White S. Life's bottleneck: sustaining the world's phosphorus for a food secure future. Annu Rev Environ Resour. 2014;39:161-88. https://doi.org/10.1146/annurev-environ-010213-113300

Estrada-Bonilla GA, Durrer A, Cardoso EJBN. Use of compost and phosphate-solubilizing bacteria affect sugarcane mineral nutrition, phosphorus availability, and the soil bacterial community. Appl Soil Ecol. 2021;157:103760. https://doi.org/10.1016/j.apsoil.2020.103760

Food and Agriculture Organization of the United Nations - Faostat. Faostat [internet]. Rome: FAO; 2021 [cited 2024 May 22]. Available from: https://www.fao.org/faostat/en/#home.

Fernandes AC. Cálculos na agroindústria da cana de açúcar. 3. ed. Piracicaba, SP: Stab; 2011.

Ferreira EB, Cavalcanti PP, Alves ND. Package "ExpDes.pt." [internet]; 2021. Available from: https://cran.r-project.org/web/packages/ExpDes.pt/index.html

Freiling M, von Tucher S, Schmidhalter U. Factors influencing phosphorus placement and effects on yield and yield parameters: A meta-analysis. Soil Till Res. 2022;216:105257. https://doi.org/10.1016/j.still.2021.105257

Gama AJM. Sistema de rotação e adubação fosfatada na cultura da cana-de-açúcar no cerrado [thesis]. Uberlândia: Universidade Federal de Uberlândia; 2007.

Gao W, Blaser SRGA, Schlüter S, Shen J, Vetterlein D. Effect of localised phosphorus application on root growth and soil nutrient dynamics in situ – comparison of maize (*Zea mays*) and faba bean (*Vicia faba*) at the seedling stage. Plant Soil. 2019;441:469-83. https://doi.org/10.1007/s11104-019-04138-2

Gee GW, Bauder JW. Particle-size analysis. In: Klute A, editor. Methods of soil analysis: Part 1 Physical and mineralogical methods. 2nd ed. Madison: American Society of Agronomy, Inc. Soil Science Society of America; 1986. p. 383-411. https://doi.org/10.2136/sssabookser5.1.2ed.c15

Heinrichs R, Otto R, Magalhães A, Meirelles GC. Importance of sugarcane in Brazilian and world bioeconomy. In: Dabbert S, Lewandowski I, Weiss J, Pyka A, editors. Knowledge-driven developments in the bioeconomy. Economic complexity and evolution. Cham: Springer; 2017. p. 205-17. https://doi.org/10.1007/978-3-319-58374-7_11

Li Z, Wu S, Liu Y, Yi Q, Hall M, Saha N, Wang J, Huang Y, Huang L. Arbuscular mycorrhizal fungi regulate plant mineral nutrient uptake and partitioning in iron ore tailings undergoing eco-engineered pedogenesis. Pedosphere. 2024;34:385-98. https://doi.org/10.1016/J.PEDSPH.2023.04.004

Liu J, Sui P, Cade-Menun BJ, Hu Y, Yang J, Huang S, Ma Y. Molecular-level understanding of phosphorus transformation with long-term phosphorus addition and depletion in an alkaline soil. Geoderma. 2019;353:116-24. https://doi.org/10.1016/j.geoderma.2019.06.024

Lopes CM, Silva AMM, Estrada-Bonilla GA, Ferraz-Almeida R, Vieira JLV, Otto R, Vitti GC, Cardoso EJBN. Improving the fertilizer value of sugarcane wastes through phosphate rock amendment and phosphate-solubilizing bacteria inoculation. J Clean Prod. 2021;298:126821. https://doi.org/10.1016/j.jclepro.2021.126821

Lu D, Song H, Jiang S, Chen X, Wang H, Zhou J. Integrated phosphorus placement and form for improving wheat grain yield. Agron J. 2019;111:1998-2004. https://doi.org/10.2134/agronj2018.09.0559

Menezes-Blackburn D, Giles C, Darch T, George TS, Blackwell M, Stutter M, Shand C, Lumsdon D, Cooper P, Wendler R, Brown L, Almeida DS, Wearing C, Zhang H, Haygarth PM. Opportunities for mobilizing recalcitrant phosphorus from agricultural soils: A review. Plant Soil. 2018;427:5-16. https://doi.org/10.1007/s11104-017-3362-2

Oliveira LEZ, Sousa DMG, Figueiredo CC, Nunes RS, Malaquias JV. Long-term phosphate fertilization strategies evaluation in a Brazilian Oxisol. Agron J. 2020;112:4303-20. https://doi.org/10.1002/agj2.20324

Pavinato PS, Cherubin MR, Soltangheisi A, Rocha GC, Chadwick DR, Jones DL. Revealing soil legacy phosphorus to promote sustainable agriculture in Brazil. Sci Rep. 2020;10:15615. https://doi.org/10.1038/s41598-020-72302-1

Penn C, Camberato J. A critical review on soil chemical processes that control how soil pH affects phosphorus availability to plants. Agriculture. 2019;9:120. https://doi.org/10.3390/agriculture9060120

R Development Core Team. R: A language and environment for statistical computing. Vienna, Austria: R Foundation for Statistical Computing; 2022. Available from: http://www.R-project.org/.

Rein TA, Santos Junior JDG, Sousa DMG, Carvalho WP, Lemes GC. Corrective and maintenance phosphorus fertilization on sugarcane yield in Oxisols. Pesq Agropec Bras. 2021;56:e02160. https://doi.org/10.1590/s1678-3921.pab2021.v56.02160

Rein TA, Sousa DMG. Sugarcane response to phosphorus sources and placement in a very clayey Oxisol of the Brazilian Cerrado. Proc Int Soc Sugar Cane Technol. 2013;28:477-82.

Rein TA, Souza DMG, Santos Júnior JDG, Nunes RS, Korndörfer GH. Manejo da adubação fosfatada para cana-de-açúcar no Cerrado. Planaltina, DF: Embrapa Cerrados; 2015. (Circular técnica, 29).

Reis EL, Cabala-Rosand P. Respostas da cana-de-açúcar ao nitrogênio, fósforo e potássio em solo de tabuleiro do sul da Bahia. Rev Bras Cienc Solo. 1986;10:129-34.

Santos VR, Soltangheisi A, Franco HJ, Kolln O, Vitti A, Dias CS, Pavinato P. Phosphate sources and their placement affecting soil phosphorus pools in sugarcane. Agronomy. 2018;8:283. https://doi.org/10.3390/agronomy8120283

Saied HSH, Aboelenin SM, Kesba H, El-Sherbieny AEA, Helmy AM, Dahdouh SM, Soliman MM. Chemical evaluation of partially acidulated phosphate rocks and their impact on dry matter yield and phosphorus uptake of maize. Saudi J Biol Sci. 2022;29:3511-8. https://doi.org/10.1016/J.SJBS.2022.02.022

Schröder JJ, Smit AL, Cordell D, Rosemarin A. Improved phosphorus use efficiency in agriculture: A key requirement for its sustainable use. Chemosphere. 2011;84:822-31. https://doi.org/10.1016/j.chemosphere.2011.01.065

Silva AMS, Oliveira ECA, Willadino LG, Freire FJ, Rocha AT. Corrective phosphate application as a practice for reducing oxidative stress and increasing productivity in sugarcane. Rev Cienc Agron. 2019;50:188-95. https://doi.org/10.5935/1806-6690.20190022

Silva AMM, Estrada-Bonilla GA, Lopes CM, Matteoli FP, Cotta SR, Feiler HP, Rodrigues YF, Cardoso EJBN. Does organomineral fertilizer combined with phosphate-solubilizing bacteria in sugarcane modulate soil microbial community and functions? Microb Ecol. 2022;84:539-55. https://doi.org/10.1007/s00248-021-01855-z

Soil Survey Staff. Keys to soil taxonomy. 13th ed. Washington, DC: United States Department of Agriculture, Natural Resources Conservation Service; 2022.

Sousa DMG, Lobato E. Cerrado: Correção do solo e adubação. 2. ed. Brasília, DF: Embrapa Informação Tecnológica; 2004.

Sousa RTX, Korndörfer GH, Soares RAB, Fontoura PR. Phosphate fertilizers for sugarcane used at pre-planting (phosphorus fertilizer application). J Plant Nutr. 2015;38:1444-55. https://doi.org/10.1080/01904167.2014.990567

Sousa RTX, Korndorfer GH. Efeito da aplicação de fertilizantes fosfatados na produtividade e variáveis tecnológicas da cana-de-açúcar. Encicl Bioesfera. 2011;7:1-10.

Tarumoto MB, Campos M, Momesso L, Nascimento CAC, Garcia A, Coscolin RBS, Martello JM, Crusciol CAC. Carbohydrate partitioning and antioxidant substances synthesis clarify the differences between sugarcane varieties on facing low phosphorus availability. Front Plant Sci. 2022;13:888432. https://doi.org/10.3389/fpls.2022.888432

Tomaz HVQ. Fontes, doses e formas de aplicação de fósforo na cana-de-açúcar [dissertation]. Piracicaba: Universidade de São Paulo - Escola Superior de Agricultura “Luiz de Queiroz”; 2009. https://doi.org/10.11606/D.11.2010.tde-24022010-093150

van Raij B, Andrade JC, Cantarella H, Quaggio JA. Análise química para avaliação da fertilidade de solos tropicais. Campinas: Instituto Agronômico; 2001.

Wickham H. Data analysis. In: ggplot2. Use R!. Cham: Springer; 2016. https://doi.org/10.1007/978-3-319-24277-4_9

Zambrosi FCB. Phosphorus fertilizer reapplication on sugarcane ratoon: Opportunities and challenges for improvements in nutrient efficiency. Sugar Tech 2021;23:704–708. https://doi.org/10.1007/s12355-020-00925-9

Zambrosi FCB, Ribeiro RV, Machado EC, Garcia JC. Phosphorus deficiency impairs shoot regrowth of sugarcane varieties. Exp Agric. 2017;53:1-11. https://doi.org/10.1017/S0014479715000290

Zhao Y, Li R, Huang Y, Sun X, Qin W, Wei F, Ye Y. Effects of various phosphorus fertilizers on maize yield and phosphorus uptake in soils with different pH values. Arch Agron Soil Sci. 2022;68:1746-54. https://doi.org/10.1080/03650340.2021.1926997

SUPPLEMENTARY MATERIAL

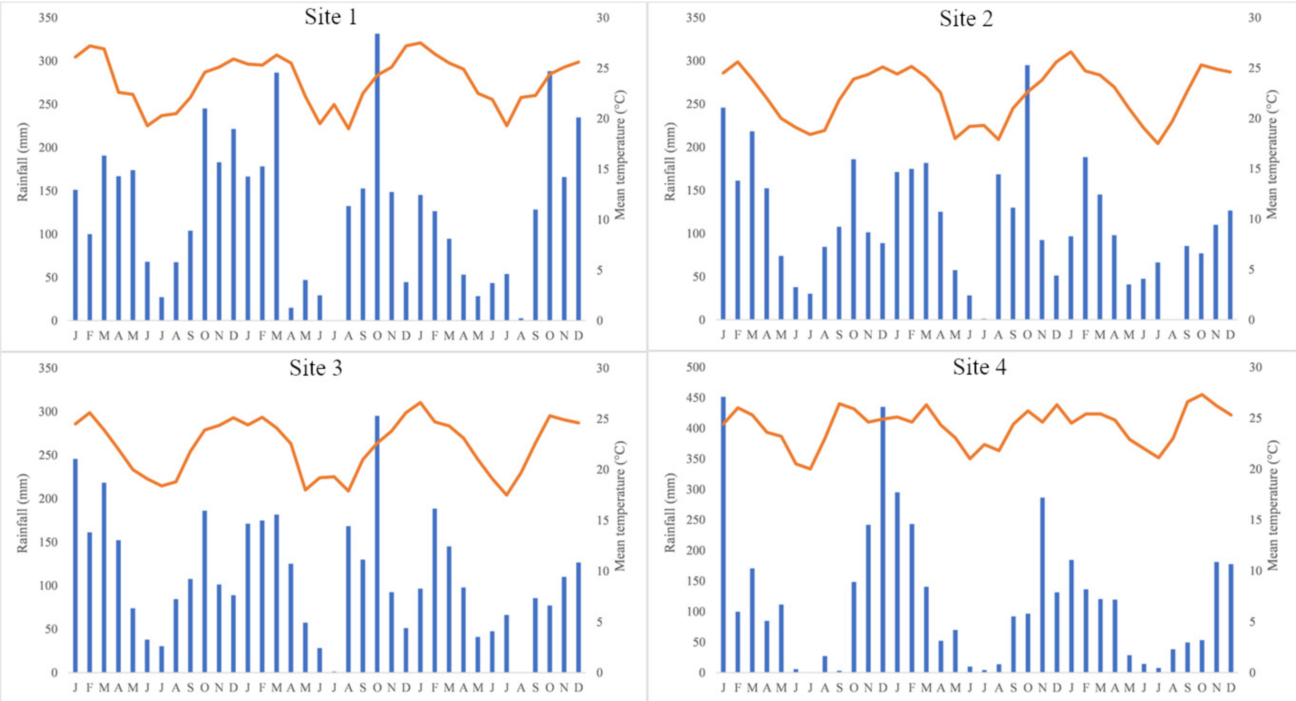

Figure S1- Average rainfall (bars) and temperature (lines) at each site (January/2017 – December/2019).

Table S1. Description of each experimental site in south-central Brazil during the experimental set up.

Sites	Location	Geographic coordinates	Altitude (m)	Soil classification[(a)]	Climate [(b)]	Sugarcane Variety	Application ($Mg\ ha^{-1}$)			History of crop rotation
							Lime	Gypsum	Filter cake	
1	Ivinhema/MS	22°30’10” S 53°49’21” W	343 m	Rhodic Hapludox	Aw	CTC 4	1.5	1.0	-	-
2	São Pedro do Turvo/SP	22°50’23” S 49°47’12” W	520 m	Rhodic Hapludox	Cfa	CTC 4	3.0	1.5	-	-
3	Chavantes/ SP	23°03’54” S 49°45’09” W	485 m	Rhodic Hapludox	Cfa	CTC 4	5.5	1.0	-	-
4	Suzanápolis/ SP	20°21’20” S 51°4’43” W	371 m	Rhodic Kandiudox	Aw	RB92579	2.0	1.0	-	-

[(a)] According to USDA-Soil Taxonomy (Soil Survey Staff, 2022); [(b)] According to Köppen’s climate classification: Aw – tropical climate with dry winter; Cfa – humid subtropical climate with hot summer without dry season (Alvares et al., 2013)

Table S2. Soil granulometric and chemical characterization at each experiment site before the trials set up.

Site/Location	Soil depth	pH	P	S	K	Ca	Mg	Al	H+Al	CEC	BS	Al	Sand	Silt	Clay
	(cm)		mg dm^{-3}		mmol$_c$ dm^{-3}							%	g kg^{-1}		
1 – Ivinhema/MS	0-25	4.8	5.0	7.0	7.0	10.0	7.0	0.0	34.0	52.3	35	0	724	23	253
	25-50	4.5	3.0	5.0	5.0	5.0	4.0	2.0	42.0	51.6	19	17	676	21	303
	50-75	4.5	3.2	6.0	6.0	4.0	2.0	3.0	38.0	44.5	15	32	693	20	287
	75-100	4.5	7.0	6.0	6.0	2.0	2.0	4.0	38.0	42.4	10	48	662	22	316
2 – São Pedro do Turvo/SP	0-25	5.1	6.0	34.0	0.7	24.0	3.0	2.0	20.0	47.7	58	3	802	24	175
	25-50	4.6	8.0	12.0	0.6	11.0	1.2	2.0	28.0	40.6	31	14	779	20	201
	50-75	4.2	8.0	9.0	0.6	8.0	0.7	5.0	34.0	43.6	22	34	760	26	214
	75-100	4.2	6.0	11.0	0.4	7.0	0.7	4.0	34.0	42.4	20	32	747	16	237
3 – Chavantes/SP	0-25	4.6	7.0	12.0	1.9	18.0	9.0	1.2	38.0	66.9	43	3	143	179	677
	25-50	4.7	5.0	23.0	1.1	14.0	6.0	0.9	42.0	63.1	33	5	128	156	716
	50-75	4.6	4.0	52.0	0.6	13.0	4.0	2.0	34.0	51.6	34	10	134	141	725
	75-100	4.6	4.0	68.0	0.6	13.0	3.0	2.0	38.0	54.6	30	11	132	150	719
4 – Suzanápolis/SP	0-25	6.5	13.0	6.0	2.1	14.0	9.0	0.0	11.0	36.1	70	0	803	21	176
	25-50	5.8	4.0	4.0	1.6	8.0	5.0	0.0	20.0	34.6	42	0	770	29	201
	50-75	5.4	3.0	9.0	0.7	12.0	7.0	0.6	18.0	37.7	52	5	696	27	277
	75-100	5.1	4.0	6.0	0.7	15.0	8.0	1.0	22.0	45.7	52	4	710	14	276

Contents of P, K, Ca, and Mg were extracted using an ion exchange resin method ($NaHCO_3$, 1 mol L^{-1} at pH 8.5). S (Calcium phosphate 0.01 mol L^{-1}); pH in $CaCl_2$ (solution 0.01 mol L^{-1}). Soil chemical analysis was performed according to Raij et al. (2001), and soil particle size by Gee and Bauder (1986)

Table S3. Influence of corrective phosphate (CP) and P fertilizer rates (monoammonium phosphate - MAP) on sugarcane production parameters in the cane plant, first and second ratoon cycles at each site

Sites	MAP Rates of P_2O_5	Corrective Phosphate	Cane Plant			First ratoon			Second ratoon		
			TCH	TAH	ATR	TCH	TAH	ATR	TCH	TAH	ATR
	0		109.6	15.4	140.2	109.4	18.3	167.1	82.2	12.6	153.8
	50		106.1	16.3	153.8	124.2	20.8	167.0	87.2	13.2	151.7
	100	With	106.4	16.0	149.8	126.9	21.6	170.1	83.6	11.9	142.5
	150		105.5	15.6	147.5	128.1	21.6	168.7	84.7	12.3	145.5
	200		109.7	16.6	151.7	130.6	20.6	157.5	91.7	13.5	147.1
	0		104.2	15.2	146.2	110.3	17.0	154.6	81.1	12.3	151.2
Site 1	50		109.2	15.8	144.5	109.7	18.5	168.4	85.0	12.8	150.4
	100	Without	108.1	17.0	157.5	119.4	19.1	160.0	94.2	14.0	148.5
	150		107.8	15.6	144.2	108.1	18.0	166.6	91.5	14.2	155.3
	200		111.4	16.4	147.3	110.0	18.6	169.2	92.8	13.5	145.2
	p-value (Corrective P - CP)		0.74	0.88	0.74	<0.01	**<0.01**	0.14	0.06	0.04	0.38
	p-value (Rates of P_2O_5-MAP)		0.72	0.11	0.02	<0.01	**<0.01**	0.04	<0.01	0.25	0.21
	p-value (CPxMAP)		0.65	0.65	**0.04**	**0.02**	**0.51**	**<0.01**	**0.06**	**0.01**	0.32
	CV (%)		5.8	6.8	4.1	5.9	6.9	2.9	5.6	7.1	4.8
	0		111.4	15.2	136.6	69.1	9.5	136.7	68.0	11.2	164.4
	50		110.3	13.5	122.6	56.9	7.8	136.8	74.7	12.4	166.2
	100	With	110.7	14.5	130.6	65.2	8.9	135.8	68.2	11.4	167.3
	150		108.0	14.4	133.7	73.1	10.1	138.2	61.3	10.3	167.4
	200		113.5	14.4	127.2	69.7	9.6	138.5	64.7	10.9	168.8
	0		106.7	14.2	133.3	58.9	8.0	136.2	64.9	10.4	159.6
Site 2	50		109.1	14.5	129.4	68.1	9.3	136.9	60.9	9.8	160.3
	100	Without	106.4	13.6	127.8	65.4	9.3	141.1	59.7	9.8	164.2
	150		109.7	13.8	126.2	80.5	11.1	136.5	68.2	10.8	158.3
	200		110.1	13.9	126.1	77.4	10.6	137.1	73.5	11.6	157.4
	p-value (Corrective P - CP)		0.20	0.19	0.34	0.27	0.27	0.58	0.23	0.01	**<0.01**
	p-value (Rates of P_2O_5-MAP)		0.80	0.60	**0.01**	**0.01**	**0.02**	0.97	0.24	0.52	0.53
	p-value (CPxMAP)		0.80	0.32	0.12	0.17	0.25	0.79	**<0.01**	**<0.01**	0.36
	CV (%)		5.4	7.1	4.1	13.5	14.5	4.6	7.6	9.1	2.7
	0		125.7	16.6	131.9	109.2	18.1	165.9	104.3	17.0	162.4
	50		124.8	16.2	129.6	106.0	17.5	164.9	103.8	16.5	159.1
	100	With	129.4	17.4	134.3	106.1	17.4	164.1	102.3	16.2	158.6
	150		121.5	16.2	133.3	97.9	15.9	162.0	105.0	16.7	159.8
	200		128.5	17.1	133.4	102.4	16.8	163.3	103.8	15.9	160.7
	0		118.0	15.2	129.2	108.3	18.2	167.7	106.7	17.9	160.8
Site 3	50		121.2	16.4	135.3	106.8	17.6	164.7	95.3	15.3	161.4
	100	Without	116.7	15.6	134.0	110.7	17.8	164.1	94.5	14.9	157.8
	150		122.1	15.7	128.2	109.7	18.2	166.2	92.8	15.2	163.7
	200		124.6	16.2	129.8	109.6	18.2	166.1	102.8	16.3	158.6
	p-value (Corrective P - CP)		<0.01	**<0.01**	0.50	**0.08**	**0.03**	0.16	**0.09**	0.27	0.76
	p-value (Rates of P_2O_5-MAP)		0.28	0.27	0.72	0.76	0.57	0.59	0.55	0.20	0.26
	p-value (CPxMAP)		**0.09**	0.17	0.38	0.56	0.33	0.73	0.59	0.44	0.37
	CV (%)		3.9	5.0	4.4	7.7	7.3	2.3	9.9	9.7	2.2

Site 4	0	With	78.9	11.3	143.1	108.4	-	-	84.0	12.3	146.8
	50		92.0	13.0	141.3	114.7	-	-	86.0	13.0	151.8
	100		99.1	14.2	142.9	112.9	-	-	77.3	11.9	154.0
	150		93.2	13.7	147.3	108.2	-	-	87.3	13.6	156.0
	200		88.7	12.8	144.2	112.2	-	-	79.3	13.2	165.8
	0	Without	83.2	11.8	142.0	105.8	-	-	58.0	8.8	151.8
	50		89.2	12.4	139.2	117.3	-	-	78.0	12.6	162.3
	100		91.4	13.3	145.3	114.0	-	-	76.8	12.2	158.0
	150		88.5	13.0	147.3	110.5	-	-	74.0	11.0	147.8
	200		85.1	12.0	141.2	110.3	-	-	77.3	12.1	157.3
	p-value (Corrective P - CP)		0.15	0.13	0.52	0.87	-	-	**<0.01**	**0.01**	0.79
	p-value (Rates of P2O5 -MAP)		**<0.01**	**<0.01**	**0.01**	**0.08**	-	-	0.34	0.11	<0.01
	p-value (CPxMAP)		0.43	0.63	0.66	0.88	-	-	0.17	0.20	**0.02**
	CV (%)		7.1	7.8	2.6	5.8	-	-	14.4	14.8	4.2

Contents of P, K, Ca, and Mg were extracted using an ion exchange resin method ($NaHCO_3$, 1 mol L^{-1} at pH 8.5). S (Calcium phosphate 0.01 mol L^{-1}); pH in CaCl2 (solution 0.01 mol L^{-1}). Soil chemical analysis was performed according to Raij et al. (2001), and soil particle size by Gee and Bauder (1986)