

Phosphorus Fertilizer Placement and Tillage Affect Soybean Root Growth and Drought Tolerance

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ABSTRACT

Tillage system and P fertilizer placement can affect plant root growth and therefore water and nutrient uptake. The objective of this study was to evaluate the effect of P fertilizer placement and tillage system on soybean [*Glycine max* (L.)] root growth and grain yield under induced drought stress. A field study was performed at two locations in southern Brazil, during the 2014/2015 season. Phosphorus fertilizer placement and tillage combinations were evaluated using triple superphosphate at 31 kg P ha⁻¹. Treatments included: (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); and (v) no-till with surface-band (NT-SB). Root length density (RLD) and root diameter were evaluated at 0- to 25-cm depth in 5-cm intervals. Yield was evaluated under rainfed as well as under induced drought conditions. The ST-DB treatment showed increased total RLD among treatments, with about 58% greater RLD than the NT-BR treatment, and 46% greater RLD than the NT-B treatment at the 15- to 25-cm soil depth. Furthermore, the soybean yield penalty with the ST-DB treatment was lower than any other treatment with a yield reduction of about 9 and 0.3% at respective locations under induced drought stress. Results from our study showed that the ST-DB treatment contributed to enhance soybean root growth at deeper soil layers and improved overall resilience to induced drought.

Core Ideas

- Phosphorus placement affect root system growth.
- Strip-till plus deep band P enhance deeper soybean root growth
- Soybean root growth at deeper soil layers improve resilience to induced drought.

NO-TILL SYSTEM (NT) can provide substantial improvements in physical, chemical, and biological soil characteristics, reducing nutrient loss and soil erosion, as well as increasing soil organic matter and soil water retention (Amado et al., 2006; Bolliger et al., 2006). However, the low soil disturbance associated with NT can result in higher nutrient concentration near the soil surface (stratification), especially for immobile nutrients such as P (Howard et al., 1999; Adey et al., 2016; da Costa and Crusciol, 2016). Stratification of nutrients can affect plant root growth and therefore impact plant response to soil moisture and precipitation conditions.

Plant root systems typically show high adaptability during the growing season, adjusting to environmental conditions as well as water and nutrient availability (Williamson et al., 2001). Crop root biomass is generally higher around areas of high nutrient concentration due to fertilizer application, especially in the 0- to 10-cm soil layer (Li et al., 2017). Greater root growth near the soil surface can also be associated with genetic traits (Salisbury and Ross, 1992). However, previous studies have shown that P fertilizer placement can affect root morphology and growth (Borkert and Barber, 1985; Lu and Miller, 1993; Denton et al., 2006). Phosphorus contributes to induce the initiation and subsequent extension of primary and secondary roots (Drew, 1975; Salisbury and Ross, 1992).

Broadcast application of P fertilizer can provide savings in time and labor and therefore a popular practice among producers. However, under the NT system surface P fertilizer application can promote high concentration of available P near the surface (0–2 cm), stimulating shallower root growth (Williamson et al., 2001). Therefore, plant P uptake may decrease during periods of drought with very low soil moisture near the surface (Borges and Mallarino, 2000). In addition to shallow fertilizer placement, other factors, such as the increase in soil bulk density and soil acidity at deeper soil depths resulted in physical and chemical limitations for

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Abbreviations: NT, no-till; NT-B, no-till with band-applied 5 by 5 cm; NT-BR, no-till with broadcast; NT-SB, no-till with surface-band; RLD, root length density; SPR, soil penetration resistance; ST-B, strip-tillage with band-applied 5 by 5 cm; ST-DB, strip-tillage with deep band; STP, soil test phosphorus.

deeper plant root growth in tropical soils. These factors have led in some cases to the implementation of tillage operations in fields otherwise managed under NT (Calonego et al., 2017). On the other hand, band application of P fertilizer can contribute to reduce potential P fixation in Oxisol soils (Balastreire and Coelho, 2000) increasing P availability to the root system (Shen et al., 2011). Furthermore, the combination of P fertilizer placement and some level of tillage such as strip-tillage may provide benefits under some specific production conditions (Adee et al., 2016).

Changes in root distribution promoted by deep placement of P fertilizer may contribute to increase P use efficiency; and may affect the resilience of the plant to short-term drought stress. Recent studies demonstrated that deep root systems have an important role in water use efficiency (Hatfield et al., 2001; Fageria and Moreira, 2011; Joris et al., 2013). On the other hand, roots near the soil surface can become dependent on the water provided by rainfall events (Lynch, 2013; Tron et al., 2015). Therefore drought is considered as the main factor contributing to the year-to-year yield variability in rainfed and dryland agriculture (Purcell et al., 2000).

Studies evaluating soybean root growth characteristics under different P fertilizer placement and tillage systems are lacking. Likewise, the potential implications of soybean root growth on plant resilience to short periods of drought has not been evaluated. The objective of this study was to assess the effect of P fertilizer placement and tillage on soybean root growth and yield response under imposed drought stress conditions.

MATERIALS 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, southern Brazil. The study was performed during the 2014–2015 growing season. Both locations were established at farmers' fields with different management history. In Location 1, NT was adopted for over 30 yr and Location 2 was a recently established NT with approximately 6 yr under NT. The crop rotation used in both fields were soybean/corn (*Zea mays* L.). The soil at Location 1 was

classified as a Typic Haplortox, and Location 2 as Typic Paleudalf (USDA–NRCS, 2003). Additional soil, as well as climate characteristics for the study locations were presented in Hansel et al. (2017). Soil chemical characteristics for both locations are presented in Fig. 1.

The experimental design was a randomized complete block with five treatments and three replications. Individual plot size was 15 by 200 m and soybean row spacing was 45 cm. Treatments consisted of P fertilizer placement and tillage combinations: (i) ST–DB; (ii) ST–B; (iii) NT–BR; (iv) NT–B; and (v) NT–SB. For the ST–DB treatment the fertilizer was applied at 20-cm depth. The P fertilizer was applied at a rate of 31 kg P ha⁻¹ for all treatments using triple superphosphate [(0–46–0), (N–P₂O₅–K₂O)]; no other nutrients were applied. The soybean varieties used were NA5909 RG (Nidera, Brazil) at Location 1, and Monsoy 5917 IPRO (Monsanto, Brasil) at Location 2 at a seeding rate of 330,000 and 300,000 seeds ha⁻¹, respectively. The full description of tillage and planting equipment used in the study were reported by Hansel et al. (2017).

Mobile rain-out shelters were installed for four selected treatments (ST–DB, NT–BR, NT–B, and NT–SB) to assess the impact of a drought stress during the reproductive soybean growth stage particularly grain filling. The induced drought stress was imposed for 25 d at approximately the R3 growth stage when soybean is considered to be more susceptible to environmental stresses (including water and/or diseases). The number of pods is determined during the early stage of pod development (Dybing et al., 1986), and a drought stress at this stage can significantly increase the rate of pod abortion thus decreasing final grain yield (Liu et al., 2003). The rain-out shelters were 3 by 4 m in size and built with a wood frame and using a plastic cover of 0.1 mm transparent plastic polyethylene film excluding 100% of the rainfall. Drains were built around the rainout shelters to prevent the effect of water runoff. Soybean was harvested for yield inside the rain-out shelters excluding 0.5 m of the borders. The total precipitation in both locations during the experimental period is shown in Fig. 2.

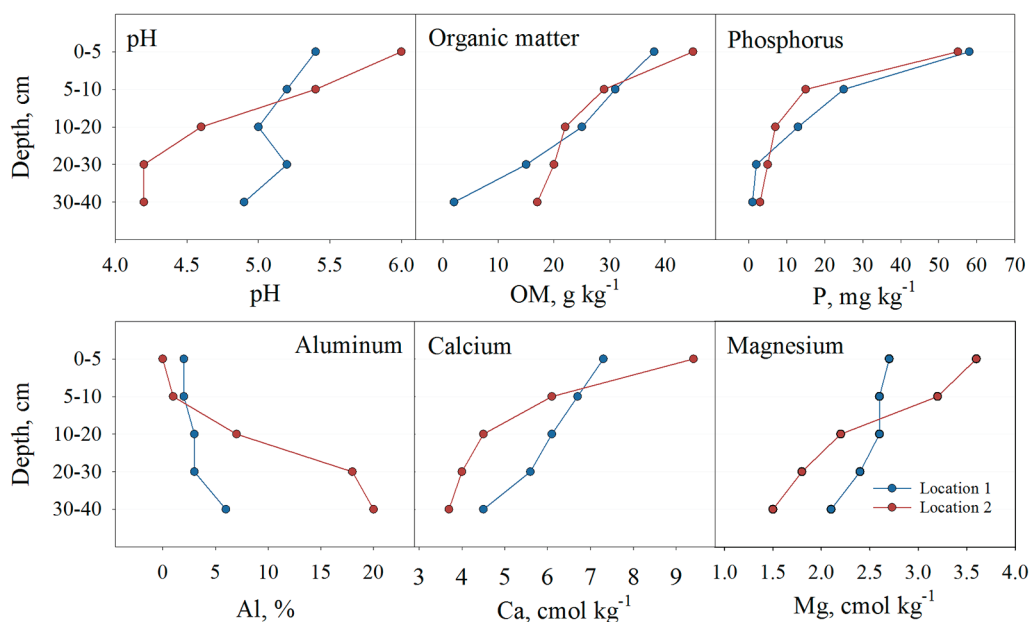


Fig. 1. Soil chemical characteristics at the two study locations in the state of Rio Grande do Sul, Brazil. Adapted from Hansel et al. (2017).

Sampling and Analyses

Soil characterization was completed prior to planting collecting a total of 10 soil cores in the study area at the 0- to 5-, 5- to 10-, 10- to 20-, 20- to 30-, and 30- to 40-cm sampling depth. Soil samples were air-dried at 40°C, ground to pass a 2-mm sieve and stored in plastic containers. Samples were analyzed for soil texture (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; 1.0 mol L⁻¹ KCl-extractable Ca, Mg, and Al (EMBRAPA, 1979). Phosphorus was determined by colorimetry (Nelson et al., 1953), and Al was titrated with NaOH 0.025 mol L⁻¹ (EMBRAPA, 1979).

Soybean root growth was evaluated at approximately the R3 growth stage using the Needle Board Monolith method and rooting profile (adapted from Görbing, 1948; Böhm, 1979; Li et al., 2017). The monoliths were 30 by 40 by 10 cm (height by length by width) with needles spaced in a 5 by 5 cm grid. The total soil volume collected with this method was 8.75 dm³. A 2-mm stainless steel mesh was placed on the board through the needles before sampling to help keep the soybean roots in its original place during the root washing process. A trench of approximately 60 cm in length, 40 cm wide and 40-cm deep was opened in the field to allow access to the root system. The needle boards were pressed against the vertical walls of the trenches perpendicular to the soybean rows using a hydraulic jack, and removing a soil block with intact roots. The monoliths were centered on the soybean row to maximize the volume of root sampled. One monolith was collected for each plot (a total of three replications). The monoliths were covered with plastic wrap for transportation and storage. After prior wetting, the monoliths were immersed in a 6% NaOH solution, where they remained for 60 min to promote soil dispersion and minimize roots damage during washing. Clean roots were cut off in sections of 5 cm in depth and analyzed separately. The evaluation of total RLD was performed by digitalizing the roots with a scanner (Epson Expression 11000XL, Epson America, Inc., Long Beach, CA), in a 600 dpi resolution. The generated images were analyzed using the WinRhizo Pro software (Régent Instruments, Québec City, QC, Canada). Root classes were established based on root diameter values and divided in three categories (<0.25 mm, 0.25–0.5 mm, and >0.5 mm).

Grain yield was obtained by hand harvesting three randomly selected subsamples within each plot. Harvest area for each subsample was 8 m² for a total of 24 m² of harvested area from each plot. Grain weight and moisture were measured for each plot and yield was reported at 130 g kg⁻¹ moisture content.

Soil penetration resistance (SPR) was measured prior to soybean planting and after harvest using an electronic penetrometer (PLG1020- PenetroLOG, Falker, São Geraldo, Brazil) collecting a total of 10 randomly selected subsamples for each location, sampling was completed for 0- to 35-cm depth and values were reported for every 5-cm increments. After harvest, SPR measurements were completed for the three selected treatments (ST–DB, NT–BR, NT–SB), a total of 10 subsamples per treatment were collected in the soybean row.

Statistical Analysis

All statistical analyses were completed in SAS Studio (version 9.4; SAS, Cary, NC). Soybean root data were analyzed using PROC GLIMMIX (restricted maximum likelihood estimation) procedure. Phosphorus fertilizer placement and tillage treatments were considered as fixed factors in the model, and blocks were considering as random factor. Sampling depth was included as repeated measure in the model (Littell et al., 2006). The covariance structure used in the model was the compound symmetry. Corrected denominator degrees of freedom were obtained using the Kenward–Roger adjustment. Mean comparison was done using the LSMEANS and SLICE option in PROC GLIMMIX.

RESULTS AND DISCUSSION

Soybean Root Length Density

Phosphorus fertilizer placement strategies affected soybean root growth and distribution in the soil profile (Table 1). The exposure of the root system to zones with high P concentrations due to fertilizer application combined with soil disturbance promoted by tillage systems resulted in changes in the root architecture. Highly weathered tropical soils usually has low soil test phosphorus (STP) levels, in part due to the high content of Fe and Al oxides and low soil pH. These soil characteristics are more pronounced near the subsurface (Friesen et al., 1997). However, crop residue and P fertilizer input can result in higher P concentration near the soil surface

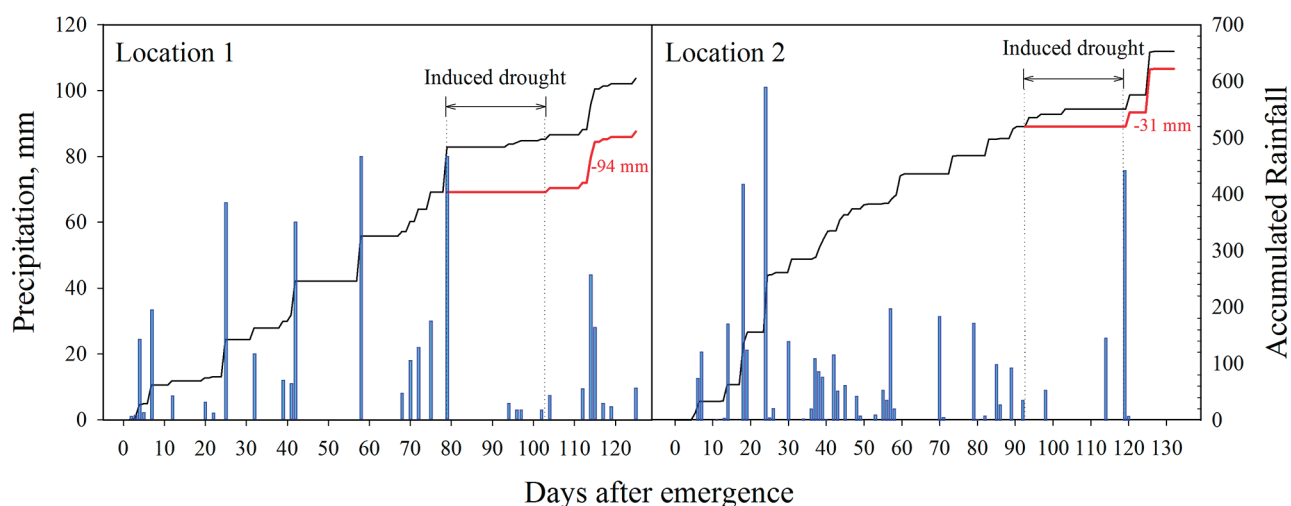


Fig. 2. Precipitation during the soybean growing season at Locations 1 and 2. Rain-out shelters were installed at approximately the R3 soybean growth stage and left for 25 d (Period of R3 to approximately R5).

while changes in the subsoil are typically minimum (da Costa and Crusciol, 2016). In addition to low soil P in the subsoil, root growth can be inhibited by high Al saturation associated with low pH (Kochian, 1995; da Costa and Crusciol, 2016). In our study, the STP value at the 20- to 30-cm depth corresponds to about 3 and 9% of the STP value at the 0- to 5-cm depth for Locations 1 and 2, respectively (Fig. 1). This result suggests that the P fertilizer management used in previous years at these locations were efficient at increasing the STP values for shallow layers only. As the P has low mobility in the soil the build up in the subsoil did not occur.

Table 1. Significance of *F* values for the effect of P placement treatments and sampling depth on root length density, root diameter, and soil penetration resistance.

Fixed effect	Locations	
	Location 1	Location 2
	$P > F$	
	<u>Root length density</u>	
Treatment (T)	<0.001	<0.001
Depth (D)	<0.001	<0.001
T × D	<0.001	<0.001
	<u>Root diameter</u>	
Treatment (T)	<0.001	<0.001
Depth (D)	<0.001	<0.001
T × D	<0.001	<0.001
	<u>Penetration resistance</u>	
Treatment (T)	<0.001	<0.001
Depth (D)	<0.001	<0.001
T × D	<0.001	<0.001

The treatment ST-DB with subsoil placement of P fertilizer promoted an increase in soybean root growth shown by the higher RLD in deeper soil layers at both locations (Fig. 3). In the 20- to 25-cm sampling depth, the total average RLD for the ST-DB treatment was 76 and 85% greater than the ST-B at Locations 1 and 2, respectively (Fig. 3). The deep placement application of P fertilizer resulted in increased STP levels at the 20-cm depth (data presented in Hansel et al. [2017]) which likely contributed to stimulate root growth at this sampling depth (Fig. 1). It was also possible that P fertilizer application contributed to reduce any possible negative effect of soluble Al to the root growth (Meurer et al., 2006). Thus, a greater density of roots in deeper soil layers with the ST-DB treatment is likely due to the combination of P fertilizer placement as well as tillage (Fig. 3 and 4). (Drew, 1975; Granato and Raper, 1989).

The fertilizer placement and tillage systems that fostered higher concentrations of P close to the surface (ST-B, NT-B, and NT-SB) also promoted a shallow preferential zone for soybean root growth. In our study, those treatments (ST-B, NT-B, and NT-SB) showed about 69 and 59% of the total roots in the 0- to 10-cm layer at Locations 1 and 2, respectively (Fig. 3). The higher nutrient availability and nutrient cycling near the soil surface is typically more pronounced under NT system due to a higher amount of crop residues kept on the soil surface. The high soil organic matter in the soil surface as well as higher soil pH due to lime application can also prevent P fixation by Fe and Al oxides in tropical soils (da Costa and Crusciol, 2016). As a consequence, highly branched root system to the detriment of the primary root are formed; and characterized by the stimulated formation and emergence of lateral roots and root hairs (Bates and Lynch, 1996; Williamson et al., 2001; Linkohr

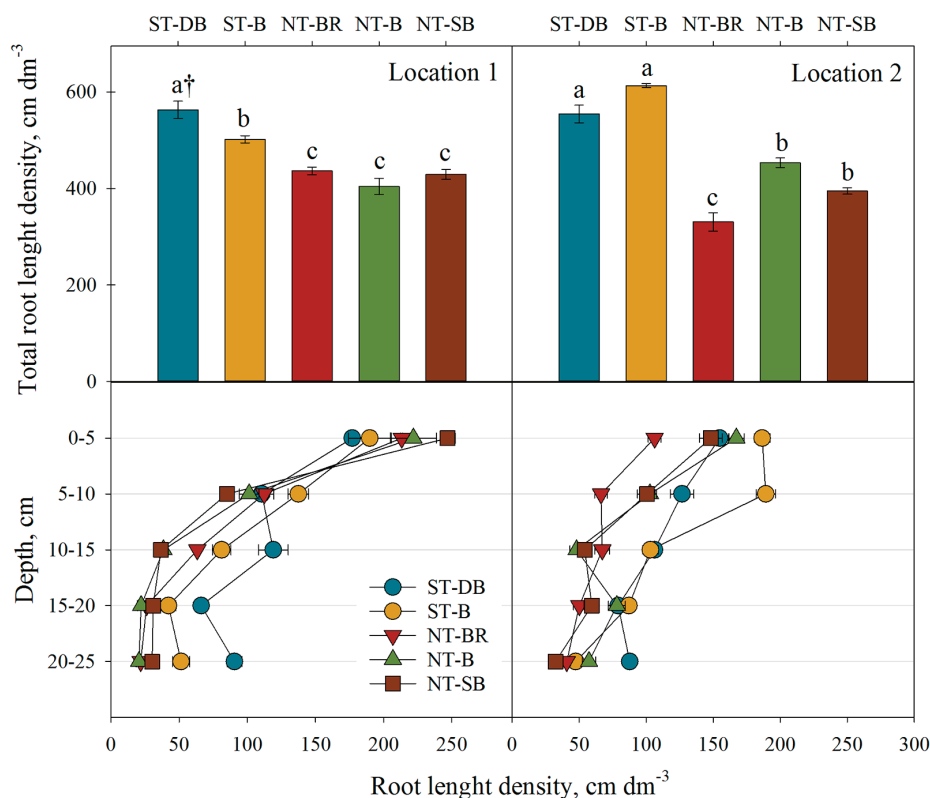


Fig. 3. Effect of P placement on soybeans root growth at Locations 1 and 2. Values followed by the same letter indicate no statistically significant difference at the $p \leq 0.05$ probability level. Strip tillage with deep band (ST-DB); strip tillage with band-applied 5-cm deep and 5 cm to the side (5 by 5) of the seed with the planter (ST-B); no-till with broadcast (NT-BR); no-till with band-applied 5 by 5 with the planter (NT-B); and no-till with surface band with the planter (NT-SB). Error bars indicate the standard error of the mean.

et al., 2002; López-Bucio et al., 2002; Péret et al., 2011; Niu et al., 2012). High root density near the soil surface can be efficient for plant P uptake provided good soil moisture and no drought stress.

A greater RLD was observed for the ST-B treatment when compared with NT-B. In Location 1, the ST-B showed greater total RLD for all sampling depths when compared to NT-B, except in the 0- to 5-cm sampling depth (Fig. 3). In Location 2, the ST-B treatment showed greater total RLD in the 5- to 10- and 10- to 15-cm sampling depth when compared to the NT-B treatment, but no difference at other sampling depths (Fig. 3). The use of strip tillage (ST-B treatment) resulted in lower SPR values in the entire soil profile allowing an increase in RLD growth (Fig. 3 and 4). Previous studies reported a negative relation between SPR and soybean root growth. Soybean root growth can be reduced by 50% with SPR values of 0.69 MPa near the soil surface; and root growth can be completely inhibited with SPR values of 2.00 MPa (Rosolem et al., 1994). Other studies reported SPR of 0.5 MPa as detrimental for soybean root dry matter (Fernandez et al., 1995). Thus, the greater root growth found in the ST-B treatment compared to the NT-B treatment can also be related to the soil disturbance generated with the strip tillage, the effect of the planter's shank was limited to 0- to 10-cm layer (Fig. 4).

Under NT system, P fertilizer application either as broadcast or band-applied with the planter (NT-BR and NT-B treatments) resulted in similar RLD values in the 0- to 5-cm sampling (Fig. 3). These results are different from previous studies suggesting that surface P fertilizer application in NT system can increase the overall root growth near the soil surface when compared to planter-banded P fertilizer application (Williamson et al., 2001). The initial STP level at the 0- to 10-cm sampling depth was high at both locations (35 and 42 g kg⁻¹ for Locations 1 and 2, respectively) it was likely that additional P fertilizer application to the surface resulted in little or no additional effect on soybean root growth (Fig. 1 and Hansel et al. [2017]). Root system growth and maintenance represent a high energy cost for the plant (Eissenstat and Yanai, 1997). Therefore, under a high soil P availability, the plant will likely limit root biomass growth given that smaller root systems can supply the plant nutrient demands. On the other hand, root growth can be stimulated by nutrient starvation (Nacry et al., 2005), and roots tend to grow widely in the soil to access a larger soil volume, or develop localized roots proliferation around higher nutrient availability zones in the soil profile (Borkert and Barber, 1985). This strategy promotes a

more efficient use of energy in the plant, investing in root development only when and where necessary.

Results from our study showed an increase in root length in the 10- to 15-cm sampling depth for the NT-BR treatment (Fig. 3) compared with the NT-B treatment and the NT-SB treatment (without strip-tillage). The root distribution with the NT-BR treatment may limit the access to P fertilizer when compared to the planter-banded and surface-banded P fertilizer treatments (NT-B, NT-SB). With the NT-BR treatment, soybean plants stimulated lateral root growth contributing to increase the volume of soil exploration and increase the surface area in contact with the soil to improve P uptake efficiency (Williamson et al., 2001).

Soybean Root Diameter

Soybean root diameter was also affected by P fertilizer placement and tillage treatments. The root distribution in the soil profile (Fig. 5) shows the NT-B treatment categorized in three diameter classes. Results showed that regardless the treatment evaluated in this study, most of the roots were <0.5 mm in diameter at all sampling depths. The root function as well as the energetic costs to produce and maintain these roots are determined primarily by their structure and especially by their diameter (Raven and Edwards, 2001). Also, the uptake of a nutrient with a low concentration and low diffusion coefficients in the soil, such as P, can be higher per unit of root biomass for structures of smaller diameter (McCully, 1999; Raven and Edwards, 2001). Therefore, fine roots explore a much larger volume of soil per root volume unit improving water and nutrient uptake.

The NT-B can be considered one of the most widely used P fertilizer placement options and therefore we used as baseline comparison for other treatments (Fig. 6). When the NT-B treatment was compared to the ST-DB treatment we found higher RLD for most classes of root diameter at the 10- to 25-cm depth, in both locations. At Location 1, ST-DB showed 44% higher total RLD for the <0.5 mm diameter over the NT-B treatment, whereas for Location 2 this difference was about 20%.

The tillage effect in the ST-B treatment also promoted an increase in total RLD for the <0.25 and 0.25 to 0.5 mm root diameter. About 21 and 33% more roots were observed in the ST-B treatment when compared with the NT-B treatment for the same root diameter classes in Locations 1 and 2, respectively (Fig. 6). Fertilizer P was placed at the same depth for the ST-B and the

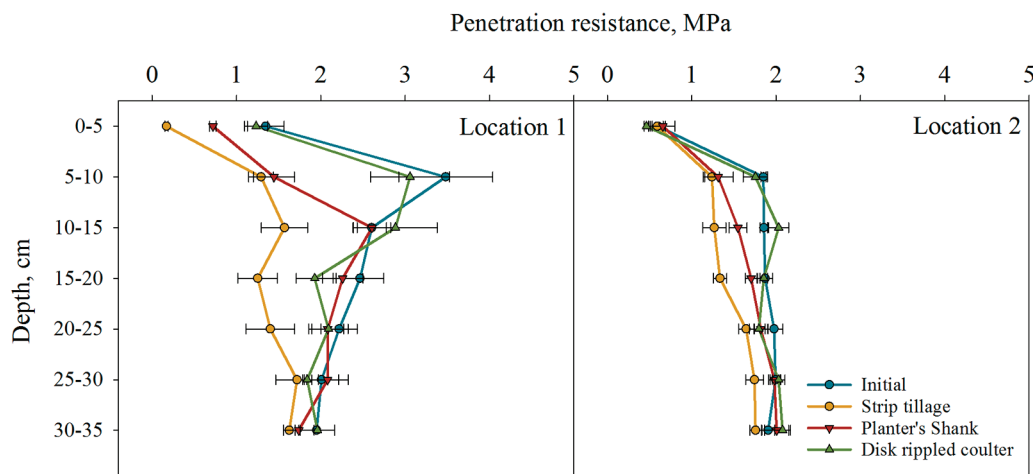


Fig. 4. Soil penetration resistance (SPR) collected before the application of P fertilizer placement treatments and after harvest of the soybean.

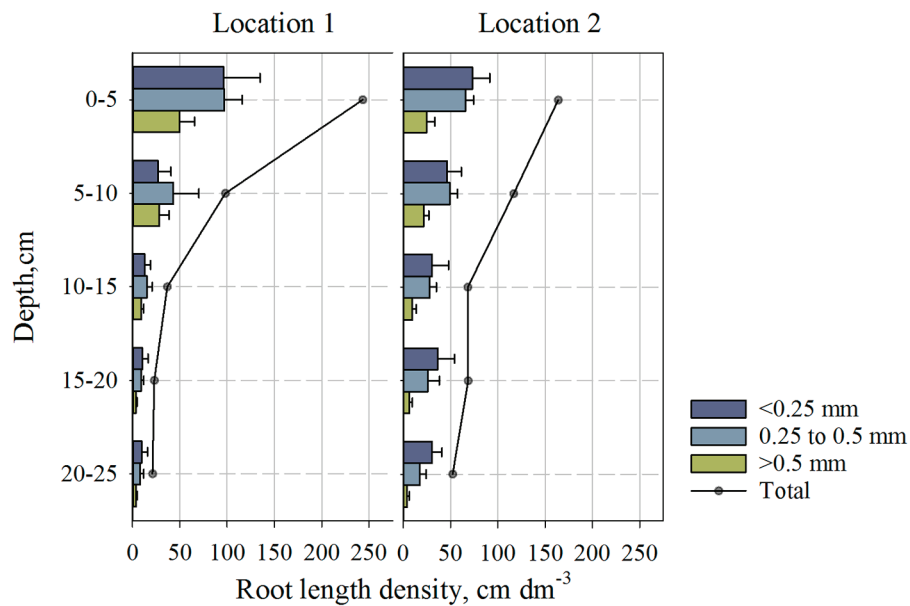


Fig. 5. Root diameter and length growth in no-till with band-applied 5 by 5 (NT-B) at Locations 1 and 2. Root diameter classified in <0.25 mm, 0.25 to 0.5 mm, and >0.5 mm.

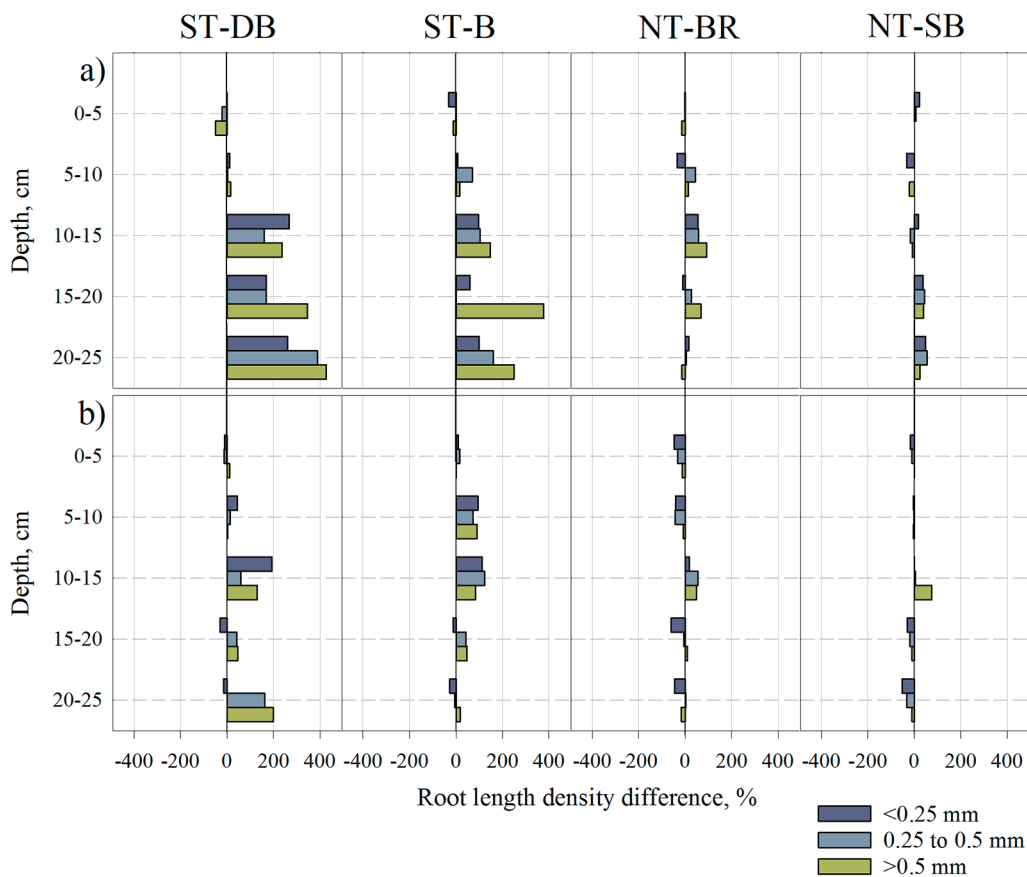


Fig. 6. Root length density as affected by P placement strategies in Locations (a) 1 and (b) 2. Root length density was divided in three categories of root diameter classes and it is expressed as relative value to no-till with band-applied 5 by 5 with the planter (NT-B). Strip tillage with deep band (ST-DB); 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); no-till with broadcast (NT-BR); and no-till with surface band with the planter (NT-SB).

NT-B treatments, and therefore is likely that the higher RLD found in the ST-B treatment was in part due to the tillage component from the strip-till operation (particularly for Location 1). On the other hand, when similar tillage systems are compared (ST-DB and ST-B treatments), we observed an effect of the deep placement of P, with the ST-DB treatment showing an increase of 85 and 78% in RLD at the 20- to 25-cm depth in Locations 1 and 2, respectively. The exposure of the root system to zones with high P concentrations in the soil profile likely generated an increase in the initiation and subsequent extension of the primary and secondary roots reaching deeper soil layers (Drew, 1975; Salisbury and Ross, 1992). The ST-DB treatment showed a decrease in STP stratification promoted by NT and a substantial increase of root growth in deeper soil layers which was not observed for the ST-B treatment.

Comparing the NT-BR treatment with the NT-B there was no clear influence of the P fertilizer placement on root diameter (Fig. 6). It should be highlighted that P fertilizer placement at or near the soil surface for these two treatments (NT-BR and NT-B) was to a soil surface with already high STP levels that may play a key role in root growth. However, the broadcast treatment promoted an increase of roots of <0.5 mm diameter at 10- to 15-cm sampling depth, corresponding to 57 and 39% to Locations 1 and 2, respectively. These

results suggest that under NT system soybean can have higher root growth with broadcast P fertilizer placement (compared to NT-B and NT-SB). Other studies also found that plant root growth can be higher when P fertilizer was not concentrated in one area, likely incentivizing overall root growth (Niu et al., 2012). The NT-SB treatment showed a similar root diameter distribution to the NT-B treatment for all sampling depths. The possible effect of P fertilizer placement at the soil surface with the NT-B and NT-SB treatments were likely masked by already high STP values.

Soybean Yield under Induced Drought

An induced water stress was imposed to the P fertilizer placement and tillage treatments using rain-out shelters to exclude rainfall at the soybean reproductive growth stage. The total precipitation during the study as well as the reduction in precipitation achieved with the use of rain-out shelters are presented in Fig. 2.

The ST-DB treatment promoted the highest resilience to drought stress from the treatments evaluated in this study at both locations (Fig. 7). The impact of a drought event resulted in 9% reduction in grain yield at Location 1 and 0.3% at Location 2 with the ST-DB treatment. There was a yield penalty of 4 kg ha⁻¹ mm⁻¹ of water restricted at Location 1 and 1 kg ha⁻¹ mm⁻¹ at Location 2.



Fig. 7. Soybean grain yield and root length density distribution under different P placement treatments under normal rainfall condition and induced drought conditions. Locations (a) 1 and (b) 2. The error bars show the standard deviation of the mean. Selected treatments included: strip tillage with deep band (ST-DB); no-till with broadcast (NT-BR); no-till with band-applied 5 by 5 with the planter (NT-B); and no-till with surface band with the planter (NT-SB).

The deeper root growth promoted by the ST–DB treatment likely allowed for plants to access profile water more efficiently, helping to meet the high demand at the critical seed filling growth stage considered to be approximately 7 to 9 mm d⁻¹ (Ribas-Carbo et al., 2005).

No-till with broadcast P treatment (NT–BR) showed intermediate sensibility to water stress showing a grain yield penalty of 20% at Location 1 and 2% at Location 2 (Fig. 7). In the NT–BR treatment was observed a yield reduction of 9 kg ha⁻¹ mm⁻¹ of water restricted at Location 1 and 3 kg ha⁻¹ mm⁻¹ at Location 2. The increment of roots at the 10- to 15-cm layer found for the NT–BR in relation to NT–B (Fig. 3) could have led to a better exploration of the soil profile stored water.

Management that resulted in a greater RLD on the soil surface showed the greatest yield penalty due to the induced drought stress (treatments NT–B and NT–SB) (Fig. 7). Roots near the soil surface likely became dependent on the moisture provided by rainfall events (Lynch, 2013; Tron et al., 2015). The yield penalty for the NT–B treatment due to drought stress was about 28 and 4% at Locations 1 and 2, respectively. In the NT–SB treatment we observed a yield penalty of 30 and 13% at Locations 1 and 2, respectively. These treatments showed lower water use efficiency with yield reductions of 12 and 6 kg ha⁻¹ mm⁻¹ of water for the NT–B treatment; and 13 and 18 kg ha⁻¹ mm⁻¹ of water for the NT–SB treatment at Locations 1 and 2, respectively. These results suggest that the mulch effect (residue promoted by NT systems) was not enough to increase water-use efficiency under drought events and P fertilizer placement and tillage systems that promote deep root growth contributes to improve soybean resilience to drought events. The total yield penalty observed at Location 2 was generally lower (Fig. 7). This may be due in part to the total amount of water restricted at each location with 94 mm at Location 1 and 31 mm at Location 2 (Fig. 2).

In the last decades, several studies evaluated P fertilizer placement strategies worldwide and most studies show little or no difference in soybean yield due to P fertilizer placement under optimum production conditions (Nkebiwe et al., 2016). However, changes in the root system promoted by P placement strategies has not been evaluated under field conditions, and these changes in root growth can affect the capacity of the plant to adapt to water stresses. Drought is considered as one of the main factors contributing to year-to-year yield variability in rainfed and dryland agriculture (Purcell et al., 2000). Therefore, it is likely that a closer evaluation of drought stress and the timing of the stress may help explain the results observed in previous studies evaluating the effect of P fertilizer placement in soybean. Results from our study showed that P fertilizer placement and tillage system affect soybean root growth and resilience to short-term drought stress. The ST–DB treatment showed a significant increase in root growth at deeper soil layers resulting in an effective drought mitigation strategy when compared to other traditional system used by farmers.

CONCLUSIONS

In long-term NT, in soils with high P fixation capacity, we found a clear development of a nutrient gradient in the soil profile which can favor a shallow soybean root growth. Phosphorus fertilizer placement strategies modified root growth and affected the adaptability of the soybean plant to environment stress. Changes in root system interfere directly with plant–soil interactions, altering nutrient and water uptake. Thus, all changes in P fertilizer management will likely influence root growth and can affect crop yield. The ST–DB

treatment promoted an increase of RLD in the 20- to 25-cm soil layer. The strip tillage promoted lower soil penetration resistance values with a consequent increase in the root system growth in the soil profile. However, greater RLD were found with the combination of strip tillage and deep band P fertilizer placement (ST–DB). Values for RLD near the soil surface were generally similar for the NT–BR, NT–B, and NT–SB treatments. As an indirect effect of root growth, P fertilizer placement methods affected the drought tolerance of soybean plants, where treatments that promoted deeper root system growth showed reduced yield penalties under induced drought. Thus, our results showed that the combination of some soil disturbance combined with deep placement of P fertilizer (ST–DB) has the potential to mitigate the negative effects of short-term drought stress during soybean reproductive growth stages.

REFERENCES

- Adee, E., F.D. Hansel, D.A. Ruiz Diaz, and K. Janssen. 2016. Corn response as affected by planting distance from the center of strip-till fertilized rows. *Front. Plant Sci.* 7:1232–1241. doi:10.3389/fpls.2016.01232
- Amado, T.J.C., C. Bayer, P.C. Conceição, E. Spagnollo, B.H.C. De Campos, and M. Da Veiga. 2006. Potential of carbon accumulation in no-till soils with intensive use and cover crops in southern Brazil. *J. Environ. Qual.* 35:1599–1607. doi:10.2134/jeq2005.0233
- Balastreire, L.A., and J.L.D. Coelho. 2000. Aplicação Mecanizada de Fertilizantes e Corretivos, São Paulo, ANDA-Associação Nacional para Difusão de Adubos- Boletim Técnico 7:51.
- Bates, T.R., and J.P. Lynch. 1996. Stimulation of root hair elongation in *Arabidopsis thaliana* by low phosphorus availability. *Plant Cell Environ.* 19:529–538. doi:10.1111/j.1365-3040.1996.tb00386.x
- Böhm, W. 1979. Methods of studying root systems. *Ecological Studies* 33. Springer, New York. doi:10.1007/978-3-642-67282-8
- Bolliger, A., J. Magid, T.J.C. Amado, F.N. Skora, M.F.R. Santos, A. Calegari et al. 2006. Taking stock of the Brazilian ‘Zero Till revolution’: A review of landmark research and farmers practice. *Adv. Agron.* 91:47–110. doi:10.1016/S0065-2113(06)91002-5
- Borges, R., and A.P. Mallarino. 2000. Grain yield, early growth, and nutrient uptake of no-till soybean as affected by phosphorus and potassium placement. *Agron. J.* 92:380–388. doi:10.2134/agronj2000.922380x
- Borkert, C.M., and S.A. Barber. 1985. Soybean shoot and root growth and phosphorus concentration as affected by phosphorus placement. *Soil Sci. Soc. Am. J.* 49:152–155. doi:10.2136/sssaj1985.03615995004900010031x
- Bouyoucos, G.J. 1962. Hydrometer method improved for making particle size analyses of soils. *Agron. J.* 54:464–465. doi:10.2134/agronj1962.00021962005400050028x
- Calonego, J.C., J.P. Raphael, J.P. Rigon, L. de Oliveira Neto, and C.A. Rosolem. 2017. Soil compaction management and soybean yields with cover crops under no-till and occasional chiseling. *Eur. J. Agron.* 85:31–37. doi:10.1016/j.eja.2017.02.001
- da Costa, C.H.M., and C.A.C. Crusciol. 2016. Long-term effects of lime and phosphogypsum application on tropical no-till soybean–oat–sorghum rotation and soil chemical properties. *Eur. J. Agron.* 74:119–132. doi:10.1016/j.eja.2015.12.001
- Denton, M.D., C. Sasse, M. Tibbett, and M.H. Ryan. 2006. Root distribution of Australian herbaceous perennial legumes in response to phosphorus placement. *Funct. Plant Biol.* 33:1091–1102. doi:10.1071/FP06176
- Drew, M.C. 1975. Comparison of the effects of a localized supply of phosphate, nitrate, ammonium and potassium on the growth of the seminal root system, and the shoot, in barley. *New Phytol.* 75:479–490. doi:10.1111/j.1469-8137.1975.tb01409.x

- Dybing, C.D., H. Ghiasi, and C. Paech. 1986. Biochemical characterization of soybean ovary growth from anthesis to abscission of aborting ovaries. *Plant Physiol.* 81:1069–1074. doi:10.1104/pp.81.4.1069
- Eissenstat, D.M., and R.D. Yanai. 1997. The ecology of root lifespan. In: A.M. Fitter, editor, *Advances in ecological research*. Vol. 27. Academic Press, San Diego. p. 1–60. doi:10.1016/S0065-2504(08)60005-7
- EMBRAPA. 1979. Handbook of soil analysis methods. (In Portuguese.) Empresa Brasileira de Pesquisa Agropecuária. Serviço Nacional de Levantamento e Conservação de Solos, Rio de Janeiro, Brazil.
- Fageria, N.K., and A. Moreira. 2011. The role of mineral nutrition on root growth of crop plants. *Adv. Agron.* 110:251–331. doi:10.1016/B978-0-12-385531-2.00004-9
- Fernandez, E.M., C.A.C. Crusciol, C.A.S. Thimoteo, and C.A. Rosolem. 1995. Soybean nutrition and dry matter yield as affected by phosphorus fertilisation and soil compaction. *Scientific* 23:117–132.
- Friesen, D.K., I.M. Rao, R.J. Thomas, A. Oberson, and J.I. Sanz. 1997. Phosphorus acquisition and cycling in crop and pasture systems in low fertility tropical soils. *Plant Soil* 196:289–294. doi:10.1023/A:1004226708485
- Granato, T.C., and C.D. Raper, Jr. 1989. Proliferation of maize (*Zea mays* L.) roots in response to localized supply of nitrate. *J. Exp. Bot.* 40:263–275. doi:10.1093/jxb/40.2.263
- Görbing, J. 1948. Simple spade methods. In: W. Böhm, editor, *Methods of studying root systems*. Springer-Verlag, Berlin. p. 20–21.
- Hansel, F.D., D.A. Ruiz Diaz, T.J.C. Amado, and L.H.M. Rosso. 2017. Deep banding increases phosphorus removal by soybean grown under no-tillage production systems. *Agron. J.* 109:1091–1098. doi:10.2134/agronj2016.09.0533
- Hatfield, J.L., T.J. Sauer, and J.H. Prueger. 2001. Managing soils to achieve greater water use efficiency. *Agron. J.* 93:271–280. doi:10.2134/agronj2001.932271x
- Howard, D.D., M.E. Essington, and D.D. Tyler. 1999. Vertical phosphorus and potassium stratification in no-till cotton soils. *Agron. J.* 91:266–269. doi:10.2134/agronj1999.00021962009100020014x
- Joris, H.A.W., E.F. Caires, A.R. Bini, D.A. Scharr, and A. Haliski. 2013. Effects of soil acidity and water stress on corn and soybean performance under a no-till system. *Plant Soil* 365:409–424. doi:10.1007/s11104-012-1413-2
- Kochian, L.V. 1995. Cellular mechanisms of aluminum toxicity and resistance in plants. *Annu. Rev. Plant Biol.* 46:237–260. doi:10.1146/annurev.pp.46.060195.001321
- Li, H., A. Mollier, N. Ziadi, Y. Shi, L.É. Parent, and C. Morel. 2017. Soybean root traits after 24 years of different soil tillage and mineral phosphorus fertilization management. *Soil Tillage Res.* 165:258–267. doi:10.1016/j.still.2016.09.002
- Linkohr, B.I., L.C. Williamson, A.H. Fitter, and H.M.O. Leyser. 2002. Nitrate and phosphate availability and distribution have different effects on root system architecture of *Arabidopsis*. *Plant J.* 29:751–760.
- Littell, R.C., G.A. Milliken, W.W. Stroup, R.D. Wolfinger, and O. Schabenberber. 2006. SAS for mixed models. 2nd ed. SAS Inst., Cary, NC.
- Liu, F., M.N. Andersen, and C.R. Jensen. 2003. Loss of pod set caused by drought stress is associated with water status and ABA content of reproductive structures in soybean. *Funct. Plant Biol.* 30:271–280. doi:10.1071/FP02185
- López-Bucio, J., E. Hernández-Abreu, L. Sánchez-Calderón, M.F. Nieto-Jacobo, J. Simpson, and L. Herrera-Estrella. 2002. Phosphate availability alters architecture and causes changes in hormone sensitivity in the *Arabidopsis* root system. *Plant Physiol.* 129:244–256. doi:10.1104/pp.010934
- Lu, S., and M. Miller. 1993. Determination of the most efficient phosphorus placement for field-grown maize (*Zea mays* L.) in early growth stages. *Can. J. Soil Sci.* 73:349–358. doi:10.4141/cjss93-037
- Lynch, J. 2013. Steep, cheap and deep: An ideotype to optimize water and N acquisition by maize root systems. *Ann. Bot. (Lond.)* 112:347–357. doi:10.1093/aob/mcs293
- McCully, M.E. 1999. Roots in soil: Unearthing the complexities of roots and their rhizospheres. *Annu. Rev. Plant Physiol. Plant Mol. Biol.* 50:695–718. doi:10.1146/annurev.arplant.50.1.695
- Meurer, E.J., D. Rhenheimer, and C.A. Bissani. 2006. Fenômenos de sorção em solos. In: E.J. Meurer, editor, *Fundamentos de química do solo*. 3rd ed. Evangraf, Porto Alegre. p. 117–162.
- Nacry, P., G. Canivenc, B. Muller, A. Azmi, H. Van Onckelen, M. Rossignol, and P. Dumas. 2005. A role for auxin redistribution in the responses of the root system architecture to phosphate starvation in *Arabidopsis*. *Plant Physiol.* 138:2061–2074. doi:10.1104/pp.105.060061
- Nelson, W.L., A. Mehlich, and E. Winters. 1953. The development, evaluation and use of soil tests for phosphorus availability. In: W.H. Pierre and A.G. Norman, editors, *Soil fertilizer phosphorus*. Academic Press, New York. p. 153–188.
- Niu, Y.F., R.S. Chai, G.L. Jin, H. Wang, C.X. Tang, and Y.S. Zhang. 2012. Responses of root architecture development to low phosphorus availability: A review. *Ann. Bot. (Lond.)* 112:391–408. doi:10.1093/aob/mcs285
- Nkebiwe, P.M., M. Weinmann, A. Bar-Tal, and T. Müller. 2016. Fertilizer placement to improve crop nutrient acquisition and yield: A review and meta-analysis. *Field Crops Res.* 196:389–401. doi:10.1016/j.fcr.2016.07.018
- Péret, B., M. Clément, L. Nussaume, and T. Desnos. 2011. Root developmental adaptation to phosphate starvation: Better safe than sorry. *Trends Plant Sci.* 16:442–450. doi:10.1016/j.tplants.2011.05.006
- Purcell, L.C., C.A. King, and R.A. Ball. 2000. Soybean cultivar differences in ureides and the relationship to drought tolerant nitrogen fixation and manganese nutrition. *Crop Sci.* 40:1062–1070. doi:10.2135/cropsci2000.4041062x
- Raven, J.A., and D. Edwards. 2001. Roots: Evolutionary origins and biogeochemical significance. *J. Exp. Bot.* 52:381–401. doi:10.1093/jxb/52.suppl_1.381
- Ribas-Carbo, M., N.L. Taylor, L. Giles, S. Busquets, P.M. Finnegan, D.A. Day et al. 2005. Effects of water stress on respiration in soybean leaves. *Plant Physiol.* 139:466–473. doi:10.1104/pp.105.065565
- Rosolem, C.A., J.S. Assis, and A.D. Santiago. 1994. Root growth and mineral nutrition of corn hybrids as affected by phosphorus and lime. *Commun. Soil Sci. Plant Anal.* 25:2491–2499. doi:10.1080/00103629409369202
- Salisbury, F.B., and C.W. Ross. 1992. *Plant physiology*. 4th ed. Wadsworth, Belmont, CA.
- Shen, J., L. Yuan, J. Zhang, H. Li, Z. Bai, X. Chen, W. Zhang, and F. Zhang. 2011. Phosphorus dynamics: From soil to plant. *Plant Physiol.* 156:997–1005. doi:10.1104/pp.111.175232
- Shoemaker, H.E., E.O. McLean, and P.F. Pratt. 1961. Buffer methods for determining lime requirement of soils with appreciable amounts of extractable aluminum. *Soil Sci. Soc. Am. J.* 25:274–277. doi:10.2136/sssaj1961.03615995002500040014x
- Tron, S., G. Bodner, F. Laio, L. Ridolfi, and D. Leitner. 2015. Can diversity in root architecture explain plant water use efficiency? A modeling study. *Ecol. Modell.* 312:200–210. doi:10.1016/j.ecolmodel.2015.05.028
- USDA–NRCS. 2003. *Soil taxonomy: Keys to soil taxonomy*. 9th ed. USDA–NRCS, Washington, DC.
- Walkley, A., and I.A. Black. 1934. An examination of the Degtjareff method for determining soil organic matter and a proposed modification of the chromic acid titration method. *Soil Sci.* 37:29–38. doi:10.1097/00010694-193401000-00003
- Williamson, L.C., S.P.C.P. Ribrioux, A.H. Fitter, and H.M.O. Leyser. 2001. Phosphate availability regulates root system architecture in *Arabidopsis*. *Plant Physiol.* 126:875–882. doi:10.1104/pp.126.2.875