Deep Banding Increases Phosphorus Removal by Soybean Grown under No-Tillage Production Systems

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ABSTRACT

Phosphorus fertilizer placement can have significant agronomic and environmental implications in long-term no-till (NT) systems. The objective of this study was to evaluate soybean [*Glycine max* (L.) Merr.] response to P fertilizer placement strategies under long-term NT management. A field study was performed near Nao-Me-Toque-RS (Location 1) and Sao Sepe-RS (Location 2), southern Brazil, during the 2014/2015 growing season. The experimental design was a randomized complete block with three replications. Triple superphosphate was applied using five strategies: (i) strip tillage with deep band (ST-DB); (ii) strip tillage with band-applied 5 by 5 cm (ST-B); (iii) no-till with broadcast (NT-BR); (iv) no-till with band-applied 5 by 5 cm (NT-B); (v) and no-till with surface band (NT-SB). Plant height, dry weight, and P uptake were evaluated at 20, 40, 60, and 80 d after emergence (DAE) as well as P removed and grain yield at harvest. The ST-B application promoted greater plant height, dry weight, and P uptake at 80 DAE. However, ST-DB showed the greatest P removal compared to other treatments. Also, greater yields were obtained for ST-DB and NT-BR. Soil sampling after harvest showed that ST-DB increased soil test P levels by 19 and 11% at the 15- to 25-cm layer for Locations 1 and 2, respectively. While NT-BR increased soil test P by 43 and 36% at the 0- to 5-cm layer for Locations 1 and 2, respectively. Deep band P fertilizer placement maintained or increased soybean yield and P use under long-term NT in tropical soils.

Core Ideas

- Deep band P is a potential strategy to reduce P losses by runoff.
- Deep band P improve soil fertility in subsurface in no-till system.
- Greater amount of P removed with grain compared to the total P input.

Published in Agron. J. 109:1–8 (2017)
doi:10.2134/agronj2016.09.0533
Received 20 Sept. 2016
Accepted 16 Feb. 2017

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Phosphorus is an essential nutrient for plant growth and development, playing a crucial role in signaling, metabolism, and photosynthesis (Lan et al., 2012). Thus, the soil must provide this element in enough quantity to support plant needs, and consequently, promote high crop yields (Bender et al., 2015). Therefore, P fertilizer application is typically required for most crop production conditions (Fageria, 2009).

Conservation tillage systems such as NT provides important improvements in physical, chemical, and biological soil quality, reducing nutrient loss and soil erosion, as well as increasing soil organic matter and soil water retention (Ciotta et al., 2002; Costa et al., 2003; Mendes et al., 2003; Carneiro et al., 2004). However, the absence of soil plowing and surface fertilizer application in NT can results in higher nutrient concentration near the soil surface, especially for immobile nutrients such as P (Eltz et al., 1989; Rheinheimer and Anghinoni, 2001). The resulting vertical P gradient could affect P uptake by plants.

In a recent study, Bender et al. (2015) verified that changes in soybean cultivars and management practices during the last 80 yr, resulted in increased biomass production, grain yield, and harvest indices with subsequent increases in nutrient accumulation. Therefore, P management practices that enhance root system access to the nutrient can play an important role to improving P acquisition (Shen et al., 2011), and support yield potentials (Adee et al., 2016).

Phosphorus fertilizer placement has been widely studied in recent years, due to low P use efficiency from fertilizers (Nkebiwe et al., 2016), and a worldwide concern about natural resource conservation (Fan et al., 2011). However, soils and climate factors can have a direct effect on P availability and use efficiency, and therefore the results from different studies can vary. Furthermore, P placement can affect root growth (Barber, 1995; Williamson et al., 2001), shoot development, and consequently alter P uptake in soybean (Farmaha et al., 2012; Rosa and Ruiz Diaz, 2015). Phosphorus uptake early in the season as well as availability during the reproductive growth stage can influence yield. A better understanding of how P fertilizer placement affects soybean response under tropical/subtropical soils managed under long-term NT can help to improve P fertilizer use efficiency. The objective of this study was to evaluate soybean response to different P fertilizer placement strategies under long-term NT.

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Abbreviations: DAE, days after emergence; NT, no-till; PNB, partial nutrient balance.

MATERIAL AND METHODS

Field Sites and Experimental Design

Two field experiments were performed near Nao-Me-Toque (Location 1) and Sao Sepe (Location 2), in the state of Rio Grande do Sul (RS), southern Brazil. The study was performed during the 2014–2015 growing season. These two locations have similar precipitation, temperature, and incident solar radiation (Table 1). The two study locations were established at farmers' fields with different management history. Location 1 was managed for more than 30 yr under NT, and Location 2 a recently established NT with approximately 6 yr under NT. Despite the difference in the amount of time under NT, these two locations showed similar levels of organic matter (OM) accumulation and P vertical distribution (Table 2). The soil at Location 1 is classified as a Typic Haplortox, and Location 2 as Typic Paleudalf (USDA–NRCS, 2003). Soil chemical and physical characteristics for both locations are presented in Table 2.

The experimental design was a randomized complete block with three replications. Individual gross plot size was 15 m wide by 200 m long. Treatments consisted of five P placements strategies: (i) strip tillage with deep band P (ST-DB); (ii) strip tillage with band-applied 5-cm deep and 5 cm to the side (5 by 5) of the seed with the planter (ST-B); (iii) no-till with broadcast (NT-BR); (iv) no-till with band-applied 5 by 5 with the planter (NT-B); and (v) no-till with surface band with the planter (NT-SB). The strip till implement used a coulter followed by a shank spaced every 30 cm, and fertilizer was placed at a depth of approximately 20 cm. Band-applied 5 by 5 as well as surface band fertilizer application was completed with the planter using fertilizer application attachments. The surface band fertilizer application was completed using a disk rippled coulter system to slightly incorporate the fertilizer above the row to a depth of approximately 1 to 2 cm. The broadcast treatment was applied immediately prior to planting; using a self-propeller spreader Hercules 5.0 (STARA, Nao-Me-Toque, RS, Brazil) and the fertilizer was not incorporated. The P fertilizer was applied at a rate of 31 kg P ha^{-1} for all treatments using triple superphosphate [(0–46–0), ($N–P_2O_5–K_2O$)].

Soybean planting was completed with a Victoria DPS 4050 planter (STARA, Nao-Me-Toque, RS, Brazil) at 45-cm row spacing. The soybean varieties used were the NA 5909 RG (Nidera, Brazil) at Location 1, and Monsoy 5917 IPRO (Monsanto, Brasil) at Location 2 at 330,000 and 300,000 seeds ha^{-1}, seeding rate, respectively. Both varieties have maturity group 5.9 and indeterminate growth habit and are genetically modified for tolerance to glyphosate [*N*-(phosphonomethyl)glycine]. Other management factors such as planting date and pest control during the growing season were those typically used by the producer and recommended for the region.

Table 1. Climate characterization for the study locations in the state of Rio Grande do Sul, Brazil.

	Locations	
Parameters	Nao-Me-Toque (Location 1)	Sao Sepe (Location 2)
Latitude	28°30′ S	30°15′ S
Longitude	52°46′ W	53°46′ W
Mean annual precipitation, mm	1950	1600
Mean annual temperature, °C	18	19
Elevation, m	475	202
Incident solar radiation, MJ m^{-2} d^{-1}	16	14
Köppen climate classification	Cfa†	Cfa

† Humid subtropical climate.

Sampling and Analyses

The P fertilizer placement treatments were evaluated for effects on plant height, plant dry weight, and P uptake with measurements at the 20, 40, 60, and 80 DAE. Grain P content and grain yield were measured at harvest. Plant height was measured from the soil surface to the growing point, for five consecutive plants in the same row. The soybean plants evaluated for height measurements were marked and all evaluations during the season were on the same plants. Plant dry weight was measured collecting five consecutive plants in the same row, aboveground biomass was dried at 65°C, weighed, and ground to pass through a 1.0 mm screen. Tissue samples were digested by the nitric-perchloric acid digestion (Johnson and Ulrich, 1959), and P was determined calorimetrically. All plant sampling was completed by collecting three subsamples within each plot spaced 50 m from each other.

Grain yield was obtained by hand harvesting three subsamples within each plot of 8 m^2 each (for a total of 24 m^2 from each plot), these subsamples were spaced 50 m from each other. Grain weight and moisture were measured for each plot and reported at 130 g kg^{-1} moisture content. Phosphorus uptake was calculated using P tissue concentration and total plant dry weight. Phosphorus removed with the grain was calculated using grain P concentration and yield. Partial nutrient balance (Dobermann et al., 2005; Syers et al., 2008; Fixen et al., 2015) was calculated through the balance method, that is, dividing the value of P removed with grain by the value of P applied as fertilizer and multiplied by 100. Soil sampling was completed before and after the study to evaluate the effect of P placement on soil test P at different depths. Before the study, a general soil characterization was completed collecting a total of 10 subsamples for the experimental area at the 0- to 5-, 5- to 10-, 10- to 20-, 20- to 30-, and 30- to 40-cm depth. After harvest, soil sampling was completed collecting three subsamples per plot in slabs. These soil slabs were divided into grids of 15 cm long by 5-cm depth by 5 cm wide afterward analyzed separately to evaluate soil nutrient distribution. Soil test P at the end of study was quantified using the average of soil P level in mg dm^{-3} of the three subsamples in each layer. Soil samples were air-dried (40°C), sieved through a 2-mm mesh, and stored in covered plastic containers. Samples were analyzed for soil clay, silt, and sand content (Bouyoucos, 1962); soil pH (1:1 soil/water ratio) (Shoemaker et al., 1961); soil organic carbon (SOC) (Walkley and Black, 1934); Mehlich I–extractable P (Mehlich, 1953); 1.0 mol L^{-1} KCl–extractable Ca, Mg, and Al (EMBRAPA, 1979). Phosphorus was determined by colorimetry and K by flame photometry (Nelson et al., 1953), and Al was titrated with NaOH 0.025 mol L^{-1} (EMBRAPA, 1979). The effective cation exchange capacity (CEC) of the soil was determined by the sum of the exchangeable bases (K, Ca, and Mg) plus Al.

Statistical Analyses

Statistical analyses were completed using SAS Studio (version 9.4; SAS Inst., Cary, NC). Plant height, plant dry weight, and P uptake at the 20, 40, 60, and 80 DAE, soil test P values and measurements of P in soybean grain were analyzed using PROC GLIMMIX procedure. The main effects of fertilizer placement

Table 2. Soil chemical and physical characteristics at two experimental locations in the state of Rio Grande do Sul.

Sampling depth	pH	OM	P†	K	Ca	Mg	Al	CEC‡	Al§	Clay	PR¶
cm		g kg^{-1}	mg kg^{-1}		———— cmol$_c$ dm^{-3} ————				%	g kg^{-1}	MPa
						Location 1					
0–5	5.4	38	58	306	7.3	2.7	0.2	10.9	2	42	1.22
5–10	5.2	31	25	268	6.7	2.6	0.2	10.3	2	50	3.07
10–20	5.0	25	13	157	6.1	2.6	0.2	9.4	3	57	2.51
20–30	5.2	15	2	100	5.6	2.4	0.3	8.5	3	80	2.11
30–40	4.9	2	1	57	4.5	2.1	0.4	7.1	6	84	1.91
						Location 2					
0–5	6.0	45	55	251	9.4	3.6	0.0	13.6	0	30	0.61
5–10	5.4	29	15	194	6.1	3.2	0.1	9.8	1	28	1.74
10–20	4.6	22	7	130	4.5	2.2	0.5	7.5	7	30	1.82
20–30	4.2	20	5	88	4.0	1.8	1.3	7.2	18	32	1.97
30–40	4.2	17	3	59	3.7	1.5	1.3	6.5	20	35	1.93

† P-Mehlich-1.

‡ CEC, cation exchange capacity

§ Percentage of Al in the effective CEC.

¶ PR, penetration resistance.

treatments were considered as fixed factor and the block as random factor in the model. Sampling days and sampling depth were included as a repeated measure. Corrected denominator degrees of freedom were obtained using the Kenward–Roger adjustment. A Tukey post-hoc comparison of means test were done using the LSMEANs and SLICE option for PROC GLIMMIX.

RESULTS AND DISCUSSIONS

Initial Plant Development

Phosphorus placement strategies affected ($p < 0.001$) initial plant development as indicated by plant dry weight, plant P uptake and plant height at the 20, 40, 60, and 80 DAE (Table 3). Due to the absence of soil disturbance, soils under NT can show an increased soil bulk density, decreased soil permeability and consequently impacting root and shoot growth compared to sandier soils (Jones, 1983). Therefore, the differences in initial plant growth (at 20 and 40 DAE) among locations in this study can be partially related to the disturbance effect of the strip tillage, in addition to differences in growing conditions (temperature and rainfall).

Treatments with strip till (ST-DB and ST-B) showed lower plant shoot development at 20 DAE; however, these treatments showed higher plant dry weight later in the season (Fig. 1). This might be due to the initial lower soil resistance in these treatments (data not shown), which can induce a more aggressive initial root growth (Colombi and Walter, 2016). Therefore, plants are allocating resources in the growing organs with higher energetic demand (root system), promoting a biomass imbalance in the plant (Hermans et al., 2006) with reduction of shoot growth. However, at 40 DAE, the effect of P fertilizer placement is the most likely factor driving plant growth, where band fertilizer treatments have shown an increase in shoot development due to the access of the plants' root system to the fertilized soil area. At the flowering stage (80 DAE), ST-DB and ST-B treatments showed greater plant height and plant dry weight compared to the others treatments at Location 1 (Fig. 2). However, the tillage effects were not as evident at Location 2 (Fig. 3), possibly because of the lighter soil texture (lower clay content) with naturally lower soil bulk density and higher permeability (Jones, 1983).

Plant Phosphorus Uptake

Band placement treatments showed greater ($p < 0.001$) P uptake in the initial growth stages across locations (Fig. 1). The proximity of the nutrient with the root system likely promoted an increase in P absorption by the plant (Barber, 1958; Barbosa et al., 2015; Borges and Mallarino, 2000). However, NT-B and NT-SB placement did not result in increased P uptake at 80 DAE. At Location 1, the NT-B and NT-SB P uptake was 22.1 and 23.4 kg P ha^{-1}, respectively at the 80 DAE. The mean total P uptake at flowering stage was 60 kg P ha^{-1} at Location 2, this value was twice the amount measured at Location 1 (27 kg P ha^{-1}) during the same growth stage (Fig. 2 and 3). These results are a consequence of the greater aboveground biomass produced at

Table 3. Significance of F values for the effects of plant dry weight, plant P uptake, plant height, grain yield and post-harvest soil test P as affected by treatment (P placement), soil depth when applicable, growth stages, and interactions.

	Locations		
Fixed effect	Location 1	Location 2	Across locations
	————	$p > F$	————
		Plant dry weight	
Treatment (T)	<0.001	<0.001	0.013
Growth stage (S)	<0.001	<0.001	<0.001
T × S	<0.001	<0.001	<0.001
		Plant P uptake	
Treatment (T)	<0.001	<0.001	<0.001
Growth stage (S)	<0.001	<0.001	<0.001
T × S	<0.001	<0.001	<0.001
		Plant height	
Treatment (T)	<0.001	<0.001	<0.001
Growth stage (S)	<0.001	<0.001	<0.001
T × S	<0.001	<0.001	<0.001
		Grain yield	
Treatment (T)	0.632	<0.001	<0.001
		Post-harvest soil test P	
Treatment (T)	0.020	0.001	–
Depth (D)	<0.001	<0.001	–
T × D	<0.001	<0.001	–

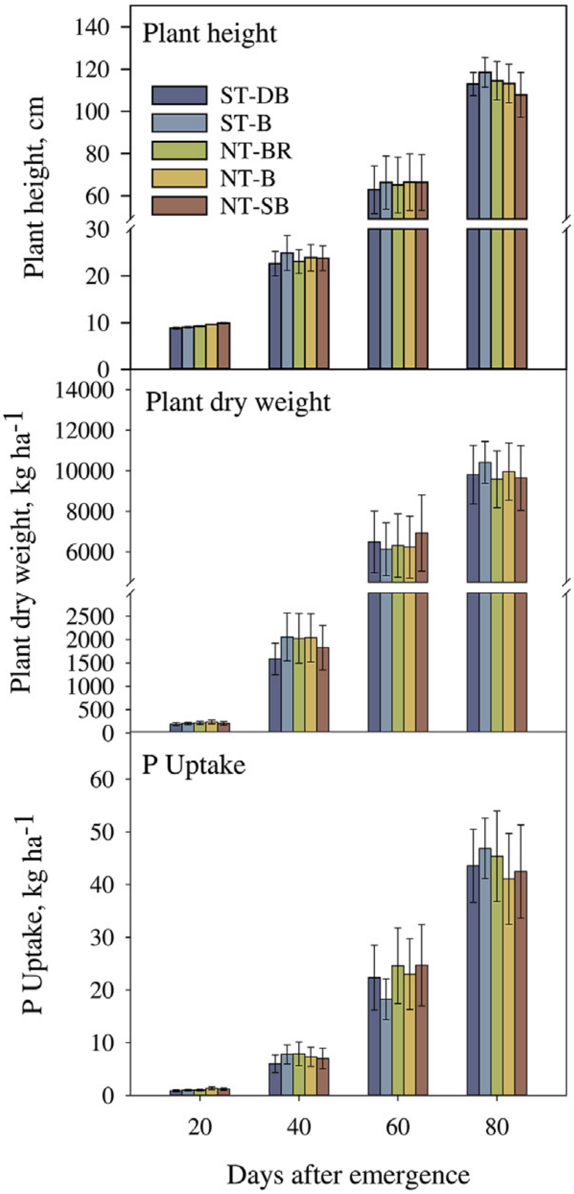

Fig. 1. Plant height, plant dry weight, and P uptake at the 20, 40, 60, and 80 d after soybean emergence across locations for strip tillage with deep band P (ST-DB); strip tillage with band-applied 5 by 5 at planting (ST-B); no-till with broadcast (NT-BR); no-till with band-applied 5 by 5 at planting (NT-B); and no-till with surface band (NT-SB).

Location 2 (12,915 kg ha^{-1}) than Location 1 (6855 kg ha^{-1}), likely promoted by varietal and environmental differences. Crop above ground biomass obtained is the driving factor for nutrient accumulation (Bender et al., 2015). These results are greater than those found by Bender et al. (2015), but similar to those published by Flannery (1986) and proposed for modern soybean cultivars (Kurihara et al., 2013).

Results from this study showed that the initial increase in P uptake did not increase yields. These results agree with previous work showing that P supplementation during the initial crop development is crucial for optimizing crop growth (Grant et al., 2005), despite P supply at later growth stages is expected to show greater correlation with yield. Furthermore, other studies suggest that P availability and plant stress during early growth has a minimal impact on yield on soybean.

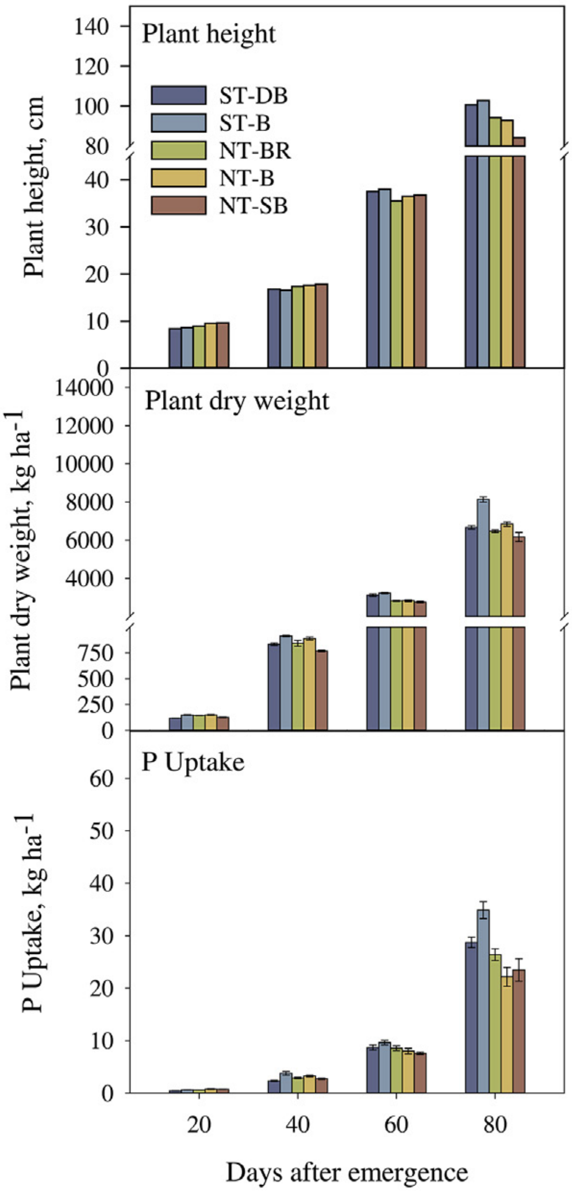

Fig. 2. Plant height, plant dry weight, and P uptake at the 20, 40, 60, and 80 d after soybean emergence in Location 1 for strip tillage with deep band P (ST-DB); strip tillage with band-applied 5 by 5 at planting (ST-B); no-till with broadcast (NT-BR); no-till with band-applied 5 by 5 at planting (NT-B); and no-till with surface band (NT-SB).

Phosphorus Balance and Use

During the vegetative stage, the plant is developing photosynthetic and absorptive organs (e.g., leaves, roots, etc.), storing nutrients and saving energy for the reproductive stage (Bender et al., 2013). During the grain-filling stage, most nutrients stored in the different tissues begin to be remobilized to the grain (Bender et al., 2015). However, results from this study showed that P supply varied during the growing season for different conditions (Locations 1 and 2, Fig. 4). In Location 1, the amount of P present in the tissue at the flowering growth stage was lower than that removed with the grain, suggesting that a significant amount of the grain P was absorbed from the soil after the R2 growth stage. On the other hand, at Location 2, there was greater amount of P uptake at the flowering stage than removed with grain. These results can also be partially related to each specific soybean variety,

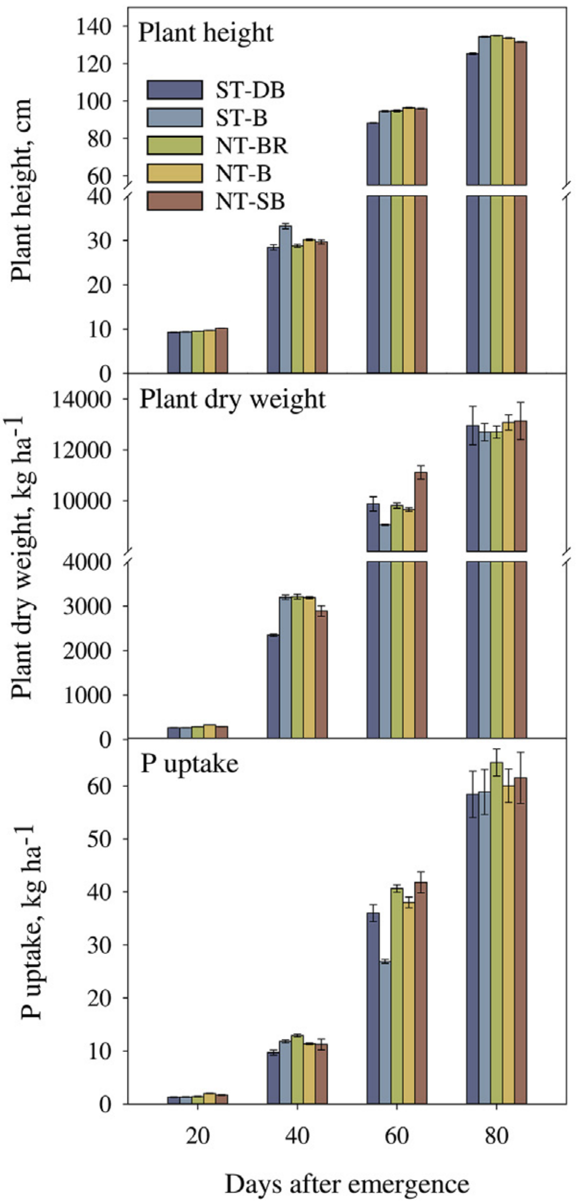

Fig. 3. Plant height, plant dry weight, and P uptake at the 20, 40, 60, and 80 d after soybean emergence in Location 2 for strip tillage with deep band P (ST-DB); strip tillage with band-applied 5 by 5 at planting (ST-B); no-till with broadcast (NT-BR); no-till with band-applied 5 by 5 at planting (NT-B); and no-till with surface band (NT-SB).

where certain varieties can accumulate P after onset of seed filling to developing grain tissues or remobilize from various plant organs (Xue et al., 2014). In the first case, the soil P availability to supply P after the R2 stage become more important than the initial P supply and other factors besides P placement can drive P uptake during the growing season.

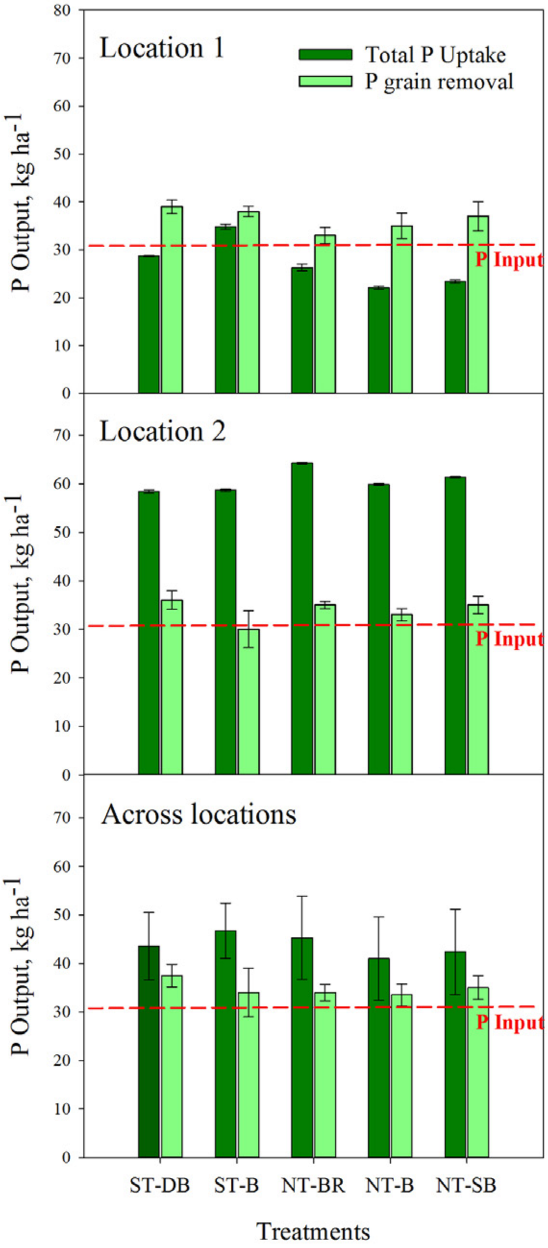

Fig. 4. Phosphorus input and output as affected by different P placement strategies in: (a) Location 1, (b) Location 2, and (c) Across locations. Phosphorus uptake was calculated at the 80 d after emergence (DAE) (flowering stage–R2). Phosphorus removed with grain was calculated using P concentration in the grain and yield. (ST-DB) strip tillage with deep band P; (ST-B) strip tillage with band-applied 5-cm deep and 5 cm to the side of the seed; (NT-BR) no-till with broadcast; (NT-B) no-till with band-applied 5-cm deep and 5 cm to the side of the seed; and (NT-SB) no-till with surface band.

Based on the balance of P input and output, a greater amount of P was removed with grain (output) than the total input with the applied fertilizer for both locations (Fig. 4). In our study, the average P removed with the grain was 36 and 34 kg P ha^{-1} for Locations 1 and 2, respectively. The difference in P uptake was provided by the soil P pool (Buresh et al., 1997; Damon et al., 2014). The nutritional requirements of soybean are mainly related to the yield potential and total nutrient removal with the grain, therefore a combination of optimum P fertilizer application rates and close monitoring of soil test P are required to maintain long- term productivity.

Partial nutrient balance (PNB) is a method to determine P use and P recovery efficiency, this value is expressed as nutrient output per unit of nutrient input (Fixen et al., 2015). This method has been widely used and consider the heterogeneity and the complexity of biological, chemical, and physical environment of the soil (Syers et al., 2008). Thereby, nutrient management and efficiency of nutrient use are being accounted considering changes in all nutrient pools at a system level (Dobermann et al., 2005).

Since the amount of removed P by the grain in this study surpassed the total P applied by fertilization (Fig. 4), the P-PNB was greater than 100%. Deep band placement treatment resulted in 121% P-PNB, indicating greater P use among the different P placement treatments (Table 4). In addition, greater yields were obtained in ST-DB and NT-BR. The lowest P-PNB value was observed for NT-BR at Location 1 and ST-B at Location 2, with 107 and 97%, respectively. Values above 100% were likely due to the high yield levels and P provided by the soil with soil test P levels that were already above the critical level for both locations (9 and 12 mg dm^{-3}, for Locations 1 and 2 respectively; CQFS, 2004).

Table 4. Soybean yield (kg ha^{-1}), P removed with grain (kg ha^{-1}) and partial P balance (P-PNB) under different P placements. P applied as fertilizer was in the rate of 31 kg P ha^{-1}.

Tillage	Placement	Yield	Grain P removal	P-PNB†
		——— kg ha^{-1} ———		%
		Location 1		
Strip-till	Deep band	4051	39a‡	126
Strip-till	Band 5 by 5	3912	38a	122
No-till	Broadcast	4055	33c	107
No-till	Band 5 by 5	3912	34bc	111
No-till	Surface band	4012	36ab	118
		Location 2		
Strip-till	Deep Band	5255a	36a	116
Strip-till	Band 5 by 5	4800b	30b	97
No-till	Broadcast	5142a	35a	114
No-till	Band 5 by 5	4525c	33ab	106
No-till	Surface band	4480c	34a	112
		Across locations		
Strip-till	Deep band	4654a	38a	121
Strip-till	Band 5 by 5	4356b	34b	110
No-till	Broadcast	4599a	34b	111
No-till	Band 5 by 5	4248b	34b	109
No-till	Surface band	4249b	35b	115

† P-PNB was calculated dividing the value of P removed with grain by the value of P applied as fertilizer, multiplied by 100. Lower levels than 100 suggest changes in management could improve efficiency or soil fertility could be increasing. Higher levels than 100 suggest soil fertility may be declining.

‡ Values followed by same letter within each column for each location indicate no significant difference at the $p \leq 0.05$ probability level.

The differences between P use at each location can be related to varietal differences, management, and soil characteristic at each location. In addition, under ultisoil and oxisoil soil conditions P is considered more limiting under clay soils. Therefore, broadcasting P at the surface at Location 1, characterized by a high percent of clay, resulted the least efficient treatment in P utilization. Also, ST-B was the least efficient at Location 2, with lower clay content. Tillage can increase soil water evaporation in the shallow layer (Blevins et al., 1971; Schwartz et al., 2010). Diffusion is the main process to P transportation in the soil (Barber, 1962) and it is affected by water content (Costa et al., 2006). The lower efficiency of ST-B could be related to a decrease in P availability in the 10-cm layer, combined with a reduction in superficial water content, and consequently P diffusion. The deeper P placement by the ST-DB treatment with limited tillage likely leave more water available in deeper soil layers.

Residual Soil Phosphorus

A significant P placement × soil depth interaction (Table 3) indicated that P placement influenced P distribution in the soil (Fig. 5). These results showed the potential challenges for soil sampling and soil test determination at whole-field scale by traditional sampling strategies (Fernández and Schaefer, 2012). In the long term, plant P uptake and P partitioning between plant parts can also promote a non-uniform re-distribution of P in the soil profile (Clarkson et al., 1978, Xue et al., 2014). For example, deep banding of P could reduce soil surface P and increase P concentration at the subsurface because most of the P uptake still occurs from the surface layer (Farmaha et al., 2012, Randall and Vetsch, 2008).

In this study, ST-DB increased residual P levels in the 15- to 20-cm and the 20- to 25-cm layer at Location 1 and showed no difference in Location 2. This increase in subsurface P levels was attributed to the P fertilizer placement from the fertilizer band. However, in Location 2 likely a combination of accuracy

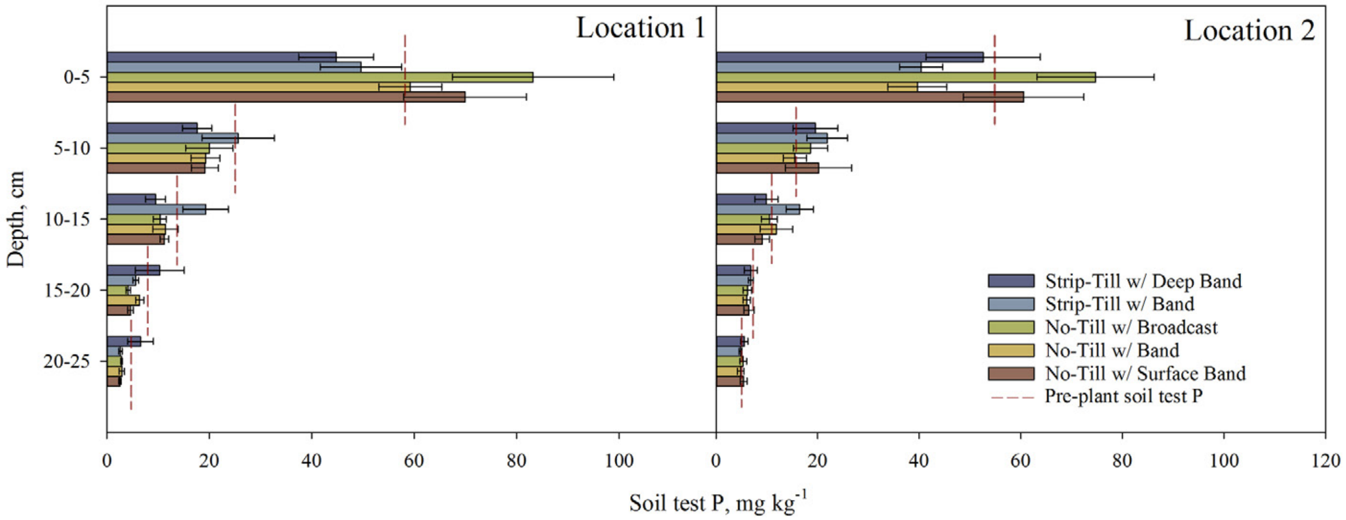

Fig. 5. Residual soil P levels after soybean crop season under different P placement treatments for Locations 1 and 2. The vertical lines represent the initial soil P level before study was established.

with soil sampling and higher Al saturation in deeper layers can reduce the effect of P placement on soil test P. High Al saturation is typically associated with P reactions with hydroxide of Al than can form inner-sphere complexes (Meurer et al., 2006). It is possible that the P applied as fertilizer in this study was not enough to increase soil test P levels under these conditions of high Al.

On the other hand, the NT-BR placement generated an increase of P levels for 0- to 5-cm layer of 43 and 36% related to initial soil test P values, respectively in Locations 1 and 2 (Fig. 5). Similar results were reported in previous studies (Fernández and Schaefer, 2012; Mallarino and Borges, 2006). Comparing residual P from NT-BR vs. ST-DB, the results from this study suggest that deep band fertilization has lower potential for runoff and environmental P loses (Hale et al., 2015; Nkebiwe et al., 2016). Other P placement management practices did not affect significantly soil P levels in the soil profile.

CONCLUSIONS

Band placement promoted greater P uptake during the initial plant growth, with no effect on grain yield at the end of the season. Under good plant growth conditions, a larger volume of soil can be explored by roots, and this may be a contributing factor for the low relevance of P placement for P uptake late in the season. The difference in total P uptake between locations can also be attributed to differences in soybean varieties and aboveground biomass. This study also showed that a greater amount of P was removed with the grain (output), exceeding the input with the applied fertilizer, suggesting that a close monitoring of soil test P is needed for long-term management. We also found greater concentration of P in the grain than what was reported in the literature, and this value can also contribute with the overall variability in P removal values. Overall, this study provides new information regarding the effect of P placement on P uptake, plant development, and P use after long-term NT management system. Deep band P presents an opportunity to reduce P losses by runoff while maintaining or increasing yields in tropical soils.

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