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Tropical soybean yield response to reduced or zero phosphorus fertilization depends on soils

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Abstract

Oxisol soils with high P sorption capacity are widespread in Brazil, which is the world's second largest producer of soybean [*Glycine max* (L.) Merr.]. To counter low P availability within highly weathered soils, Brazilian soybean producers commonly fertilize with approximately twice as much P as is harvested in soybean. This has led to the accumulation of P in the soil, especially during the 2000s and 2010s, but the degree to which producers can capitalize on this residual soil P stock to offset fertilizer inputs remains unclear. We tested the effect of residual soil P in a field trial in Mato Grosso, Brazil on a field that has been fertilized for a decade. We grew soybean under three P treatments: 0, 50, and 100% of the farm's standard P fertilization rate for soybean (38 kg P ha^{-1} yr^{-1}). This experiment was conducted for one growing season on two sites within the same farm field that had different soil texture, $Al_2O_3 + Fe_2O_3$ (R_2O_3), soil test P, and degree of P saturation. Soybean yield on the soil with greater clay content and R_2O_3 showed yield declines under reduced P input but yields on sandier soils that had higher soil test P were unaffected by reduced P inputs. These results highlight opportunities to enhance P fertilizer use efficiency in intensive tropical agriculture on highly weathered soils by using site-specific soil fertility management to harness residual soil P.

Abbreviations: AIC, Akaike information criterion; DPS, degree of phosphorus saturation; OM, organic matter; PC, soil principal component; PCA, principal components analysis; P_{out}, phosphorus in harvested soybean grain; PSI, phosphate sorption index; R_2O_3, sesquioxides of Al and Fe; S_{rem}, remaining P sorption capacity; STP, soil test phosphorus; VIF, variance inflation factors.

1 | INTRODUCTION

Core Ideas

- A decade of fertilizer input increased soil test P and P saturation in 0-to-20-cm soils.
- Soybean grown on two sites with different soil texture, R_2O_3, soil test P, and P saturation.
- Soybean yield declined with reduced P fertilizer at clayey site but not at sandier site.
- Soil-specific fertilizer management could increase P use efficiency and reduce costs.

Phosphorus (P) is an essential element for life on Earth and commonly limits plant growth across terrestrial ecosystems (Hou et al., 2020). In many regions, producers have overcome soil P limitation of crop yields using inputs of mineral P fertilizers mined from finite phosphate rock resources (Cordell, Drangert, & White, 2009). These P inputs are often in surplus of the P contained in harvested crops, leading to residual P, sometimes referred to as "legacy P," remaining in the soil (Rowe et al., 2016). Harnessing residual soil P that has accumulated over time to support crop yields could greatly reduce the amount of P fertilizer use needed to support the global food system in the future and thereby conserve vital non-renewable P resources (Sattari, Bouwman, Giller, & van Ittersum, 2012). Evidence from some temperate regions indicates that P fertilization rates can be substantially reduced without compromising yields by capitalizing on existing residual soil P stocks (Sattari et al., 2012). Whether this same opportunity exists for agricultural hotspots in the tropics characterized by P-fixing soils (Oxisols and Ultisols) remains unclear (Roy et al., 2016). These highly weathered tropical soils are characterized by a high capacity to sorb P, decreasing the availability of P inputs to crops (Sousa & Lobato, 2003).

Brazil was the second largest soybean [*Glycine max* (L.) Merr.] producer and third largest consumer of P fertilizer in the world in 2017 (FAOSTAT, 2020). Soybean plants in Brazil are commonly grown on high P-fixing soils that receive high P fertilizer inputs (Riskin, Porder, Schipanski, Bennett, & Neill, 2013a; Roy et al., 2016). For example, previous research in the Brazilian state of Mato Grosso has shown that P fertilizer inputs for soybean production (mean $\pm$ 1 SD = 43 $\pm$ 4 kg P ha^{-1} yr^{-1}) are approximately double P outputs in soybean harvests (21 $\pm$ 2 kg P ha^{-1} yr^{-1}) (Roy et al., 2017). As a result, the stock of residual soil P in Brazil is growing at farm, state, and national levels (Roy et al., 2017; Withers et al., 2018). A majority of this P is associated with Al- and Fe-oxides in the top 20 cm of soil (Riskin et al., 2013b; Rodrigues, Pavinato, Withers, Teles, & Herrera, 2016), and some may potentially become available to crops (Rodrigues et al., 2016; Roy et al., 2017; Withers et al., 2018). A recent chronosequence study in Mato Grosso showed that soil P sorption capacity declines slowly with years of intensive P fertilization, but in some cases remains relatively high even after three decades of fertilization (Roy et al., 2017).

If residual soil P can support crop production, even on highly weathered, high P-fixing soils, this could reduce the need for fertilizers derived from finite phosphate rock resources while creating substantial operating cost savings for producers (Meade et al., 2016). Soil P measurements, such as soil test P (STP) (e.g., Mehlich-1 P or Bray-1 P) or labile P (e.g., P extracted by $NaHCO_3$), are commonly used to approximate plant-available P in cropland soils to inform P management (Frank, Beegle, & Denning, 1998; Hedley, Stewart, & Chauhan, 1982). Sousa and Rein (2011) recommend that P fertilization can be reduced by 50% in Brazilian Oxisols when Mehlich-1 P exceeds a critical level corresponding to the soil's clay content; however published field research that tests this recommendation remains scarce. The rate of increase in STP caused by surplus fertilization of soybean fields can be much slower in high P-fixing soils common to Brazil compared with soils elsewhere with more inherent P fertility (Roy et al., 2017). The extent and plant-availability of accumulated residual soil P in the high P-fixing soils of Mato Grosso after 10+ yr of surplus P fertilization is not well documented.

In this study, we tested whether residual soil P, accumulated through a decade of management during which P inputs were approximately double outputs, can support soybean yields on highly weathered soils. Specifically we asked:

1. Does reduced or zero P fertilization affect soybean yield during a 1-yr trial?
2. Do soil characteristics influence the effect of treatment on yield response?
3. How do changes in P inputs and yields affect P mass balance per hectare?

2 | MATERIALS AND METHODS

2.1 | Study area

The study took place during the 2018–2019 harvest season at Tanguro Ranch, an 86,000-ha property in eastern Mato

Grosso, of which about 36,000 ha are cultivated. Mean annual precipitation at Tanguro Ranch is 1,800 mm, the majority of which falls during the wet season (November–April). Soybean plants are planted in early November and harvested in February–March. More than half of the farm is currently double cropped, with soybean followed by corn (*Zea mays* L.) in the same growing season. For double-cropped fields, corn is directly seeded using no-till methods immediately after soybean harvest. The former vegetation at Tanguro Ranch is evergreen tropical forest typical of the forest near the boundary with the Cerrado (Ivanauskas, Monteiro, & Rodrigues, 2004).

Two experimental sites were located on opposite ends of a single 2-km^2 field that had received uniform crop and fertilizer management. The field was first deforested and converted to pasture in 1990, planted with soybean in 2009, and has been double-cropped with soybean and corn since 2015. Site A (center plot = 13°1′54.38“ S, 52°22′2.74″ W) was located upland on a plateau interfluve, whereas Site B (center plot = 13°1′0.76″ S, 52°21′50.87″ W) was located near a riparian zone.

2.2 | Experimental design

Both experimental sites were arranged in a randomized block design with five replications for each of the three P treatments: 0, 50, and 100% of historical annual P fertilizer (N–P–K, 0–27–9) for soybean, which was 87 kg P_2O_5 ha^{-1} yr^{-1}, or 38 kg P ha^{-1} yr^{-1}. In the experimental plots, mineral P fertilizer was broadcast across each 10 by 12 m area (n = 30) by hand within 2 d of planting. For all treatments, solid KCl was broadcast to approximate standard K management on the farm (25 kg K ha^{-1} yr^{-1}). All other management practices prior to harvest (liming, tillage, planting, pesticide application, and desiccation) were consistent with the farm's typical management schedule. Fields were planted in November and harvested in March.

2.3 | Soil sampling

Soil was sampled prior to planting and fertilization at depths of 0–10, 10–20, and 20–30 cm from the surface. Samples were collected from three random locations across each plot and then composited (i.e., one composite sample per soil layer per plot). Bulk density for each layer was measured by collecting volumetric rings from two small pits located randomly within the bounds of each experimental site.

2.4 | Soil analysis

All soil samples (n = 90) were analyzed for texture (sand, silt, clay), pH, organic matter (OM), cation exchange capacity, total exchangeable bases, potential acidity (H + Al), base saturation, aluminum saturation, and Mehlich-1 P and K in the soil analytical laboratory of the Escola Superior de Agricultura "Luiz de Queiroz" (ESALQ) at the University of São Paulo in Brazil. Subsamples from the 0-to-10-cm and 10-to-20-cm layers were composited for each plot (n = 30) and analyzed for total P, Al_2O_3, Fe_2O_3, and SiO_2 by lithium borate flux fusion digestion and X-ray fluorescence at ALS Chemex (Reno, NV).

Extractions for Bray-1 P (Frank et al., 1998), oxalate-extractable P, Fe, and Al (McKeague & Day 1966), and phosphate sorption index (PSI) (Bache & Williams, 1971) were conducted at Brown University for all soil samples (n = 90). Bray-1 P was extracted with a solution comprised of 0.03 M NH_4F and 0.025 M HCl that was shaken with air-dry soil (sieved to 0.25 mm) for 5 min at a soil/solution ratio of 1:10, centrifuged for 10 min (4,460 × g), filtered (0.45 μm), and P was measured in the extract by colorimetric analysis (D'Angelo, Crutchfield, & Vandiviere, 2001). Oxalate extractions were performed using 15 ml of a solution of ammonium oxalate (0.2 M) and oxalic acid (0.2 M) adjusted to pH 3 and shaken with 0.25 g of ground (< 0.15 mm) air-dried soil for 4 h in the dark followed by centrifugation for 10 min (4,460 × g) and filtering of the supernatant (0.45 μm). Phosphorus, Al, and Fe were measured in extracts using inductively coupled plasma atomic emission spectroscopy and oxalate-extractable P, Al, and Fe (i.e., P_{ox}, Al_{ox}, Fe_{ox}, mmol kg^{-1} soil) were calculated. Degree of phosphorus saturation (DPS) was then calculated as suggested by Schoumans (2009), such that:

$$\mathrm{DPS}\ \ (\%) = \frac{\mathrm{P_{ox}}}{0.5\ (\mathrm{Fe_{ox}} + \mathrm{Al_{ox}})} \times 100$$

To calculate PSI (L kg^{-1} soil), an incubation was conducted for each sample including 1 g of air-dried soil (sieved to 0.25 mm) shaken with 20 ml of a solution containing 75 mg P L^{-1} (0.01 M $CaCl_2$ solution mixed with KH_2PO_4) for 24 h (Roy et al., 2017). The soil solution was then centrifuged for 10 min (4,460 × g), and the supernatant filtered (0.45 μm) and analyzed for orthophosphate by colorimetric analysis (D'Angelo et al., 2001). Phosphate sorption index was calculated based on incubation results, such that:

$$\mathrm{PSI} = \frac{S}{\log(C_e)}$$

where S is the amount of P sorbed during the incubation experiment (mg P kg^{-1} soil) and C_e equals the concentration of P in the final equilibrium solution (mg P L^{-1}) (Bache & Williams, 1971). Using a model developed from batch isotherm experiment results presented by Roy et al. (2017), remaining P sorption capacity (S_{rem}, mg P kg^{-1} soil) was estimated as:

$$S_{rem} = 1.2682 \times \text{PSI} + 129.72$$

2.5 | Yield measurements and P mass balance

Soybean biomass was harvested by hand and cut approximately 6 cm above the ground to mimic what is removed by the combine. We harvested two randomly selected 0.5 by 5 m lengths within each plot, which were then composited into a single sample for each plot. Samples were air-dried and weighed prior to threshing. After threshing, total grain from each sample was weighed and sub-samples of both the grain and biomass were oven-dried to measure moisture content. Dry masses were calculated based on percent moisture of the grain and plant matter of each sample, and P was measured at ESALQ using standard methods (Malavolta, Vitti, & Oliveira, 1997). Yield performance for each plot was defined as mean dry grain produced per plant, calculated as total dry grain mass in each composite sample divided by the plant count in the harvested areas.

Changes to residual P stocks (kg P ha^{-1}) were calculated based on mass P inputs and P outputs per unit area. Phosphorus lost by leaching or overland flow was assumed to be negligible based on Riskin et al. (2013b) and Neill et al. (2017), and excluded from P outputs. Phosphorus inputs were defined as applied P fertilizer (kg P ha^{-1}), while P outputs (kg P ha^{-1}) were calculated based on harvested soybean grain and measured grain P concentration at each plot, such that:

$$P_{out} = (P_{grain} \times m_{grain}) \times 0.001$$

where P_{grain} represents g P per kg dry grain and m_{grain} represents dry grain mass harvested per area (kg dry grain ha^{-1}) based on the measured grain yield per plant and planting density at each plot. This calculation of P_{out} does not include the P assimilated into non-grain biomass, which is typically left on the field post-harvest.

2.6 | Data analysis

Pre-experiment soil properties for the plow layer (average of measurements for 0-to-10-cm and 10-to-20-cm soil depths) were compared between the two sites ($n = 15$ plots per site) using a two-sample t test or Mann-Whitney U test. Soil P metrics were compared across soil depths (0–10, 10–20, and 20–30 cm) at each site using Kruskal-Wallis rank sum tests with post-hoc Dunn-Bonferroni tests. Principal components analysis (PCA) using prcomp() in R was applied to plow layer soils data to extract uncorrelated variables (i.e., principal components) (Mardia, Kent, & Bibby, 1979; Becker, Chambers, & Wilks, 1988; Venables & Ripley, 2002). Soils data were log $(x + 1)$ transformed and scaled to have unit variance prior to PCA. Principal components were then used as predictors of soybean yield response (g dry grain per plant) in stepwise multiple linear regression (Juhos, Szabó, & Ladányi, 2016). Model selection was based on the stepAIC() function in R, using both backward and forward search modes (Halsey, 2019; Venables & Ripley, 2002). Stepwise multiple linear regression models were also fit to predict yield response (g dry grain per plant) for each site. All statistics were performed in R Studio version 1.2.5001.

3 | RESULTS AND DISCUSSION

3.1 | Soil characteristics and P metrics

Bulk density (g cm^{-3}) at Sites A and B were similar for 0-to-10-cm (A: 1.37, B: 1.34), 10-to-20-cm (A: 1.30, B: 1.33), and 20-to-30-cm (A: 1.35, B: 1.43) soil layers. Soils in the plow layer (0–20 cm) at Site A were characterized by greater clay content and greater bulk R_2O_3 (i.e., Al_2O_3 + Fe_2O_3) content than at Site B (Table 1). Base saturation for plow layer soils across all plots was within or slightly above the optimum range (60–70%) for legumes in Brazilian Oxisols (Fageria & Nascente, 2014), indicating effects of soil management with lime. Site A plow layer soils had lower pH, but soils at both sites were above the recommended minimum levels for tropical Oxisols to reduce Al toxicity (Espinosa, 1996; Sumner & Yamada, 2002; Sousa & Rein, 2011). Mean soil OM and potassium levels were similar for the two sites.

Soil total phosphorus (TP) was 263 ± 17 and 286 ± 25 mg P kg^{-1} for Sites A and B, respectively—in the middle of the range previously reported for Mato Grosso soybean fields (108–487 mg P kg^{-1}; Roy et al., 2017). Site A plow layer soils contained lesser amounts of Mehlich-1 P and Bray-1 P than Site B, and a lesser degree of P saturation as determined by oxalate-extractable P, Fe, and Al (Table 1). Across both sites, plow layer R_2O_3 was negatively correlated with Mehlich-1 P ($r^2 = .75$, $p < .001$), Bray-1 P ($r^2 = .87$, $p < .001$), and degree of P saturation ($r^2 = .73$, $p < .001$). Average (± 1 SD) Mehlich-1 P (8.5 ± 2.3 mg P dm^{-3}) for Site A (54 ± 3% clay) was just below the level where P inputs can

TABLE 1 Mean values (± 1 SD) for soil characteristics in the plow layer (0–20 cm) at Sites A and B ($n = 15$ per site), with significant differences based on two-sample t test or Mann-Whitney U test. For pH, data were converted to $[H^+]$ for statistical analysis and range is provided in parentheses instead of standard deviation

Soil characteristics	Site A	Site B	Significance
Sand, %	42.6 ± 3.3	55.8 ± 3.3	***
Silt, %	3.9 ± 1.6	2.5 ± 0.5	**
Clay, %	53.6 ± 2.9	41.7 ± 3.5	***
pH (H_2O)	6.07	6.23	**
	(5.89–6.30)	(6.02–6.62)	
pH ($CaCl_2$)	5.50	5.86	***
	(5.20–5.85)	(5.62–6.19)	
Organic matter, g dm^{-3}	22.8 ± 2.4	21.5 ± 3.0	
K (Mehlich-1), mg dm^{-3}	78.6 ± 29.2	96.3 ± 30.0	
Ca (1 M KCl), $cmol_c$ dm^{-3}	2.9 ± 0.3	3.5 ± 0.4	***
Mg (1 M KCl), $cmol_c$ dm^{-3}	1.2 ± 0.1	1.7 ± 0.3	***
Al (1 M KCl), $cmol_c$ dm^{-3}	0.11 ± 0.04	0.08 ± 0.05	
Potential acidity, $cmol_c$ dm^{-3}	2.5 ± 0.5	2.1 ± 0.3	
Total exchangeable bases, $cmol_c$ dm^{-3}	4.3 ± 0.5	5.4 ± 0.7	***
CEC, $cmol_c$ dm^{-3}	6.8 ± 0.6	7.6 ± 0.7	**
Base saturation, %	63 ± 6	72 ± 5	***
Al saturation, %	2.4 ± 0.9	1.4 ± 0.9	**
SiO_2, %	59 ± 1	67 ± 1	***
Al_2O_3, %	21 ± 1	18 ± 1	***
Fe_2O_3, %	4.4 ± 0.1	2.2 ± 0.1	***
Total P, mg P kg^{-1}	263 ± 17	286 ± 25	**
Mehlich-1 P, mg P dm^{-3}	8.5 ± 2.3	19.5 ± 4.0	***
Bray-1 P, mg P kg^{-1}	13.0 ± 5.2	44.1 ± 6.5	***
Degree of P saturation, %	3.9 ± 0.8	6.5 ± 0.9	***
Remaining P sorption capacity, mg P kg^{-1}	615 ± 63	597 ± 33	

**$p < .01$.
***$p < .001$.

be halved according to Sousa and Rein (2011) for 46–55% clay soils (critical Mehlich-1 = 9 mg P dm^{-3}). Site B (42 ± 4% clay) average Mehlich-1 P (19.5 ± 4.0 mg P dm^{-3}) was well above the level needed to halve P inputs for 36–45% clay soils (critical Mehlich-1 = 12 mg P dm^{-3}; de Sousa & Rein, 2011). Similarly, Bray-1 P levels in Site A and Site B plow layer soils were below and above, respectively, the level needed to alleviate P limitation for soybean production in Oxisols suggested by Smyth and Sanchez (1982) (critical Bray-1 = 11–15 mg P kg^{-1}). Remaining P sorption capacities at Sites A (615 ± 63 mg P kg^{-1}) and B (597 ± 33 mg P kg^{-1}) were similar and moderate compared with past observations in Mato Grosso soybean fields (306–918 mg P kg^{-1}; Roy et al., 2017). Differences in Mehlich-1 P, Bray-1 P, DPS, and (to a lesser extent) remaining P sorption capacity between soil layers at each site indicated that the effects of past P fertilization were largely confined to the top 20 cm of soil (Figure 1), in agreement with past observations (Riskin et al., 2013b).

Principal components analysis including all variables in Table 1 identified four principal components that together explained 83.9% of the variance in soil parameters. The first one (PC1) explained 51.6% of the variance, with clear separation between sites (PC1 < 0 for Site A, PC1 > 0 for Site B; t test, $p < .001$) (Figure 2). Variables with substantial contributions to PC1 included soil bulk chemistry measures (SiO_2, Fe_2O_3, Al_2O_3), soil texture (sand, clay), and P metrics (Bray-1 P, Mehlich-1 P, DPS). These parameters all either influence, or are a proxy for, soil P availability to growing plants (Roy et al., 2017; Sousa & Lobato, 2003). The second principal component (PC2) explained 16.5% of the variance in soil parameters and had greatest contributions

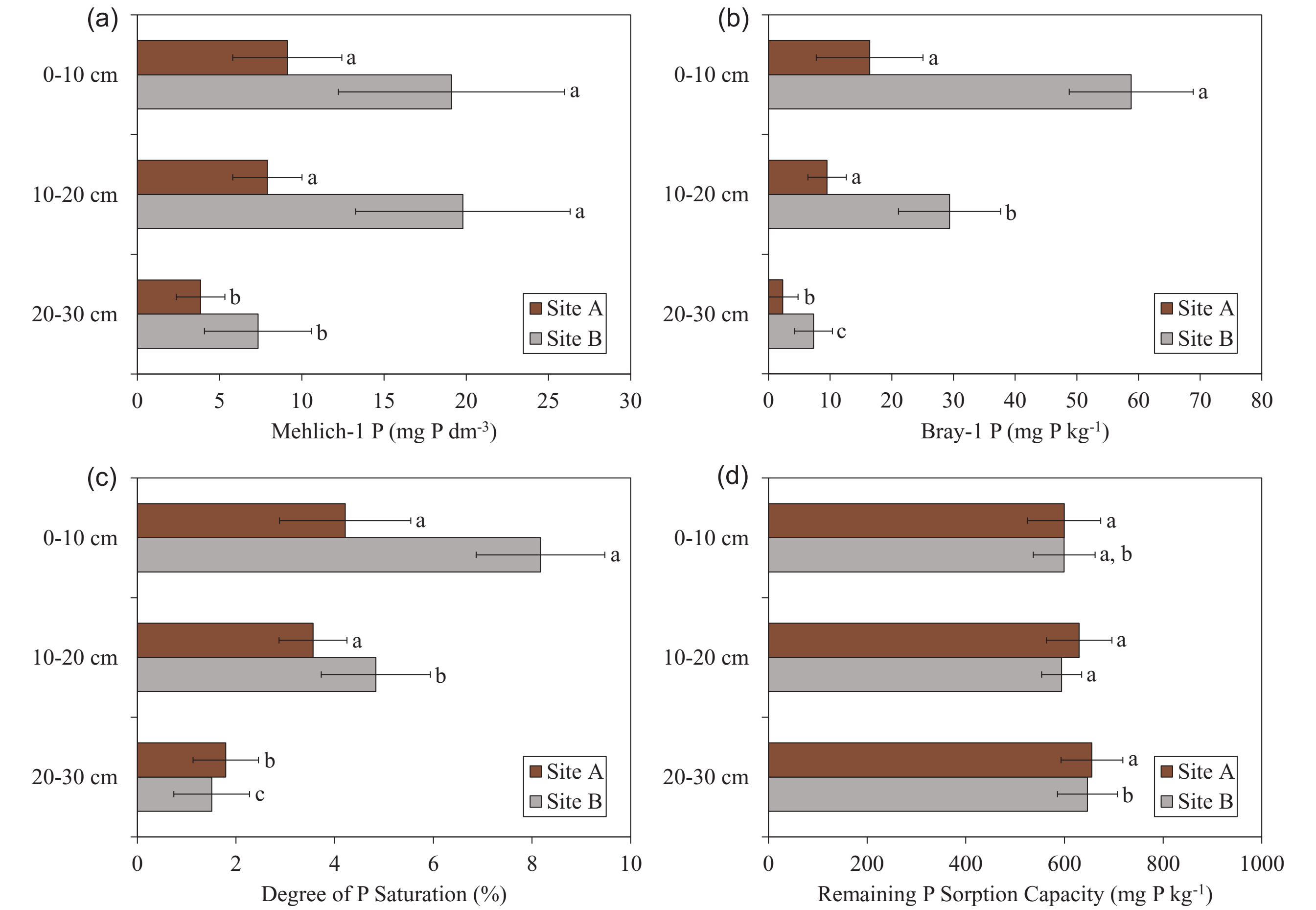

FIGURE 1 Mehlich-1 P (a), Bray-1 P (b), degree of P saturation (c), and remaining P sorption capacity (d) across the 0-to-10-cm, 10-to-20-cm, and 20-to-30-cm soil depths (n = 15 per site-layer combination). Lower case letters denote differences between soil depths at a site (Dunn-Bonferroni, $p < .025$)

(in descending order) from soil OM, exchangeable Al, CEC, potential acidity, Al saturation, and pH. These parameters all relate to soil pH buffering capacity (Teixeira, Alvarez, & Neves, 2020). The third principal component (PC3) (10.4% of variance in soil parameters) and the fourth principal component (PC4) (5.4% of variance in soil parameters) had the greatest contributions from remaining P sorption capacity (S_{rem}) and K, respectively. The PC2, PC3, and PC4 displayed no clear distinction between sites (t tests; $p = .912$, $p = .301$, and $p = .902$, respectively).

3.2 | Soybean yield response

Soybean plant density was measured in the field and was comparable to standard farm plant density (30 plants m^{-2}) based on equipment row and plant spacing for the site with higher clay content (Site A) but was greater and variable for the site with lesser clay content (Site B, 53 ± 8 plants m^{-2}). This difference was attributed to inconsistent planting density near the edge of field where Site B was located.

Soybean yields across the 30 plots ranged from 5.8 to 11.4 g dry grain $plant^{-1}$ (Figure 3). At Site A, which was uniformly characterized by the farm's standard planting density of 30 plants m^{-2}, this corresponds to yields of ∼2.0–3.9 Mg ha^{-1} (with grain mass adjusted to 13% moisture content; Antonangelo, Firmano, Alleoni, Oliveira, & Zhang, 2019). For comparison, mean soybean yield in Brazil in 2018 was 3.4 Mg ha^{-1} (FAOSTAT, 2020). Therefore, the greatest yields observed at Site A (100% P fertilization) were 0.5 Mg ha^{-1} above the 2018 national average, whereas the other treatments at Site A (0–50% P fertilization) resulted in below average soybean production. Greater planting densities at Site B led to greater estimated soybean yield per ha (4.8 ± 1.1 Mg ha^{-1}). Boxplots for Site A showed a noticeable trend of reduced median yield per plant with reduced P application. However, yield performance per plant at Site B appeared unaffected across treatments, suggesting an interaction between treatment and site (Figure 3).

Using data from both sites (n = 30 plots), stepwise multiple regression was initiated with soybean grain yield per plant predicted by fertilizer treatment, planting density,

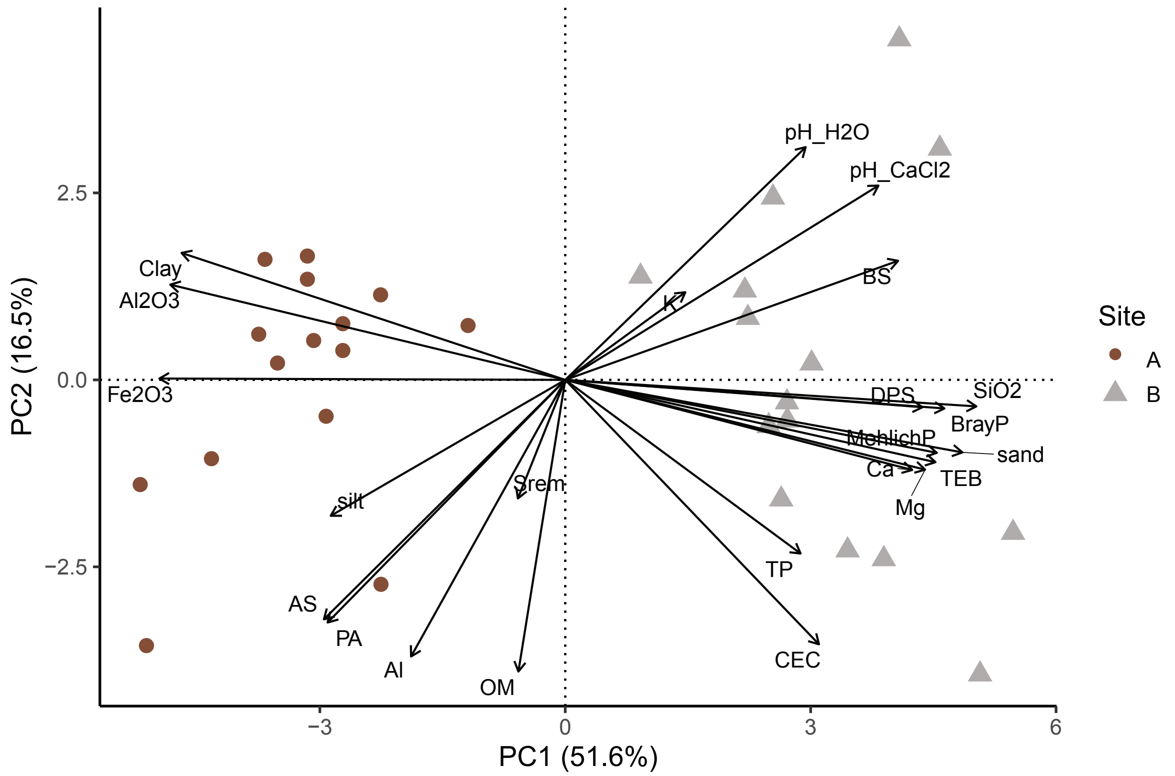

FIGURE 2 Biplot of the first two principal components of the soil properties. Al, exchangeable Al; AS, Al saturation; BS, base saturation; OM, organic matter; PA, potential acidity; TEB, total exchangeable bases. Other abbreviations are provided in the text

soil principal components PC1, PC2, PC3, and PC4, and the interaction between fertilizer treatment and PC1. The interaction term was included due to the apparent interaction between treatment and site (Figure 3) and the distinct difference in PC1 between Sites A and B (Figure 2). The final model based on the Akaike information criterion (AIC) excluded PC3 and PC4 (overall final model: multiple R^2 = .45, adjusted R^2 = .34, p = .009). Of the predictors included in the final overall model, PC2 (positive effect, p = .002) and the interaction between fertilizer treatment and PC1 (p = .008) were significant. Variance inflation factors (VIF) for planting density and PC1 were above the threshold of 3, indicating collinearity (Zuur, Ieno, & Elphick, 2010) because of the strong association of these parameters with site.

Clear separation in PC1 between the two sites (Figure 2), the significant interaction between fertilizer treatment and PC1 in the overall model, and high VIF values for planting density and PC1 in the final overall model justified subsequent analyses of each site separately. This was done using stepwise linear regression modeling including all predictors used in the initial overall model, with the exception of planting density at Site A where this parameter was uniform. Final models based on AIC for soybean grain yield per plant (Y) were $Y \sim$ fertilizer treatment + PC2 at Site A (multiple R^2 = .35, adjusted R^2 = .24, p = .078) and Y ~ planting density + PC1 + PC2 + PC4 at Site B (multiple R^2 = .63, adjusted R^2 = .48, p = .029). The VIF was below 3 for all variables included in the final models (range = 1.03–1.55). For Site A, there was evidence of decreasing yield per plant in response to decreasing P application (p = .039), whereas the effect of PC2 was not significant (p = .200). For Site B, PC2 (p = .013) had a significant positive effect on soybean grain yield per plant, with weaker effects for PC1 (negative effect, p = .098) and PC4 (positive effect, p = .055) and no clear trend with planting density (p = .111). Phosphorus fertilizer treatment was excluded from the final model for Site B based on AIC.

These findings indicate that greater soil P availability at Site B (Table 1, Figure 1), which corresponds with soil texture and bulk chemistry (i.e., lesser R_2O_3 content) (PC1; Figure 2), resulted in P not being a primary limiting factor regardless of P fertilizer treatment. Site A soils, to the contrary, still appeared to require high levels of P input to maintain yields given the low degree of soil P saturation and limited bioavailable P (Smyth & Sanchez, 1982; Sousa & Rein, 2011). The significant positive effect of PC2 on soybean grain yield per plant for the overall and Site B models suggests that other soil properties aside from P availability may also be influencing soybean yield in this field. Given the soil variables contributing to PC2—OM, exchangeable Al, CEC, potential acidity (H + Al), and Al

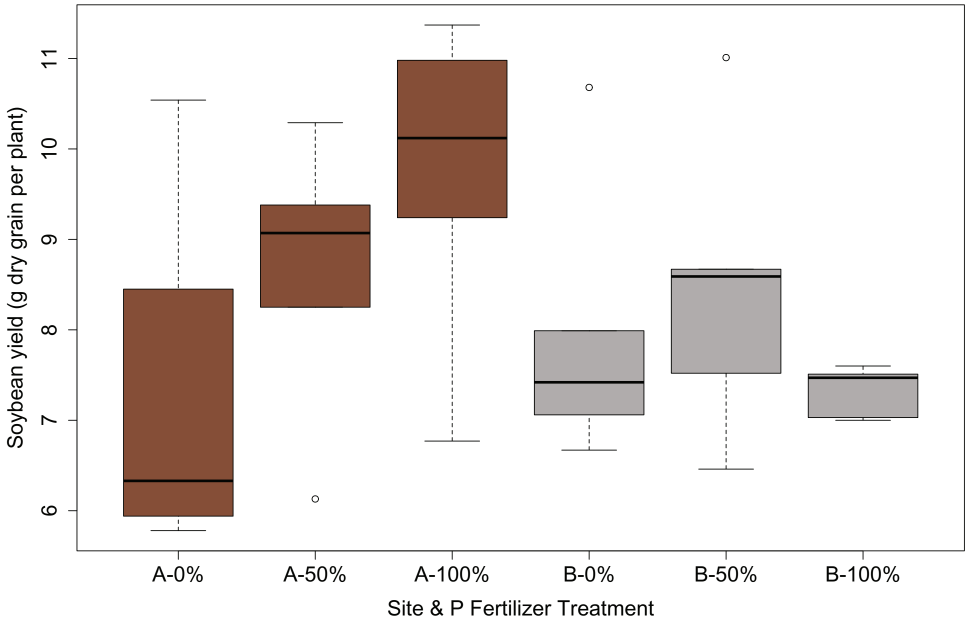

FIGURE 3 Boxplots of soybean yield response (g dry grain per plant) by site (A or B) and treatment (0, 50, and 100% of standard field P fertilization of 38 kg P ha^{-1})

saturation (negatively correlated to PC2), as well as pH (positively correlated to PC2) (Figure 2)—the observed effect appears to be related to differences in the degree to which liming has decreased soil acidity. Organic matter is the primary source of soil buffering capacity in Brazilian Oxisols (de Sá Mendonça, Rowell, Martins, & da Silva, 2006), and more lime is required for neutralization of soil acidity when soils have greater OM (Teixeira et al., 2020). Here, based on multiple regression, potential acidity (PA) was positively related to OM ($p = .045$) and clay ($p = .080$) (model: PA ~ 0.06314 OM + 0.02190 clay – 0.11098, multiple $R^2 = .21$, adjusted $R^2 = .15$, $p = .041$). Fageria, Moreira, Moraes, and Moraes (2014) reported that soybean plants grown in Oxisols can tolerate potential acidity (H + Al) up to 2.26 cmol$_c$ kg^{-1}. Plow layer soils at 14 out of 30 plots in this study exceeded that threshold (8 at Site A, 6 at Site B), indicating that soil acidity and related factors may be limiting soybean yield at these plots to some degree.

3.3 | Phosphorus balances

Phosphorus contents of soybean grain and non-grain biomass were 2.7–4.2 and 0.8–1.7 g P kg^{-1} dry biomass, respectively. Considering the entire soybean plant, grain accounted for 65 ± 4% of P assimilated into aboveground crop biomass across all plots. The P assimilated into harvested soybean grain in the 19 and 38 kg P ha^{-1} fertilizer treatments ranged from 35–106% and 20–49% of P fertilizer input, respectively. Inefficient P use during soybean production at the field's standard 38 kg P ha^{-1} fertilization rate was shown by mean residual soil P accumulations of +27 ± 2 and +23 ± 3 kg P ha^{-1} at Sites A and B, respectively (Table 2). In the zero P fertilizer treatments, soil P mining led to residual P balances of −8 ± 3 for Site A and −16 ± 3 kg P ha^{-1} for Site B. This residual P includes non-grain biomass that typically remains on the field post-harvest (5.1 ± 1.6 kg P ha^{-1}). Phosphorus mass balance metrics for the 100% fertilizer treatments fall within the ranges reported in previous studies of soybean production in Brazil (Fageria, Moreira, & Castro, 2011; Riskin et al., 2013b; Rodrigues et al., 2016; Roy et al., 2016, 2017).

3.4 | Implications

Results from this 1-yr field trial highlight that capitalizing on residual soil P in Brazilian Oxisols to reduce P fertilizer input and maintain soybean yield requires management guided by site-specific soil characteristics, which to date has typically not been the case across Mato Grosso (Roy et al., 2016, 2017). For some soils, like those at Site B with lesser clay and R_2O_3 contents, substantial increases in P use efficiency could potentially be possible after ≤10 yr of intensive management. In other soils, like those at Site A or sites with even greater soil P sorption capacity (Roy et al., 2017), our results illustrate that the soil P accumulation phase will likely need to continue for more than a decade before inputs can be reduced substantially without consequent yield declines. On fields with double-cropping of soybean and corn in Mato Grosso, such as the one in this study, the second harvest of corn can potentially draw

TABLE 2 Annual soybean production phosphorus mass balance per hectare for the different site-treatment combinations. Means ± 1 SD are shown for P harvested in soybean grain and residual P. Residual P estimates here include the P in non-grain biomass that typically remains on the field post-harvest. Note that the higher planting density at Site B resulted in greater grain yield per ha despite the lesser grain yield per plant shown in Figure 3

Treatment	P fertilizer added	P harvested in soybean grain	Residual P
	kg P ha^{-1}		
Site A			
0%	0	8 ± 3	−8 ± 3
50%	19	9 ± 2	10 ± 2
100%	38	11 ± 2	27 ± 2
Site B			
0%	0	16 ± 4	−16 ± 4
50%	19	16 ± 3	3 ± 3
100%	38	15 ± 3	23 ± 3

down a portion of the P surplus left after soybean harvest (Roy et al., 2017), which may extend the time needed before P fertilizer reductions are advisable. Our results also show trade-offs between P input and soybean yield that can be used to support the development of guidelines for producers in the event of future short-term P fertilizer price spikes (Mew, 2016).

Given the limited time duration (one growing season) and spatial extent (two sites on one field on one farm in Mato Grosso) of this study, future research is needed to further clarify effective strategies for harnessing residual soil P in tropical P-fixing soils in Brazil and beyond. Furthermore, while the 1-yr results in this study agree with the critical Mehlich-1 P levels recommended by Sousa and Rein (2011) to enable reduction in P fertilizer input, there remains considerable uncertainty about longer-term dynamics. We recommend several next steps.

First, multi-year field trials testing reduced P fertilization on fields that have received surplus P inputs for 10+ yr are needed to determine how long residual soil P can support crop productivity on Brazilian Oxisols. Studies from temperate regions with a longer history of intensive production provide examples. McCollum (1991) examined residual soil P accumulation during 8 yr of annual P fertilizer additions and then monitored STP and yield response for 18–26 yr after P fertilization ceased on a fine sandy loam under corn–soybean rotation in North Carolina. In that study, soils with high STP caused by residual soil P accumulation remained above yield-limiting STP levels for approximately one decade following the termination of fertilization. Eghball, Shanahan, Varvel, and Gilley (2003) also observed that cessation of P inputs with continuing corn harvest can reduce high STP levels while maintaining yields for multiple growing seasons in Nebraska. In both cases, the rate of STP decrease without fertilizer application was greater when initial STP was greater (Eghball et al., 2003; McCollum, 1991). Better understanding of how Mehlich-1 P and Bray-1 P respond over time to reduced or zero P fertilization in Brazilian Oxisols would enable better estimation of the degree to which P fertilizer use can be offset by capitalizing on accumulated residual P.

Second, more work is needed to clarify variability in the soil characteristics that determine residual P bioavailability across Mato Grosso, Brazil, and the tropics more broadly—and to determine how precision agriculture can be used to increase the efficiency of P fertilizer use. We suspect that our Site A is more representative of soils in soybean production across Mato Grosso than Site B, based on previously published data (Roy et al., 2017), as well as available soil maps through EMBRAPA (dos Santos et al., 2011). However, coarser-textured soils (clay content < 45%) are present in Mato Grosso as well (Donagemma et al., 2016; Roy et al., 2017) and should be targeted in efforts to improve P use efficiency. However, an important factor is whether or not the spatial variability in soil properties lends itself to more heterogeneous P management in practice. For example, our Sites A and B were located on one field that is managed as a whole. Numerous factors influence the adoption of precision agriculture in Brazil, which could be better leveraged to aid more rational use of nonrenewable P resources (Borghi, Avanzi, Bortolon, Luchiari, & Bortolon, 2016).

Finally, additional field trials are needed that test a greater diversity of soils (ranges of soil texture and accumulated residual P), P fertilization reductions (intervals between 50 and 100% P fertilizer input relative to status quo management), and additional potential management aspects (P source, crop–livestock integration, cropping rotations, etc.). In Mato Grosso, commercial fertilizers, soil conditioners, and manure together accounted for 47% of operating costs and 30% of total costs per planted area of soybean in 2010 (Meade et al., 2016). Therefore, smaller reductions in mineral P fertilizer use in Brazilian soybean production than those tested here (i.e., < 50% reductions) could still translate into meaningful savings in P fertilizer resources and costs if they are found to maintain productivity. Existing evidence suggests that high soil infiltration rates and P-fixation capacity greatly limit transport of P from intensively cropped soils to streams within Brazil's Amazon and Cerrado biomes (Neill et al., 2017). Future research should examine near-riparian areas where P loss to streams would be most likely to occur to clarify environmental costs and benefits of changing P fertilizer use. Knowledge generated through additional field research testing residual soil P effects could inform both short-term efforts to reduce costs and a longer-term effort to redesign farming systems in Brazil and elsewhere in the tropics so that they operate profitably but more sustainably with efficient P cycling (Withers et al., 2018).

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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