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LOCAL DE APLICAÇÃO DO FÓSFORO, SISTEMA RADICULAR E PRODUTIVIDADE DA CULTURA DA SOJA EM PLANTIO DIRETO

Santa Maria, RS
2016

Fernando Dubou Hansel

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Tese apresentada ao Curso de Pós-Graduação em Engengaria Agrícola, da Universidade Federal de Santa Maria (UFSM, RS), como requisito parcial para obtenção do título de **Doutor em Engenharia Agrícola.**

Orientador: Prof Dr. Telmo Jorge Carneiro Amado

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Ao vô Lino Afonso Hansel (in memorian), como resposta de suas orações e carinho.
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RESUMO

LOCAL DE APLICAÇÃO DO FÓSFORO, SISTEMA RADICULAR E PRODUTIVIDADE DA CULTURA DA SOJA EM PLANTIO DIRETO

AUTOR: FERNANDO DUBOU HANSEL
ORIENTADOR: TELMO JORGE CARNEIRO AMADO

A agricultura moderna apresenta constantes desafios, dentre eles produtivos e econômicos. A busca de maiores produtividades e eficiência no campo conduz a aprimoramentos das técnicas hoje realizadas. Diante de um sistema produtivo como a semeadura direta e seus limitantes, o manejo da fertilização, principalmente a fosfatada, ganha destaque. Para um melhor uso-eficiente deste recurso não renovável estudos visam o entendimento dos fatores responsáveis por sua disponibilidade no solo e em que magnitude a planta utiliza o fósforo (P) provindo do solo. Neste caso, estratégias relacionadas ao manejo do fertilizante fosfatado no solo podem alterar a dinâmica de absorção do P, tanto quanto a capacidade de adaptação da planta às condições ambientais diversas. O trabalho a seguir é constituído por três etapas, resultante de experimentos realizados nos municípios de Não-Me-Toque-RS (Field 1) e São-Sepé-RS (Field 2), sul do Brazil, durante o ano agrícola de 2014/2015. As condições experimentais as quais as plantas foram analisadas continham semelhantes climas, radiação solar e relevo, porém diferentes características químicas e físicas do solo. O sistema de manejo do solo adotado em ambas as áreas é o sistema de semeadura direta. O experimento foi delineado em blocos ao acaso com quatro repetições e cinco tratamentos. As parcelas possuiam dimensões de 15 x 200 m. Os tratamentos consistem de cinco profundidades de alocação de P: subsolador + fertilização profunda (20 cm), subsolador + na linha de semeadura (10 cm), a lanço, na linha de semeadura (10 cm) e acima da semente (0-5 cm). A fonte fosfatada utilizada foi o superfosfato triplo (0-42-0) na dose de 70 kg ha^{-1}. Os resultados estão apresentados e discutidos na forma de artigos científicos, sendo abordados aspectos relacionados a mudanças no crescimento radicular proporcionados pelo manejo do P (Artigo 1), uso e balanço do P em cada manejo de fertilização fosfatada (Artigo 2) e o impacto do manejo da fertilização fosfatada em situações de estresse hídrico (Artigo 3). Por fim, para uma abordagem geral do estudo fez-se necessária uma discussão abrangendo os três artigos. A fertilização fosfatada profunda proporcionou maior crescimento do sistema radicular na profundidade de 20-25 cm, maior recuperação e uso do P no solo e menores perdas em produtividade devido estresse hídrico.

Palavras-chave: Manejo do fósforo. Fertilização profunda. *Glycine max*.

ABSTRACT

PHOSPHORUS PLACEMENT, ROOT SYSTEM AND SOYBEAN CROP YIELD IN NO-TILL SYSTEM

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Modern agriculture presents constant challenges, among them productive and economical. The target on greater productivity and efficiency in the field leads to improvements of techniques performed today. Before a production system such as no-till and its limitations, the management of fertilization, especially phosphorus, is highlighted. Therefore, fertilization management can alter the P uptake dynamic, as much as the plant's capacity to adapt to different environmental conditions. The field study consists of three steps, resulting from experiments conducted near Não-Me-Toque-RS (Field 1) and Sao-Sepe-RS (Field 2), Southern Brazil, during the agricultural year 2014/2015. The experimental conditions where the plants were evaluated had similar climate, incident solar radiation and relief characteristics, but different soil physical and chemical characteristics. The soil management system adopted in both experimental areas is no-till. The experimental design was a randomized complete blocks with four replicates and five treatments. Individual plot size was 15 m wide x 200 m long. The treatments consist of five P allocation depths: subsoiler + deep band (20 cm), subsoiler + in-furrow (10 cm), broadcast, in-furrow (10 cm), and above seed (0-5 cm). The phosphorus source used was triple superphosphate (0-42-0) at rate of 70 kg ha^{-1}. The results are presented and discussed in the form of articles, and addressed aspects related to changes in root growth provided by the P placement (Article 1), use and balance of P in each P placement (Article 2) and the impact of P placement in water stress conditions (Article 3). Finally, for a general approach of the study it was necessary a discussion covering the three studies. Phosphorus deep band showed higher root growth at 20-25 cm depth, greater soil P recovery and use, and lower losses by water stress.

Keywords: Phosphorus management. Deep fertilization. *Glycine max.*

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1 INTRODUÇÃO

A agricultura brasileira ocupa hoje lugar de destaque perante o cenário mundial. Os grandes avanços tecnológicos e produtivos no setor agrícola proporcionaram ganhos econômicos significativos com relevada contribuição ao PIB nacional. Na medida que há um refinamento dos fatores que regem a produtividade das culturas, busca-se através do conhecimento específico a obtenção de maior eficiência produtiva.

Uma das maiores conquistas técnicas alcançadas nas últimas décadas foi a introdução do sistema de semeadura direta. Os avanços na área conservacionista do solo proporcionados por este sistema conduziram à avanços na qualidade química, física e biológica dos solos. A base para a expressão genética de novas cultivares, melhora na eficiência mecânica de equipamentos agrícolas, desenvolvimento da tecnologia embarcada em máquinas, aumento do uso-eficiência da água e nutrientes, entre outros, estiveram no estabelecimento da semeadura direta.

Em um ambiente altamente produtivo, o somatório de pequenos fatores podem acarretar em grandes perdas produtivas. Passados 50 anos da introdução da semeadura direta no Brasil, inúmeros estudos correlacionam fatores químicos, físicos e biológicos dos solos com fatores produtivos e de eficiência nutricional das plantas. A reduzida perturbação ao solo proporciona a formação de gradientes nutricionais, principalmente de nutrientes com baixa mobilidade no solo, densificação na camada superficial e o estabelecimento de uma rica biota no solo que interage com o sistema solo-planta.

Dentre os desafios encontrados está a forma a qual a planta obtém os nutrientes necessários para seu desenvolvimento e como o manejo do fertilizante pode impactar no aumento da eficiência nutricional das culturas. O agravante está em nutrientes como o fósforo (P), o qual apresenta baixa mobilidade no solo e alta capacidade reativa, podendo ser adsorvido especificamente aos argilominerais do solo ou precipitado com outros íons à formas pouco solúveis e indisponíveis à planta.

Devido ao importante papel do P no sistema fotossintético e desenvolvimento vegetal, há uma grande demanda deste nutriente pela planta, superando muitas vezes a capacidade difusiva e de fornecimento do solo. Neste caso, é necessária a suplementação de P através da fertilização.

Maiores concentrações de P no solo provocadas pela adição de fertilizantes fosfatados tendem a alterar morfologicamente o desenvolvimento radicular, causando uma assimetria generativa do sistema. O ajuste morfológico resultante não só influenciará no aumento da eficiência da absorção de P, como também impactará na absorção dos demais nutrientes e da água. Neste contexto destinam-se os estudos que visam o aumento da eficiência da fertilização fosfatada e a interação solo-planta.

O presente estudo está dividido em três etapas na forma de artigos científicos, os quais abordam em primeira instância o impacto da fertilização fosfatada no desenvovimento radicular da soja. Em seguida, aspectos nutricionais relacionados ao desenvolvimento vegetal, absorção de P, eficiência da fertilização e recuperação do fertilizante aplicado. Por fim, serão discutidas as possíveis causas da variação na produtividade da soja pelo manejo da fertilização fosfatada e o impacto do manejo da fertilização em condições de estresse hídrico.

2 ARTIGO 1: Phosphorus fertilizer placement affects soybean root distribution in soil profile under no-till system

2.1 ABSTRACT

Plant root growth is responsive to soil conditions including nutrient distribution and water availability. Phosphorus fertilizer placement under no-till system could affect root distribution in soil profile, nutrient uptake by plants and consequently, crop yields. Our objective was to evaluate the influence of phosphorus (P) fertilizer placement on soybean root distribution in soil profile under no-till system. A soybean field experiment was conducted near the cities of Não-Me-Toque, RS (Field 1) and São Sepé, RS (Field 2), in southern Brazil, during the 2014/2015 crop season. The sites had different climate, and soil chemical and physical proprieties. Treatments consisted of phosphorus placements: subsoiller plus deep band (DB), subsoiller plus in-furrow (SF), broadcast (B), in-furrow (F), and above seed (AS). Soybean total root length and root diameter were evaluated at the 0 to 25 cm depth in 5 cm intervals. Phosphorus placement influenced root system growth and distribution in the soil profile. There was an increase of root system length in deeper layers in response to deep P placement at both sites. Management practices that provided higher concentrations of P in furrow promoted an increase of root length in shallow layers (0- to 10 cm). Broadcast P resulted in same or lower root length growth than in-furrow treatments in the 0- to 5 cm layer and showed an increase of lateral root growth in the 10- to 15 cm layer. Phosphorus placement also influenced roots diameter proportion, especially of smaller diameters. Management practices that increase root growth allow for a better exploration of the soil volume, which may be especially important in environments limited by water or nutrients availability.

2.2 INTRODUCTION

No-tillage system (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). The absence of soil disturbance associated with NT results in higher nutrient concentration near the soil surface, especially for immobile nutrients such as P (Eltz et al., 1989; Rheinheimer & Anghinoni, 2001; Amado et al., 2006). The resulting vertical chemical gradient in NT could affect the nutrient uptake by plants and consequently, crop yields.

Plants root system have great adaptability during the growing season to respond to environmental conditions that affect root architecture, such as water and nutrient availability (Williamson et al., 2001). Although greater superficial root growth can be associated to genetic traits (Salisbury and Ross, 1992), previous studies have shown that management of P fertilizer has the potential to significantly affect the root morphology and growth of crops (Borkert & Barber, 1985; Denton et al., 2006; Lu & Miller, 1993). According to Costa et al. (2009), crop roots often accumulate over time in the most fertilized areas of the profile, especially in the 0- to 10 cm layer, which coincides with the distribution of P in the soil. As a consequence, distribution of the P fertilizer in the soil profile influenced by phosphorus placement tends to affect the distribution of root and shoot growth of plants (Klepker e Anghinoni, 1993).

Exposure of the root system to high phosphate concentrations causes a localized increase of the initiation and subsequent extension of the primary and secondary roots, when compared to the low concentration zone (Drew, 1975; Salisbury and Ross, 1992). On the other hand, other studies report the stimulation of root growth in treatments with low P concentration (López-Bucio et al., 2003; Müller and Schmidt, 2004). Physiological and hormonal signals were being sent to the roots as a response to a low P availability (Nacry et al., 2005; Péret et al., 2011) promoting root growth.

Broadcast P tends to provide the soil surface with high concentrations of P and stimulates shallow root growth (Williamson, 2001). As a consequence, nutrient availability tends to decrease during drought periods (Borges & Mallarino, 2000). On the other hand, when P is in broadcast, roots located in non-fertilized deep layers could be stimulated to develop a more extensive root system, due to low P concentration stimulus (Tornquist, 2001; Nacry et al., 2005; Peret et al., 2011) improving plants water supply.

Banding P in furrow at planting place the nutrient near the planting rows, which reduces P fixation in the soil (Balastreire & Coelho, 2000) and increases P availability to the rooting system (Shen et al., 2011). However, this system promotes a localized increase of the rooting system, resulting in less area of roots in contact with the fertilizer (Guareschi et al., 2008). As a consequence, less soil volume is explored, so nutrients and water uptake can be affected.

The use of a system with deep-band placement of P fertilizer could induce deeper root growth, increasing the plants’ access to water and nutrients other than P. Deep P banding could increase fertilizer use efficiency, early plant growth, and grain yield (Borges & Mallarino, 2001). However, it is assumed that P limitation impacts crop production when it occurs in early growth season (Grant et al., 2001), reason why in-furrow P banding is a widely accepted practice.

The influence of P management practices in soybean root growth is still unknown. The data so far does not allow recommendation of a systematic management that considers the impact on root growth, potentially affecting P, water and other nutrients uptake (Sá et al. 2013). Thus, the objective of this study was to evaluate the direct impact of P fertilizer placement on soybean root distribution, assessing changes on root length and diameter in soil profile, under no-till system.

2.3 MATERIALS AND METHODS

Site Description

Two field experiments were conducted near Não-Me-Toque, RS (Field 1) and São Sepé, RS (Field 2), southern Brazil, in the 2014/2015 crop season. These sites have similar climate, incident solar radiation and other characteristics (Table 1), as well as different soil chemical and physical composition (Table 3).

The soil management adopted in both experimental areas is long-term no-tillage. Areas have been under no-till for 5 yr in São Sepé and 30 yr in Não-Me-Toque, which corresponds to a transition and a maintenance phase of this system (Sá et al., 2001), respectively.

Treatments

The experimental design was a randomized complete block with four replicates and five treatments. Individual plot size was 15 m wide by 200 m long. Treatments consisted of five phosphorus placements: subsoiler plus deep band (DB), subsoiler plus in-furrow (SF), broadcast (B), in-furrow (F), and above seed (AS). The phosphorus source used was triple surperphosphate (0-42-0) at seeding at the rate of 70 kg P_2O_5 ha^{-1}. The equipment used to apply the fertilizer in treatment DB was developed from a previously existing commercial subsoiler FOX® (STARA®, Nao-Me-Toque, RS). This equipment has 9 straight knifes by 30 cm wide and has a fertilizer tank attached to the chassis. Thus, the P application in DB was 20 cm deep spaced each 30 cm wide. The same subsoiler used in DB was utilized in SF, but without deep fertilizer application. In SF the fertilizer was applied with planter shank (~10 cm), in planting, in order to isolate the P placement effect of DB. Broadcast treatment (B) was performed immediately prior to planting, and was not incorporated. The planting in B was realized using planter shank system without fertilizer application. In-furrow treatment was established with planter shank (fertilization on row) applying fertilizer around 10 cm deep. Treatment AS has been used in large scale by farmers in southern Brazil. It is a disk rippled coulter system coupled after fertilizer has been applied in row but above the surface. In this system the P fertilizer is slightly incorporated and lies above the seed.

Soybean planting was performed with a Victória DPS 4050 planter (STARA®, Não-Me-Toque, RS) total 4.5 m wide spacing (10 sowing lines x 45 cm wide). Thus, P placement in DB not necessary fit with planting rows. Broadcast placement was performed with a self-propeller spreader Hércules 5.0 (STARA®, Não-Me-Toque, RS) with 27 m width spread.

The soybean varieties used were the NA 5909 RG in Field 1 and Monsoy 5917 IPRO in Field 2 in the plant populations of 330,000 and 300,000 plants ha^{-1}, respectively. Varietal characteristics are given in Table 2. This study was performed on commercial areas lent by farmers, where soybean varieties, plant populations, and planting date followed agronomic recommendations to each region aiming higher yields.

Measurements

Soybean root growth was evaluated at flowering stage using the Needleboard Monolith method and rooting profile (Bohm, 1979), adapted by Pedó (1986). The monoliths were 30x40x10 cm with nails spaced 5- to 5 cm, with a total soil volume collection of 8.75 dm^3.

Field procedure consisted of opening a trench to allow access to the root system. The boards were pressed to vertical walls of the trenches (60 cm width and 40 cm depth), perpendicular to the crop row so that the nails could penetrate the soil, allowing removal of a soil block with roots intact. The monoliths were covered with plastic wrap for transportation.

After prior moistening, the monoliths were subjected to immersion in a 6% NaOH solution, where they remained for 60 minutes to favor soil dispersion and minimize roots damage. For better understanding of root distribution as affected by treatments, the entire root system was cut off in layers of 5 cm, representing the soil layers.

The evaluation of total root length (cm dm^{-3}) and root diameter (Class I- < 0.25 mm root diameter; Class II- 0.25 to 0.50 mm root diameter; Class III- 0.50 to 1.00 mm; Class IV- 1.00 to 3.00 mm root diameter; Class V- > 3.00 mm root diameter) was performed by digitalizing the roots with the scanner Epson 11000XL, in a 600 dpi resolution. The generated images were analyzed using the software WinRhizo Pro 2013. Root classes were created considering observed values, with 5 classes between the lower and higher values.

Statistical analysis

All statistical analyses were run in SAS Studio (version 9.4; SAS, Cary, NC). Soybean root data were analyzed using PROC GLIMMIX (restricted maximum likelihood estimation) procedure for generalized linear mixed models (GLMMs). The factor P placement with five levels (i.e., deep band, in-furrow plus tillage, broadcast, in-furrow, and above seed) was modeled as fixed factor; soil depth, root classes, and soil depth x root classes x treatments interactions were modeled as random effects. Corrected denominator degrees of freedom were obtained using the Kenward-Roger adjustment. A Tukey post-hoc comparison of means test was done using the LSMEANS and SLICE option for PROC GLIMMIX.

2.4 RESULTS AND DISCUSSION

Root length

Phosphorus placement influenced ($p< 0.001$) root system growth and architecture (Table 4). Data show that environmental conditions affected root system, which corroborates with Williamson et al. (2001) observations. Both, high and low P concentration promoted by P management alter root length and diameter in soil profile.

There was an increase of root system length in deeper layers in response to deep phosphorus placement ($p < 0.001$) in both sites. In Field 1 and Field 2 the total average root length in DB was 90.5 and 87.7 cm dm^{-3} in the 20- to 25 cm layer, respectively and in SF was 51.4 and 47.4 cm dm^{-3} in the 20- to 25 cm layer, respectively. Also, DB had more uniform root distribution among the entire profile (Figure 1 and 2), enabling for a more effective exploration of deeper layers. A greater concentration of roots in deeper layers in DB can be explained because root system grows toward new soil regions forming additional lateral roots before water and nutrients have been supplied (Salisbury and Ross, 1992). After reaching a fertilized area, roots proliferate more intensively (Drew 1985; Granato and Raper, 1989) improving root length in the fertilized layer. Morphological adjustments can occur in the plant (i.e, leaves, stems and roots) in order to balance the photoassimilates allocation toward organs with greatest energetic demand, matching physiological activities and functions performed by these organs (Poorter, 2012). In Field 1 the reduced plant shoot dry weight of DB compared with SF can be a signal of higher energetic expenditure for root growth (Figure 1).

Management practices that provide high concentrations of phosphorus in the row (SF, F and AS) promoted a shallow local increase of root length, with most roots concentrated in the 0- to 10 cm layer in this treatments (Table 5). Naturally, greatest proportion of root system is in shallow layers, which is a genetic trait of plants adaption (Salisbury and Ross, 1992). This occurs due to the majority of the nutrients being deposited on soil surface through the nutrient cycling process (Costa et al., 2009). In-furrow placement locates the phosphate fertilizer in the row (10 cm deep), slightly below soil surface, altering normal distribution of nutrients in the soil. Root system adapts to the nutritional availability of the environment, increasing root growth in fertilized area (Drew, 1975; Williamson et al., 2001). According to

Salisbury and Ross (1992), in a natural environment most of the plant biomass is in the root system. However, when plants are grown with adequate availability of water and nutrients supply they stop investing in root biomass to invest in shoot biomass (Bugbee and Salisbury, 1988), dramatically reducing root growth (Nacry et al., 2005).

Tillage promoted an increment in total root length when SF and F was compared, with different root distribution in soil profile (Figures 1 and 2). No-till has a tendency to increase soil bulk density, potentially influencing root architecture (Hakansson and Medvedev, 1995). According to Under and Kaspar (1994), the increase of soil bulk density can alter root distribution but not total root length in profile due to a compensatory growth effect. Notwithstanding, our study showed an increase in total root length due to tillage when compared to no-till treatment, despite the lack of a limiting physical parameter (Girardello et al., 2014).

Broadcast P treatment resulted in the lower total root length in the 0- to 5 cm layer in Field 2 and no difference between F and AS treatments in Field 1, considering the same layer (Figure 1 and 2). This result indicates no stimulus to the shallow root growth due to surface fertilization in B. The hypothesis is that the plant does not need to produce a great amount of roots, and spend energy in the process of doing so, if there are enough roots to supply the nutrient demand. Root system growth may have high build up and maintenance costs (Eissenstadt and Yanai, 1997). Therefore, signals for root growth will be sent just by a starvation stimulus (Nacry et al., 2005), so the roots can find nutrient sufficiency in a larger soil volume, or develop localized roots when there is a higher nutrient availability in a specific fertilizer placement spot (Borkert & Barber, 1985). These strategies promote a more efficient balance of energy in the plant, developing roots only when and where it is necessary.

On the other hand, the data suggest an increase of lateral root length in the 10- to 15 cm layer in the plants under B (Figure 1 and 2). In broadcast P placement, part of the root system will not access phosphate fertilizer, where the soil P content could not supply full plant demand in the rate and speed neeed, inducting a local plant-root P deficit. In this case local growth signals promoted for hormones are activated to promote root growth (Hermans et al., 2006). Previous researches have shown the role of auxin in this process (Nacry et al., 2005; López-Bucio et al., 2003; Péret et al., 2011). The balance of auxin between primary and secondary roots provides distinct behaviors of inhibition or activation of root growth (Péret et al., 2011). Thus, there is a inhibition of meristem growth of the primary root and concomitantly a stimulation of lateral root (Williamson et al., 2001; Péret et al., 2011) and proliferation of root hairs (Sánchez-Calderón et al., 2006). The plant stimulates lateral root growth to increase root area in contact with soil, improving P uptake efficiency (Williamson et al., 2001).

Root diameter

Our results show that most of root length are in the diameter classes 1, 2 and 3 (i.e, <0.25 mm, 0.25 to 0.50 mm and 0.50 to 1.00 mm root diameter) in both sites in all depths (Table 5 and Table 6). This is expected because roots with smaller diameter have singular participation in absorptive and anchorage functions of the plant (Silberbush and Barber, 1983; Boot, 1989; Clarkson, 1985) been maximized per unit of root biomass.

The various functions of roots and the energetic costs to produce and maintain roots are determined by their structure and, especially, their diameter (Raven & Edwards, 2001). The uptake of a nutrient with low concentration and low diffusion coefficients in soil (e.g. phosphate in aerobic soils) has a higher uptake rate per unit of biomass if that biomass is allocated to structures of smaller diameter (McCully, 1999; Raven and Edwards, 2011). Fine roots are in intimate contact with much larger volume of soil per root volume unit (McCully, 1999).

Deep band P placement promoted an increase in length of all classes of root diameter in 15- to 25 cm deep in both sites (*p*<0.001). In Field 1 there was the same amount of roots of the classes 1 and 2 in the 5- to 10 cm layer and in the 20- to 25 cm layer. In Field 2 there was the same amount of roots of the class 2 in the 0- to 5 cm layer and in the 20- to 25 cm layer. Conversely, in this treatment there was a decrease in roots of the classes 2, 3 and 4 in the 0- to 5 cm layer (Tables 5 and 6).

The data showed difference in classes 1 and 2 root distribution between DB and SF (small letters in Tables 5 and 6). There was difference in Classes 1 and 2 root length with an increase at the 15- to 25 cm layer in Field 1 and in Class 2 root length at the 20- to 25 cm layer in Field 2 for deep band. Similarly, an increase of class 2 root length in Field 1 and in the classes 1 and 2 in Field 2 in the 5- to 10 cm layer in row fertilized treatment was observed, presenting a chemical effect by phosphorus placement in these classes of root differing DB and SF.

These results can be related with sugar and energy balance, where photoassimilates were translocated to deep roots growth. In faster roots growth, the uptake capacity of apical root zones is insufficient and most of these required mineral nutrients and photoassimilates have to be supplied from retranslocation (Marschner et al., 1995). Roots of smaller diameter may have higher construction and maintenance costs on a unit biomass basis than larger diameter roots (Eissenstaadt and Yanai, 1997).

Comparing B and F treatments there was no clear influence of the phosphorus placement on root diameter. In Field 1 there was no difference in root length in classes 1 and 2 in 0- to 5 cm layer. However, broadcast treatment promoted an increase of the class 2 root length in the 5- to 10 cm layer and in-furrow treatment promoted an improvement of the class 1 in the 5- to 10 cm layer. In Field 2 there was a reduction of root length at the 0- to 5 cm layer in the broadcast treatment and increase of class 2 root length at the 10- to 15 cm layer. In-furrow placement promoted an increase of class 1 root length at the 10- to 15 cm deep.

Above seed treatment showed a tendency to reduced root length in classes 1 and 2 for all depths in both sites but in the 0- to 5 cm layer in Field 1. Localized high phosphorus concentration and reduced tillage in row could have influenced root growth and consequently root architecture in this treatment.

2.5 CONCLUSIONS

Phosphorus placement modifies root growth and changes the adaptability of the soybean plant to the environment. Phosphorus deep band placement promotes an increase of root length in 20- to 25 cm layers. Broadcast placement does not improve shallow root length and promotes an increase of lateral roots in the 10- to 15 cm layer. On the other hand, F and AS promoted high concentration of phosphorus in furrow limiting root growth to shallow development. Our results suggest that the increase of root growth into soil profile promoted by DB, allowing a wider exploration of soil, could it present importance in environments with water and nutrients restrictions. Changes in root system interfere directly in plant-soil interactions, altering the whole plant energy balance, nutrients and water support in the plants. Thus, all changes in soil fertility will be detected by roots and can build crop yield.

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FIGURES

Figure 1. Plant dry weight and total root length on different depth according to phosphorus placement in Não-Me-Toque, RS. Santa Maria, 2016.

[†]Upper case letters compare between treatments. ‡Upper case letters compare treatments by depths. Lowercase letters compare depths in each treatment. [§]Upper case letters compare total root length by treatments. *Values followed by same letter indicate no significant difference at the $p \leq 0.05$ probability level.

Figure 2. Plant dry weight and total root length on different depth according to phosphorus placement in São Sepé, RS. Santa Maria, 2016.

‡Upper case letters compare treatments by depths. Lowercase letters compare depths in each treatment. [§]Upper case letters compare total root length by treatments. *Values followed by same letter indicate no significant difference at the $p \leq 0.05$ probability level.

Table 1. Climate characterization for the study locations of Não-Me-Toque, RS and São Sepé, RS, Brazil.

Parameters	**Site**	
	Não-Me-Toque	**São Sepé**
Latitude	28º30’S	30º15’S
Longitude	52º46’W	53º46’W
Mean annual precipitation (mm)	1950	1600
Mean annual temperature (ºC)	18	19
Elevation (m)	475	202
Incident solar radiation (MJ m^{-2} day^{-1})	16	14
Köppen climate classification	Cfa†	Cfa

†Subtropical climates.

Table 2. Soybean variety characteristics, NA 5909 RG and Monsoy 5917 IPRO.

Characteristics†	**NA 5909 RG‡**	**Monsoy 5917 IPRO§**
Maturity group	5.9	5.9
Cycle (days)	(115-130)	(105-120)
Growth habit	Indeterminate	Indeterminate
Fertility requirement	High	Medium/High
Lodging	Resistant	Resistant

†Information obtained from companies in Brazil. ‡Não-Me-Toque, RS; §São Sepé, RS.

Table 3. Soil chemical and physical characterization in Não-Me-Toque, RS and São Sepé, RS.

Location	**Chemical**									**Physical**	
	Depth	**pH$_{H20}$**	**P$^{\#}$**	**K**	**Ca**	**Mg**	**Al**	**Al§**	**Clay**	**Depth**	**PR**
	cm		- mg dm^{-3} -		-- cmol$_c$ dm^{-3} --			%	%	cm	MPa¶
São Sepé, RS†	0-1	6.1	153	466	11.4	3.4	0	0	40		
	0-5	6.0	55	251	9.4	3.6	0	0	30	0-20	2.4
	5–10	5.4	15	194	6.1	3.2	0.1	1	28		
	10-20	4.6	7	130	4.5	2.2	0.5	7	30		
	20-30	4.2	5	88	4	1.8	1.3	18	32	20-40	2.0
	30-40	4.2	3	59	3.7	1.5	1.3	20	35		
Não-Me-Toque, RS‡	0-1	5.1	78	259	7	2.1	0.2	2	37		
	0-5	5.4	58	306	7.3	2.7	0.2	2	42	0-20	1.6
	5-10	5.2	25	268	6.7	2.6	0.2	2	50		
	10-20	5.0	13	157	6.1	2.6	0.2	3	57		
	20-30	5.2	2	100	5.6	2.4	0.3	3	80	20-40	1.9
	30-40	4.9	1	57	4.5	2.1	0.4	6	84		

†Paleudalf ‡Haplortox. §Percentage of Al in the effective CEC; ¶Penetration resistance (PR). #P-Mehlich 1.

Table 4. Significance of F values for the effect of P placement on plant dry weight by depth, classes and interactions.

Effect	P > F	
	Não-Me-Toque, RS	São Sepé, RS
Plant dry weight		
Treatment	0.048	ns
Total root length by depth		
Treatment (T)	< 0.001	< 0.001
Depth (D)	< 0.001	< 0.001
T × D	< 0.001	< 0.001
Total root length by treatment		
Treatment	< 0.001	<0.001
Root diameter		
Treatment (T)	< 0.001	< 0.001
Depth (D)	< 0.001	< 0.001
T × D	< 0.001	< 0.001
Class (C)	< 0.001	< 0.001
T × C	< 0.001	< 0.001
D × C	< 0.001	< 0.001
T × D × C	< 0.001	< 0.001

^{ns} no significance at $p \leq 0.05$.

Table 5. Soybean root length by classes of diameter and soil layers, Não-Me-Toque, RS.

Treatments	Depth	Root length																			
-	*cm*	*cm dm^{-3}*																			
		Class 1 (I)				Class 2 (II)				Class 3 (III)				Class 4 (IV)				Class 5 (V)			
DB	0-5	†* A	77.92	A ‡*	a §*	B	71.30	A	a	B	22.02	B	a	C	3.98	C	b	AB	1.74	D	a
	5-10	A	38.01	A	b	B	41.92	A	b	A	22.02	B	a	AB	6.56	C	a	A	2.06	D	a
	10-15	A	42.82	A	b	A	47.70	A	b	A	21.70	B	a	A	5.65	C	ab	A	1.20	D	a
	15-20	A	26.23	A	c	A	23.22	A	c	A	11.95	B	b	A	4.35	C	ab	A	0.38	D	b
	20-25	A	31.35	A	bc	A	40.49	A	b	A	13.15	B	b	A	5.50	C	ab	A	0.07	D	b
SF	0-5	B	53.86	B	a	AB	87.51	A	a	A	34.81	C	a	AB	12.50	D	a	BC	1.20	E	a
	5-10	A	36.86	B	b	A	69.63	A	a	A	22.13	C	a	A	6.92	D	b	A	1.91	E	a
	10-15	B	22.81	B	c	AB	37.35	A	b	A	17.44	B	b	B	3.58	C	bc	C	0.04	D	b
	15-20	B	15.60	A	d	C	8.71	B	d	A	14.64	A	d	A	3.16	C	c	B	0.02	D	b
	20-25	B	17.32	A	cd	B	21.59	A	c	A	10.00	B	c	B	2.44	C	d	A	0.00	D	b
B	0-5	A	77.39	A	a	AB	88.62	A	a	A	36.29	B	a	B	10.29	C	a	C	0.60	D	ab
	5-10	B	22.58	B	b	A	59.19	A	b	A	22.23	B	b	A	7.27	C	ab	B	1.06	D	a
	10-15	BC	18.23	B	b	B	28.79	A	c	B	10.75	C	c	AB	5.05	D	b	B	0.44	E	b
	15-20	D	8.85	A	c	BC	10.98	A	d	B	4.88	B	d	B	1.39	C	c	B	0.00	D	c
	20-25	CD	10.04	A	c	D	8.65	A	d	B	2.28	B	e	C	0.77	C	c	A	0.00	D	c
F	0-5	A	78.11	A	a	AB	89.23	A	a	A	39.18	B	a	AB	12.52	C	a	A	2.73	D	a
	5-10	A	33.98	A	b	B	40.78	A	b	AB	20.67	B	b	B	4.48	C	b	AB	1.47	D	b
	10-15	D	11.62	B	c	C	18.31	A	c	C	4.99	C	c	B	3.28	C	b	BC	0.20	D	c
	15-20	CD	9.72	A	c	BC	8.59	A	d	C	2.62	B	d	B	1.08	C	c	B	0.03	D	c
	20-25	D	8.67	A	c	D	8.27	A	d	B	2.65	B	d	C	0.87	C	c	A	0.03	D	c
AS	0-5	A	96.01	A	a	A	96.26	A	a	A	36.78	B	a	A	15.70	C	a	A	2.10	D	a
	5-10	B	22.99	B	b	B	40.98	A	b	B	15.02	C	b	B	4.34	D	b	AB	1.76	E	a
	10-15	CD	13.69	A	c	C	15.19	A	c	C	5.83	B	c	C	1.83	C	c	C	0.06	D	b
	15-20	BC	13.34	A	c	B	12.35	A	c	BC	3.38	B	d	B	1.76	C	c	AB	0.05	D	b
	20-25	BC	12.92	A	c	C	12.80	A	c	B	3.21	B	d	C	1.19	C	c	A	0.00	D	b

†Upper case letters on left of means compare treatments in each class within depths. ‡Upper case letters on right of means compare classes within treatments and depths. §Lower case letter compare means within each treatment and class. * Values followed by same letter indicate no significant difference at the P≤ 0.05 probability level. (I) < 0.25 mm root diameter. (II) 0.25 to 0.50 mm root diameter. (III) 0.50 to 1.00 mm. (IV) 1.00 to 3.00 mm root diameter. (V) > 3.00 mm root diameter.

Table 6. Soybean root length by classes of diameter and soil layers, São Sepé, RS.

Treatment	Depth									Root length											
-	*cm*									*cm dm^{-3}*											
			Class 1 (I)				Class 2 (II)				Class 3 (III)				Class 4 (IV)				Class 5 (V)		
DB	0-5	[†*] AB	75.71	A [‡*]	a [§*]	B	54.70	B	a	A	17.90	C	a	A	5.86	D	a	A	0.65	E	b
	5-10	B	52.18	A	b	B	55.41	A	a	B	14.18	B	a	C	3.80	C	b	A	1.14	D	a
	10-15	A	54.93	A	b	B	37.04	B	b	A	10.32	C	b	A	3.30	D	bc	A	0.70	E	ab
	15-20	B	32.15	A	c	A	37.77	A	b	AB	6.52	B	c	A	2.57	C	cd	A	0.15	D	c
	20-25	AB	31.30	B	c	A	45.38	A	ab	A	9.30	C	b	A	1.73	D	d	A	0.02	E	c
SF	0-5	A	91.77	A	a	A	72.25	B	a	A	18.90	C	b	B	2.90	D	b	A	0.73	E	b
	5-10	A	69.82	A	b	A	84.19	A	a	A	25.23	B	a	A	8.72	C	a	A	1.25	D	a
	10-15	B	40.06	B	c	A	51.62	A	b	AB	7.93	C	c	AB	3.02	D	b	A	0.50	E	b
	15-20	AB	39.98	A	c	A	37.90	A	c	A	7.46	B	c	AB	1.75	C	c	A	0.07	D	c
	20-25	B	26.64	A	d	B	16.37	B	d	B	3.69	C	d	B	0.70	D	d	A	0.01	E	c
B	0-5	C	44.11	A	a	C	42.68	A	a	A	15.03	B	a	B	3.79	C	a	A	0.74	D	a
	5-10	D	21.21	B	b	C	28.16	A	bc	B	10.74	C	b	BC	5.10	D	a	A	1.09	E	a
	10-15	C	22.15	B	b	B	35.81	A	ab	BC	6.36	C	c	B	2.18	D	b	A	0.73	E	a
	15-20	C	18.16	B	b	B	25.06	A	c	BC	5.40	C	c	B	1.51	D	b	A	0.02	E	b
	20-25	C	19.77	A	b	B	17.94	A	d	C	2.43	B	d	B	0.63	C	c	A	0.03	D	b
F	0-5	AB	83.36	A	a	AB	61.86	B	a	A	18.26	C	a	B	2.91	D	b	A	0.85	E	a
	5-10	C	35.81	B	b	B	48.57	A	b	B	11.40	C	b	B	5.86	D	a	A	1.17	E	a
	10-15	C	18.73	A	c	C	23.07	A	c	C	4.89	B	cd	C	1.27	C	c	B	0.06	D	b
	15-20	A	45.40	A	b	B	26.48	B	c	ABC	5.71	C	c	C	0.57	D	d	A	0.00	E	b
	20-25	A	36.35	A	b	B	17.33	B	d	B	3.55	C	d	C	0.15	D	e	A	0.00	D	b
AS	0-5	B	69.83	A	a	B	56.01	B	a	A	15.18	C	a	A	6.36	D	a	A	0.90	E	a
	5-10	C	34.63	B	b	B	48.18	A	a	B	11.70	C	a	B	5.55	D	a	B	0.62	E	a
	10-15	C	19.00	B	c	C	24.37	A	b	AB	8.24	C	b	AB	2.61	D	b	B	0.07	E	b
	15-20	B	32.14	A	b	B	21.56	B	b	C	4.53	C	c	B	1.17	D	c	A	0.00	E	b
	20-25	C	17.34	A	c	C	11.73	B	c	C	2.33	C	d	B	0.98	D	c	A	0.01	E	b

[†] Upper case letters on left of means compare treatments in each class within depths. [‡] Upper case letters on right of means compare classes within treatments and depths. [§] Lower case letter compare means within each treatment and class. *Values followed by same letter indicate no significant difference at the $P \leq 0.05$ probability level. (I) < 0.25 mm root diameter. (II) 0.25 to 0.50 mm root diameter. (III) 0.50 to 1.00 mm. (IV) 1.00 to 3.00 mm root diameter. (V) > 3.00 mm root diameter.

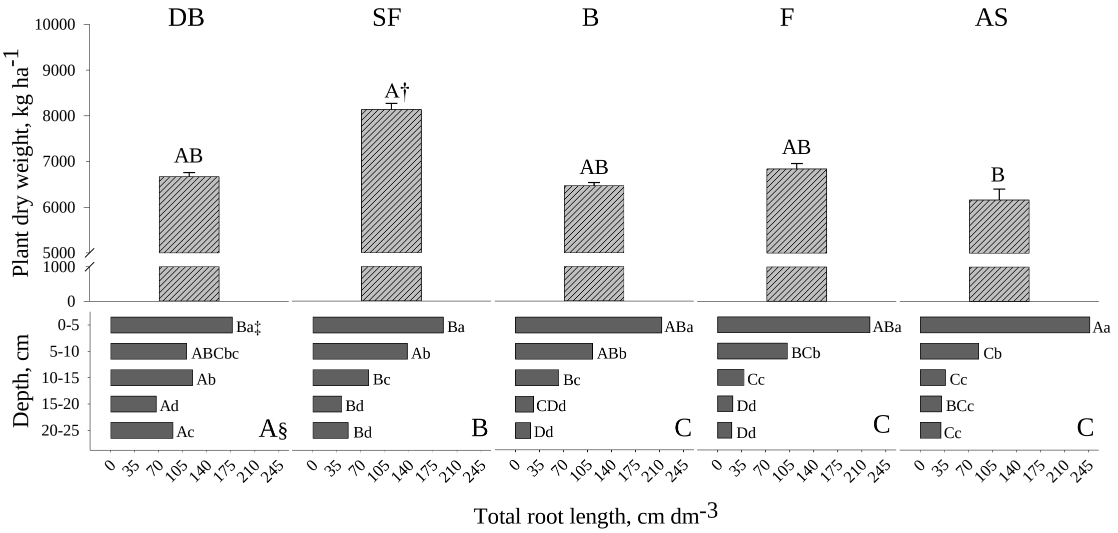

Figure 1. Plant dry weight and total root length on different depth according to phosphorus placement in Não-Me-Toque, RS.

[†]Upper case letters compare between treatments. ‡Upper case letters compare treatments by depths. Lowercase letters compare depths in each treatment. [§]Upper case letters compare total root length by treatments. *Values followed by same letter indicate no significant difference at the $p\leq 0.05$ probability level.

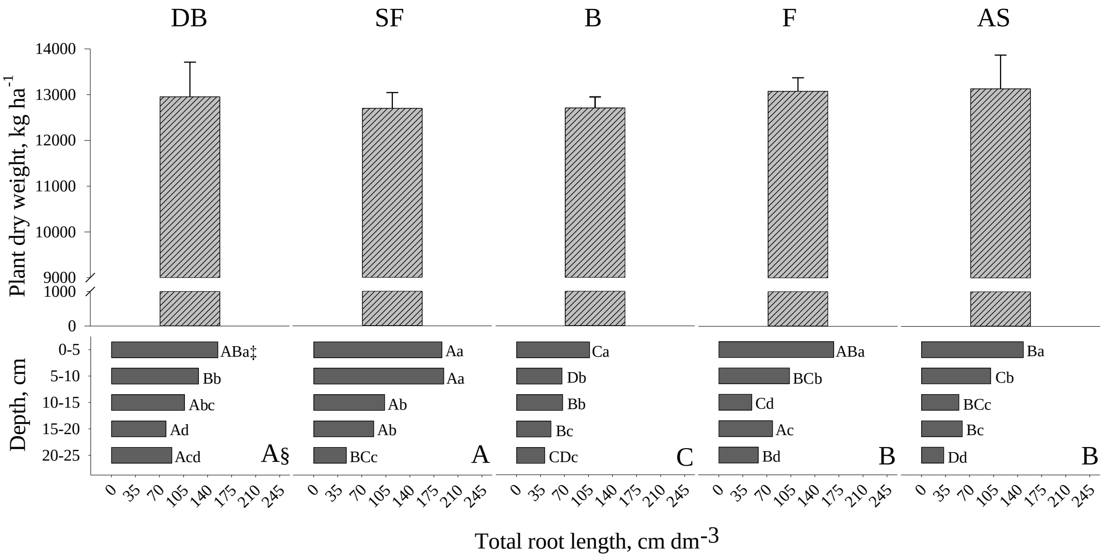

Figure 2. Plant dry weight and total root length on different depth according to phosphorus placement in São Sepé, RS.

‡Upper case letters compare treatments by depths. Lowercase letters compare depths in each treatment. §Upper case letters compare total root length by treatments. *Values followed by same letter indicate no significant difference at the *p*≤ 0.05 probability level.

3 ARTIGO 2: Soybean phosphorus balance and use under different placement of this nutrient in no-till system

3.1 ABSTRACT

Phosphorus (P) is a non-renewable resource and has generated a worldwide concern about problems with an inadequate P fertilizer management, environmental impact and consequently low P use-efficiency. The objective of this study was evaluate P balance and use in soybeans under different P placement strategies in a no-till system in Brazil. A field study was conducted near the cities of Não-Me-Toque, RS (Field 1) and São Sepé, RS (Field 2), Brazil, and consisted of phosphorus placement treatments: subsoiler plus deep band (DB), subsoiler plus in-furrow (SF), broadcast (B), in-furrow (F), and above seed (AS). Effects of P placement treatments were evaluated on plant height, plant dry weight, P uptake 20, 40, 60 and 80 days after emergence (DAE); grain P content; and grain yield. Phosphorus placement treatments altered significantly ($p < 0.001$) initial plant development as indicated by plant height, plant dry weight, plant P uptake, and consequently the partial P balance (P-PNB). In-furrow placement treatments (SF and F) showed greatest P uptake in the initial growth stages in both sites. There was higher total P uptake in Field 2 than in Field 1 during flowering (137 versus 60 kg ha^{-1} of P_2O_5, respectively). Based on the balance of inputs/outputs of P, greater amount of P was removed with grain (output) as compared to the input applied as fertilizer in both sites. The mean grain P removed was 83 and 77 kg ha^{-1} of P_2O_5 in Field 1 and Field 2, respectively. Deep band placement promoted an increase of soil P levels in the 15-to 20 cm and in 20-to 25 cm layer in Field 1 and showed no difference in Field 2 at deeper layers. Broadcast treatments promoted an increase of P levels in the 0-to 5 cm layer and similar P levels with F and AS treatments in the other layers.

3.2 INTRODUCTION

Phosphorus (P) is an essential nutrient for plant growth and development (Fan et al., 2016), playing a crucial role in signaling, metabolism, and photosynthesis (Lan et al., 2012). Thus, the soil has to provide this element in enough quantity to support the necessities of the plant, and consequently, promote high crop production (Bender et al., 2015). Therefore, because annual P uptake rate by plants exceeds the supplementation capacity of most soils, providing P via fertilizer is frequently necessary (Fageria, 2008).

In a world scale, the P fertilizer demand (P_2O_5) has raised last years, increasing from 42.7 million tons in 2014 to an expected 46.6 million tons in 2018, which corresponds to a growth rate of 2.2 percent per year (FAO, 2015). In Brazil, due to soil characteristics (i.e. weathered soils with high Al^{+3} and Fe^{+3} oxides and consequently high P adsorption) the use of P fertilization has more impact to crop yields than subtropical countries. According with ANDA (2016), the Brazilian P fertilizer shipments was 4.4 million of tons of P_2O_5 in 2015, with an increase in consumption projected of 19 percent in the world demand until 2018 (FAO, 2015). Hence, due to the high worldwide P demand, the continuum need to arise food production (Porter et al., 2014) and because P fertilizer is a non-renewable resource (Cordell et al., 2009; Scholz et al., 2013) with actually low efficiency of use, there is a worldwide concern about P fertilizer management and improving P use-efficiency to conserve natural resources.

The optimization of P in agriculture can be based on the balance of inputs/outputs of P (Shen et al., 2011). According to Sousa et al. (2009), only 46% of total P fertilizer applied in 2007 in Brazil was recovered by crops considering crop yields (rice, beans, corn, wheat, and soybeans) and P removed with grain. If only soybeans are considered, this value decreases to

32%. The authors attribute these results, among another, to problems of inadequate P fertilizer management.

Phosphate plant nutrition is predominantly controlled by P dynamics and the relations with soil/rhizosphere/plant. Management practices that promote a better contact between root system and fertilized layer can play an important role in improving P efficiency (Shen et al., 2011). Furthermore, P placement can alter root growth (Barber, 1995; Williamson, 2001), shoot development, and consequently alter nutrient uptake and P balance in the plants (Farmaha et al., 2012; Rosa and Ruiz Dias, 2015).

A better understanding of how P management affects P nutrition dynamic can help to improve P fertilizer use-efficiency by plants. The objective of this study was evaluate P balance and use in soybeans under different P placements strategies in a no-till system in Brazil.

3.3 MATERIAL AND METHODS

Site Description

Two field experiments were conducted near Não-Me-Toque, RS (Field 1) and São Sepé, RS (Field 2), southern Brazil, in the 2014/2015 crop season. These sites have similar climate, incident solar radiation and other characteristics (Table 1), as well as different soil chemical and physical composition (Table 3).

The soil management adopted in both experimental areas is long-term no-tillage. Areas have been under no-till for 5 yr in São Sepé and 30 yr in Não-Me-Toque, which corresponds to a transition and a maintenance phase of this system (Sá et al., 2001), respectively.

Treatments

The experimental design was a randomized complete block with four replicates and five treatments. Individual plot size was 15 m wide by 200 m long. Treatments consisted of five phosphorus placements: subsoiler plus deep band (DB), subsoiler plus in-furrow (SF), broadcast (B), in-furrow (F), and above seed (AS). The phosphorus source used was triple surperphosphate (0-42-0) at seeding at the rate of 70 kg P_2O_5 ha^{-1}. The equipment used to apply the fertilizer in treatment DB was developed from a previously existing commercial subsoiler FOX® (STARA®, Nao-Me-Toque, RS). This equipment has 9 straight knifes by 30 cm wide and has a fertilizer tank attached to the chassis. Thus, the P application in DB was 20 cm deep spaced each 30 cm wide. The same subsoiler used in DB was utilized in SF, but without deep fertilizer application. In SF the fertilizer was applied with planter shank (~10 cm), in planting, in order to isolate the P placement effect of DB. Broadcast treatment (B) was performed immediately prior to planting, and was not incorporated. The planting in B was realized using planter shank system without fertilizer application. In-furrow treatment was established with planter shank (fertilization on row) applying fertilizer around 10 cm deep. Treatment AS has been used in large scale by farmers in southern Brazil. It is a disk rippled coulter system coupled after fertilizer has been applied in row but above the surface. In this system the P fertilizer is slightly incorporated and lies above the seed.

Soybean planting was performed with a Victória DPS 4050 planter (STARA®, Não-Me-Toque, RS) total 4.5 m wide spacing (10 sowing lines x 45 cm wide). Thus, P placement in DB not necessary fit with planting rows. Broadcast placement was performed with a self-propeller spreader Hércules 5.0 (STARA®, Não-Me-Toque, RS) with 27 m width spread.

The soybean varieties used were the NA 5909 RG in Field 1 and Monsoy 5917 IPRO in Field 2 in the plant populations of 330,000 and 300,000 plants ha^{-1}, respectively. Varietal characteristics are given in Table 2. This study was performed on commercial areas lent by farmers, where soybean varieties, plant populations, and planting date followed agronomic recommendations to each region aiming higher yields.

Measurements

The phosphorus placement treatments were evaluated for effects on plant height, plant dry weight, and P uptake in the 20, 40, 60 and 80 days after emergence (DAE). Grain P content and grain yield were measured at harvest maturity. The plants considered for plant height measurements were marked so all evaluations in the period were in the same plants. Plant dry weight was estimated considering 5 plant in each point with 3 subsamples, 50 m spaced per plot, where after it whole plants were air-dried (65-70 ^{o}C) and weighed. The plants were ground to pass through a 0.5 mm mesh screen and the tissue digestion performed by nitric-perchloric acid method (Johnson and Ulrich, 1959). Phosphorus was determined by the ascorbic acid method (Watanabe and Olsen, 1965).

Grain yield was obtained by hand harvesting three subsamples of 8 m^2, 50 m spaced within each plot, for a total of three subsamples per plot that composes one replicate. Grain weight and moisture were measured in each plot, corrected to 13% and calculated to kg ha^{-1}.

Phosphorus uptake was calculated considering P tissue (g kg^{-1}) and dry plant weight (kg ha^{-1}) at the 80 days (flowering growth stage – R2). Phosphorus removed with grain was calculated considering P concentration in the grain (g kg^{-1}) and grain yield (kg ha^{-1}). Partial nutrient balance was calculated according with Drechsel et al., (2015) through balance method, e.i. dividing the value of P removed with grain by the value of P applied as fertilizer, multiplied by 100.

Soil was sampled before and after the study with the goal to analyze the influence of P placement treatments on the remaining P on soil. Samples were collected by soil blocks of 5 x

5 x 15 cm until the total collected soil dimensions of 25 cm depth and 45 cm wide, where the plant row was in the middle of the sampling area. After collection, the soil was air-dried (40-45^{o}C), sieved through a 2-mm mesh, and stored in covered plastic containers. A subsample of the soil was submitted to physical and chemical analyses to determine the soil clay content (Bouyoucos, 1962); soil pH (1:1 soil/water ratio) (Shoemaker et al., 1961); organic carbon (C) (Walkley and Black, 1934); Mehlich I–extractable P; 1.0 mol L^{-1} KCl–extractable calcium (Ca), magnesium (Mg), and aluminum (Al) (EMBRAPA, 1979); Phosphorus was determined by the ascorbic acid method (Watanabe and Olsen, 1965); Potassium (K) was determined by flame photometry (Nelson et al., 1953), and Al was titrated with NaOH 0.025 mol L-1 (EMBRAPA, 1979). Available soil P was quantified considering the average of soil P level in mg dm^{-3} in each layer.

Statistical analysis

Statistical analyses were performed using SAS Studio (version 9.4; SAS, Cary, NC). Plant height, plant dry weight and P uptake in the 20, 40, 60 and 80 days after emergence (DAE), soil P levels and measurements of phosphorus in soybean grain data were analyzed using PROC GLIMMIX (restricted maximum likelihood estimation) procedure for generalized linear mixed models (GLMMs). The factor P placement (five levels) was modeled as fixed factor; the block as well as sampling days factor (four levels) and depth factor (five levels), if present, were modeled as a random effect. 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.

3.4 RESULTS AND DISCUSSIONS

Initial plant development

Phosphorus placement treatments altered ($p < 0.001$) initial plant development as indicated by plant height, plant dry weight, plant P uptake, and consequently the partial P balance (Table 4). Moreover, there was site effect (Field 1 *vs* Field 2) among analyzed parameters under P placement treatments, with more evident effects in Field 1 characterized by a higher clay content in the soil (Figure 1). Soils with higher clay content can show an increased soil bulk density, decreasing soil permeability and consequently impacting root growth compared to sandier soils (Jones, 1983). As a consequence, clay soils can also alter shoot growth in view that both are coupled and form an integrated system (Gregory, 2008). Therefore, the differences in initial plant development between both sites in the present study in response to the different imposed treatments can be partially related as a physical effect of the mechanical system of planting in the 20 DAE and chemical effect by P fertilization as a secondary effect in the 40 DAE, as explained below, in addition to differences in growing conditions (temperature and rainfall).

Initially, in the 20 DAE, soil revolved treatments (DB and SF) showed lower plant shoot development (Figure 1) increasing posteriorly throughout the stages. The initial lower soil resistance in this treatments can induce a wider initial root growth (Colombi et al., 2016). In this case, plants are allocating exogenous resources in the growing organs with more energetic demand promoting an biomass imbalance in the plant (Hermans et al., 2006), and a decrease of shoot growth in favor of root development. On the other hand, at the 40 DAE, a chemical effect promoted by P fertilizer is the most likely cause of plant growth, where in-furrow treatments shown an increase in shoot development due to the strait contact of the plants' root system with fertilized area in these treatments (Barbosa et al., 2014). In the flowering stage (80 days after emergence), DB and SF treatments showed greater or no difference in plant height and plant dry weight compared to others treatments (Figure 1 and Table 5). In Field 2 due to lighter soil texture (sandy soil), these effects were not as evident, indicating reduced physical hindrance favoring a balance between root and shoot growth.

Plant P uptake

Greater initial plant P uptake did not increase soybean grain yield in this study (Figure 2). According with Grant et al. (2005) the P supplementation in the initial crop development is crucial to optimizing crop yield, where P fertilization at later growing stages is expected less correlation with yield. The reason is because the energy absorbed by chlorophyll during photosynthesis is transformed to adenosine triphosphate (ATP) and it acts as the first energetic source required in the biological process (Grant et al., 2001). Anyway, the data suggest that the factor responsible for driving soybean yield in this study was other than amount of P uptake by plant in the initial growth stages.

In-furrow placement treatments showed greater ($p < 0.001$) P uptake in the initial growth stages in both sites (Table 5). A closer contact of the fertilizer with the roots zone promotes an increase in P absorption by plant (Barber, 1958; Barbosa et al., 2014; Borges and Mallarino, 2000). On the other hand, while there is an increase in plant growth and a wider volume of soil explored by roots, F, SF and AS placement did not result in increased P uptake. In 80 DAE, F and AS showed lower total P uptake in Field 1, 49.5 and 52.4 kg ha^{-1}, respectively.

In Field 2, the total P uptake at flowering stage was 137 kg P_20_5 ha^{-1}, this value was twice the amount measured in Field 1 (60 kg ha^{-1}) during the same growth stage (Table 5). These results are a consequence of the greater aboveground biomass produced in Field 2 (12,915 kg ha^{-1}) compared to Field 1 (6,855 kg ha^{-1}). Crop aboveground biomass provides the driving force for nutrient accumulation (Bender et al., 2015). These results are greater than those found by Bender et al. (2015), but similar to the ones published by Flannery (1986) and proposed by modern soybean cultivars (Kurihara et al., 2013).

P balance and use

In vegetative stage, plant is developing photosynthetic and adsorptive organs (e.g. leaves, roots, etc.), storing nutrients and saving energy to 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), which have the goal to produce healthy and vigorous seeds (Pazzin, 2015). However, the data in this study showed that there were different forms to supply P to the grain for it to fulfill between Field 1 and Field 2 (Figure 3). In Field 1 the amount of P present in tissue in the flowering growth stage was inferior to that removed with grain, meaning that a significant amount of the grain P was absorbed from soil after R2 stage. On the other hand, in Field 2 there was greater amount of P uptake in flowering stage than removed with grain, indicating a possible luxury consumption of P. This behavior can be partially related with the genetic trait of the varieties (Specht et al., 1999; Xue et al., 2014), where certain cultivars can accumulate P after onset of seed filling direct to developing grain tissues or remobilize from various plant organs (Bender et al., 2015). 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 indirect factors besides P placement can be driving P uptake, i.e. root architecture, soil moisture, etc.

Based on the balance of P input/output, a greater amount of P was removed with grain (output) than that input rate applied as fertilizer in both sites (Figure 3). In our study, the average P removed with grain was an 83 and 77 kg P_2O_5 ha^{-1} in Field 1 and Field 2, respectively. The extra P uptaked was probably provided by the soil P pool after R2 stage

(Buresh et al., 1997; Damon et al., 2014). Some authors have reported the increase in nutritional requirements of modern soybean varieties as a result of genetic advancements and agronomic improvements (Bender et al., 2015; Kurihara et al., 2013).

Partial nutrient balance (PNB) is a method to determine P use and P recovery efficiency by crop, usually expressed as nutrient output per unit of nutrient input (Drechsel et al., 2015). This method has been widely used because it considers 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 grain in this study surpassed the total P applied by fertilization (Figure 3), the P-PNB was greater than one hundred percent. Deep band placement treatments resulted in 126 and 116 % P-PNB in Field 1 and Field 2, respectively, indicating greater P use among the studied treatments (Table 6). The lower use was observed to B in Field 1 and SF in Field 2, with 107 and 97 %, respectively. This values above 100% possibly arises because there were excellent yields and the soil P levels were already very high in both sites (Syers et al., 2008). In fact, great portion of the P in the grain actually comes from soil P pools.

The differences between P-use between management practices in each site can be related with the characteristic of soil texture present in each area and its interaction with plant P uptake and use. Because generally P is more limiting in a clay soil, a wide root system is needed for efficient P uptake (Heppell et al., 2015). Therefore, broadcasting P at the surface in Field 1, characterized by a high percent clay, was the least efficient treatment in utilizing the applied P.

Also, SF was the least efficient in Field 2, where it is a sandy soil. Tillage can increase soil 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 (Da Costa et al., 2006). The reduced efficiency of SF could be related to a decrease in P availability in the 10 cm layer, promoted by reduction in superficial water content, and consequently P diffusion, mainly in sandy soil which has lower capacity to retain water in soil compared with clay soils (Da Costa et al., 2009).

Residual soil P

A significant P placement x soil depth interaction (Table 4) indicated that P placement affected residual soil P level differently in all studied soil layers following soybean crop season (Figure 3). These results indicated that it could be challenging to determine whole-field fertility (Fernández and Schaefer, 2012) and fertilizer recommendations by traditional sampling strategies.

Plant P uptake efficiency (Xue et al., 2014) and P partitioning between parts of the plant (Clarkson et al., 1978) can promote a non-uniform redistribution of P on soil profile (Fernández and Schaefer, 2012). For example, deep banding of P could reduce soil surface P and increase P concentration at the subsurface (Randall and Vetsch, 2008) because, despite the ability of placement technique to improve deeper root system, most of the P uptake occurs from the surface layer (Farmaha et al., 2012).

In our study, DB promoted an increase of residual P levels in the 15-to 20 cm and in 20-to 25 cm layer in Field 1 and showed no difference in Field 2. This increase in subsurface P levels is attributed to localized fertility from the fertilizer band (Fernández and Schaefer, 2012; Mallarino and Borges, 2006). The increase is likely caused by residual fertilizer in soil layers from which crops normally do not uptake nutrients exclusively from fertilizer band

(Farmaha et al., 2012). A decrease in P concentration in the surface layers could not be verified in this study.

On the other hand, B promoted an increase of P levels in 0-to 5 cm layer and similar P levels with in-furrow treatments in the other layers (Figure 4). Similar results were reported in previous studies (Fernández and Schaefer, 2012; Mallarino and Borges, 2006). Comparing residual P from broadcast P versus deep band P treatments, the results from this study allows to hypothesize that deep band fertilization has lower potential for runoff (Randall and Vetsch, 2008) and environmental damages (Hale et al., 2015). Other P placement management practices did not affect significantly soil P levels in the soil profile.

3.5 CONCLUSIONS

In-furrow placement promoted greater P uptake in the initial growth stage and similar or lower compared with other treatments in flowering growth stage. So far as there is an improvement of plant growth and a wider volume of soil that can be explored by roots, P placement lost relevance to P uptake. Soybean varieties shown difference in total P uptake between sites possibly due to differing aboveground biomass. Also, greater amount of P removed with grain was observed (output), exceeding the input rate applied by fertilizer. Despite there was a greater concentration of P in the grain than what is reported in the literature, the great amount of removed P can be attributed to the higher yields observed in the study. In average, Field 1 and Field 2 showed total soybeans grain yield of 3989 kg ha^{-1} and 4841 kg ha^{-1}, respectively. Overall, this study provides new information regarding the effect of deep band P placement on P uptake, plant development and P-use, where DB can reduce P losses by runoff and improve soil fertility in subsurface layers.

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FIGURES

Figure 1. Plant height at the 20, 40, 60 and 80 days after soybean emergence. Measurements were made on the same plants throughout the period. a) Não-Me-Toque, RS and b) São Sepé, RS, 2015. *Values followed by same letter within each 20-day period indicate no significant difference at the $p \leq 0.05$ probability level.

Figure 2. Soybean grain yield and P uptake in 20 and 40 days after emergence in: a) Não-Me-Toque, RS; and b) São Sepé, RS. *Values followed by same letter indicate no significant difference at the $p \leq 0.05$ probability level. †Pearson correlation coefficient and significance levels between soybean grain yield and P uptake. ^{ns}no significant.

Figure 3. Phosphorus (P) input and output as affected by different P placement strategies. a) Não-Me-Toque, RS and b) São Sepé, RS, 2015. Phosphorus uptake was calculated considering P tissue (g kg^{-1}) and dry plant weight (kg ha^{-1}) at the 80 days (flowering stage – R2). P removed with grain was calculated considering P in the grain (g kg^{-1}) and yield (kg ha^{-1}).

Figure 4. Figure 4. Residual soil P levels after soybean crop season under different P placement treatments in Não-Me-Toque, RS and São Sepé, 2015. The red line represents the initial soil P level before study was established. *Values followed by same letter indicate no significant difference at the $p \leq 0.05$ probability level. ^{ns} no significance.

Table 1. Climate characterization for the study locations of Não-Me-Toque, RS and São Sepé, RS, Brazil.

Parameters	**Site**	
	Não-Me-Toque	**São Sepé**
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} day^{-1})	16	14
Köppen climate classification	Cfa†	Cfa

†Subtropical climates.

Table 2. Soil chemical and physical characterization at the experiment sites in Não-Me-Toque, RS and São Sepé, RS.

Location	Chemical								Physical	
	Depth	pH_{H20}	P[#]	K	Ca	Mg	Al	Al[§]	Clay	PR
	cm		- mg dm^{-3} -		-- $cmol_c$ dm^{-3} --			%	%	MPa[¶]
São Sepé, RS†	0-1	6.1	153	466	11.4	3.4	0	0	40	-
	0-5	6.0	55	251	9.4	3.6	0	0	30	0.61
	5–10	5.4	15	194	6.1	3.2	0.1	1	28	1.74
	10-20	4.6	7	130	4.5	2.2	0.5	7	30	1.82
	20-30	4.2	5	88	4	1.8	1.3	18	32	1.97
	30-40	4.2	3	59	3.7	1.5	1.3	20	35	1.93
Não-Me-Toque, RS‡	0-1	5.1	78	259	7	2.1	0.2	2	37	-
	0-5	5.4	58	306	7.3	2.7	0.2	2	42	1.22
	5-10	5.2	25	268	6.7	2.6	0.2	2	50	3.07
	10-20	5.0	13	157	6.1	2.6	0.2	3	57	2.51
	20-30	5.2	2	100	5.6	2.4	0.3	3	80	2.11
	30-40	4.9	1	57	4.5	2.1	0.4	6	84	1.91

[†] Paleudalf [‡] Haplortox. [§] Percentage of Al in the effective CEC; [¶] Penetration resistance (PR). [#] P-Mehlich 1.

Table 3. Soybean variety characteristics, NA 5909 RG and Monsoy 5917 IPRO.

Characteristics†	**NA 5909 RG‡**	**Monsoy 5917 IPRO§**
Maturity group	5.9	5.9
Cycle (days)	(115-130)	(105-120)
Growth habit	Indeterminate	Indeterminate
Fertility requirement	High	Medium/High
Lodging	Resistant	Resistant

†Information obtained from companies in Brazil. ‡Não-Me-Toque, RS; §São Sepé, RS.

Table 4. Significance of F values for the effects of plant dry weight, plant phosphorus (P) uptake, plant height, grain yield and residual soil P as affected by treatment (phosphorus placement), soil depth when applicable, growth stages, and interactions.

Effect	P > F	
	Não-Me-Toque, RS	São Sepé, RS
Plant dry weight		
Treatment (T)	< 0.001	< 0.001
Stage (S)	< 0.001	< 0.001
T × S	< 0.001	< 0.001
Plant P uptake		
Treatment (T)	< 0.001	< 0.001
Stage (S)	< 0.001	< 0.001
T × S	< 0.001	< 0.001
Plant height		
Treatment (T)	< 0.001	< 0.001
Stage (S)	< 0.001	< 0.001
T × S	< 0.001	< 0.001
Grain yield		
	ns	< 0.001
Soil P		
Treatment (T)	0.02	0.001
Depth (D)	< 0.001	< 0.001
T × D	< 0.001	< 0.001

^{ns} no significance at $p \leq 0.05$.

Table 5. Plant dry weight and P uptake at the 20, 40, 60 and 80 days after soybean emergence. Não-Me-Toque, RS and São Sepé, RS, 2015.

Treatments	20 days		40 days		60 days		80 days†	
	Plant dry weight	P Uptake‡	Plant dry weight	P Uptake	Plant dry weight	P Uptake	Plant dry weight	P Uptake
	-------------------- kg ha^{-1} --------------------							
	Não-Me-Toque, RS							
Subsoiler + Deep Band	117.3 b*	1.0 d	837.4 b	5.2 d	3131.7 a	19.4 b	6668.2 bc	64.1 b
Subsoiler + In-furrow	149.3 b	1.5 bc	917.6 a	8.4 a	3235.6 a	21.5 a	8107.7 a	77.8 a
Broadcast	143.8 a	1.4 c	847.5 b	6.4 c	2830.7 b	19.1 b	5998.1 c	58.9 c
In-furrow	150.3 a	1.7 a	892.8 a	7.3 b	2836.8 b	17.8 bc	6968.5 b	49.5 d
Above Seed	125.7 a	1.6 ab	771.7 c	6.1 c	2766.6 b	16.9 c	6432.2 d	52.4 d
	São Sepé, RS							
Subsoiler + Deep Band	250.4 ^{ns}	2.8 b	2243.2 b	21.7 b	9447.2 b	80.3 b	12955.9 ^{ns}	130.4 b
Subsoiler + In-furrow	251.4	2.9 b	3059.3 a	26.3 a	8662.2 c	60.0 c	12607.8	131.3 ab
Broadcast	274.0	3.1 b	3072.0 a	28.8 a	9381.9 cb	90.7 a	12560.4	143.7 a
In-furrow	313.5	4.4 a	3051.7 a	25.4 ab	9234.9 cb	84.8 ab	12200.3	133.9 ab
Above Seed	277.2	3.8 ab	2763.1 a	25.1 ab	10633.5 a	93.3 a	12611.4	137.3 ab

†Flowering stage (R2). ‡ Plant P uptake (P_2O_5) was calculated multiplying plant dry weight (kg ha^{-1}) by P tissue (g kg^{-1}). *Values followed by same letter each 20-day period indicate no significant difference at the $p \leq 0.05$ probability level. ^{ns} no significance.

Table 6. Soybean yield (kg ha^{-1}), P removed with grain (kg ha^{-1} P_2O_5) and partial P balance (P-PNB) under different P placements. P applied as fertilizer was in the rate of 70 kg of P_2O_5 ha^{-1}. Não-Me-Toque, RS and São Sepé, RS, 2015.

Treatments	**Yield**	**P removed with grain**	**P-PNB†**
	kg ha^{-1}	kg ha^{-1} P_2O_5	%
		Não-Me-Toque, RS	
Subsoiler + Deep Band	4051.3 ^{ns}	90 a	126
Subsoiler + In-furrow	3912.3	87 a	122
Broadcast	4055.8	76 c	107
In-furrow	3912.6	79 bc	111
Over Seed	4012.8	84 ab	118
		São Sepé, RS	
Subsoiler + Deep Band	5255.7 a	82 a	116
Subsoiler + In-furrow	4800.1 b	69 b	97
Broadcast	5142.8 a	81 a	114
In-furrow	4525.4 c	75 ab	106
Over Seed	4480.4 c	79 a	112

†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 indicate no significant difference at the $p \leq 0.05$ probability level. ^{ns} no significance.

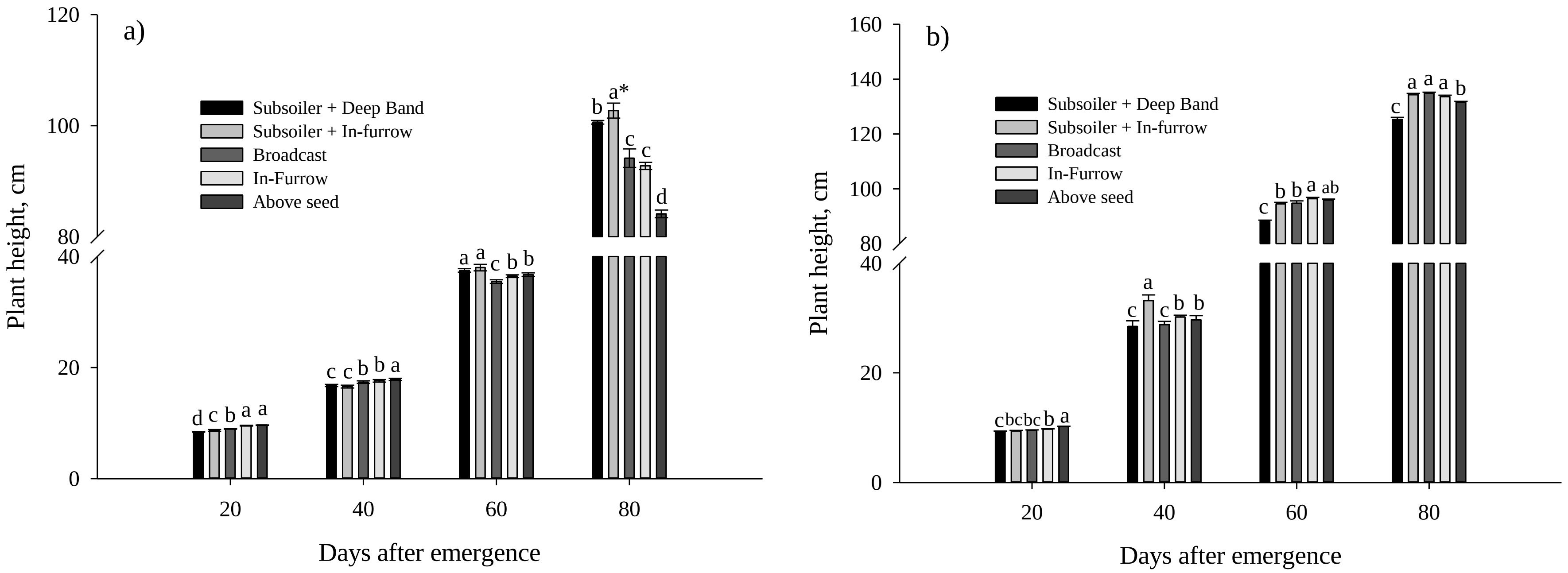
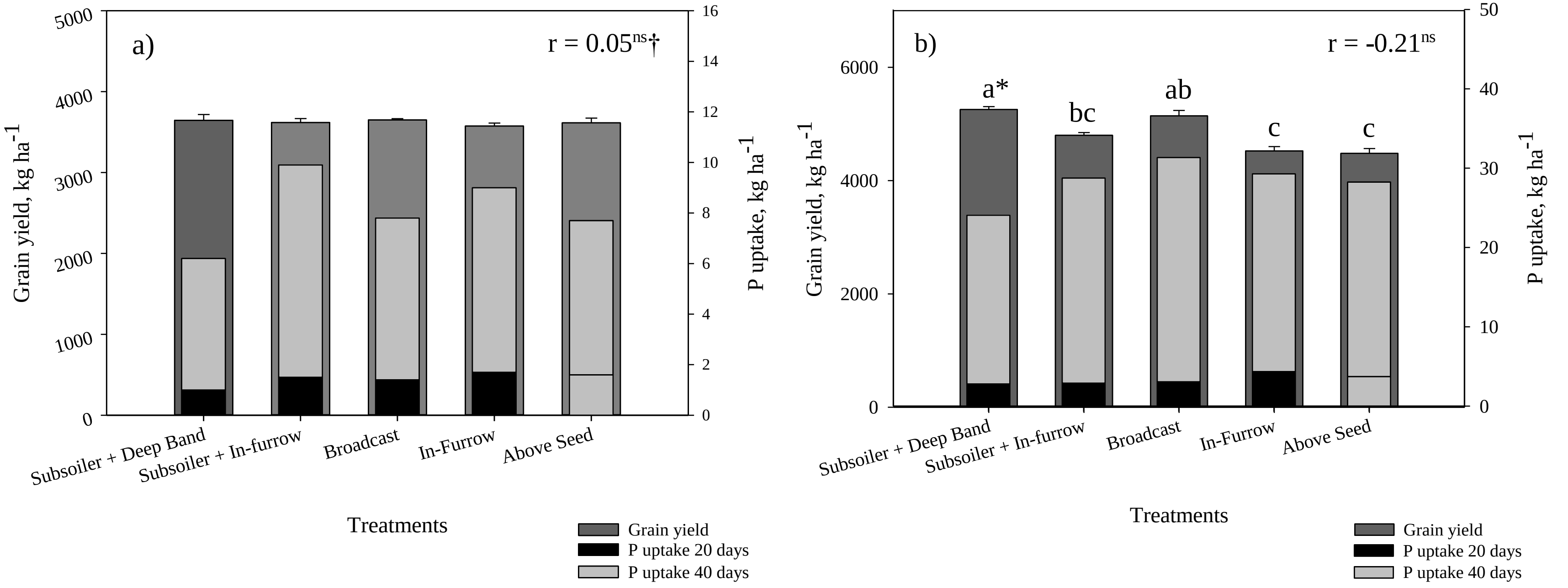


Figure 1. Plant height at the 20, 40, 60 and 80 days after soybean emergence. Measurements were made on the same plants throughout the period. a) Não-Me-Toque, RS and b) São Sepé, RS, 2015. *Values followed by same letter within each 20-day period indicate no significant difference at the *p*≤ 0.05 probability level.



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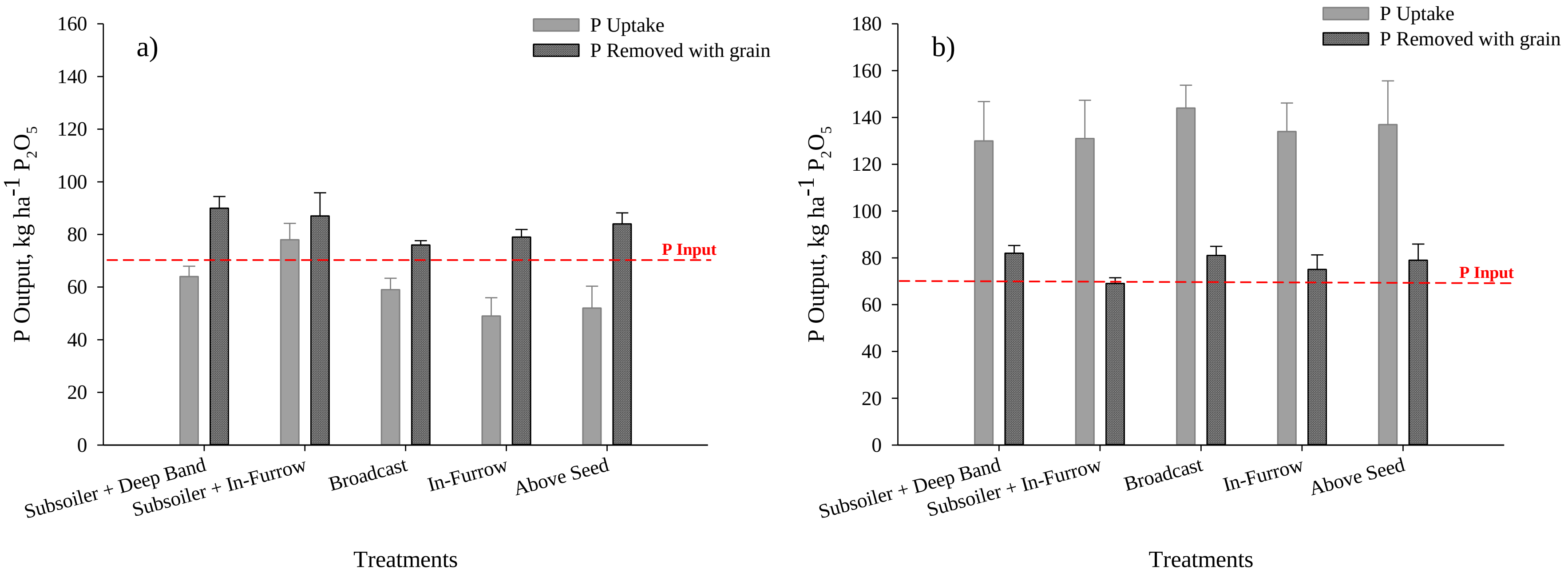

Figure 3. Phosphorus (P) input and output as affected by different P placement strategies. a) Não-Me-Toque, RS and b) São Sepé, RS, 2015. Phosphorus uptake was calculated considering P tissue (g kg^{-1}) and dry plant weight (kg ha^{-1}) at the 80 days (flowering stage – R2). P removed with grain was calculated considering P in the grain (g kg^{-1}) and yield (kg ha^{-1}).

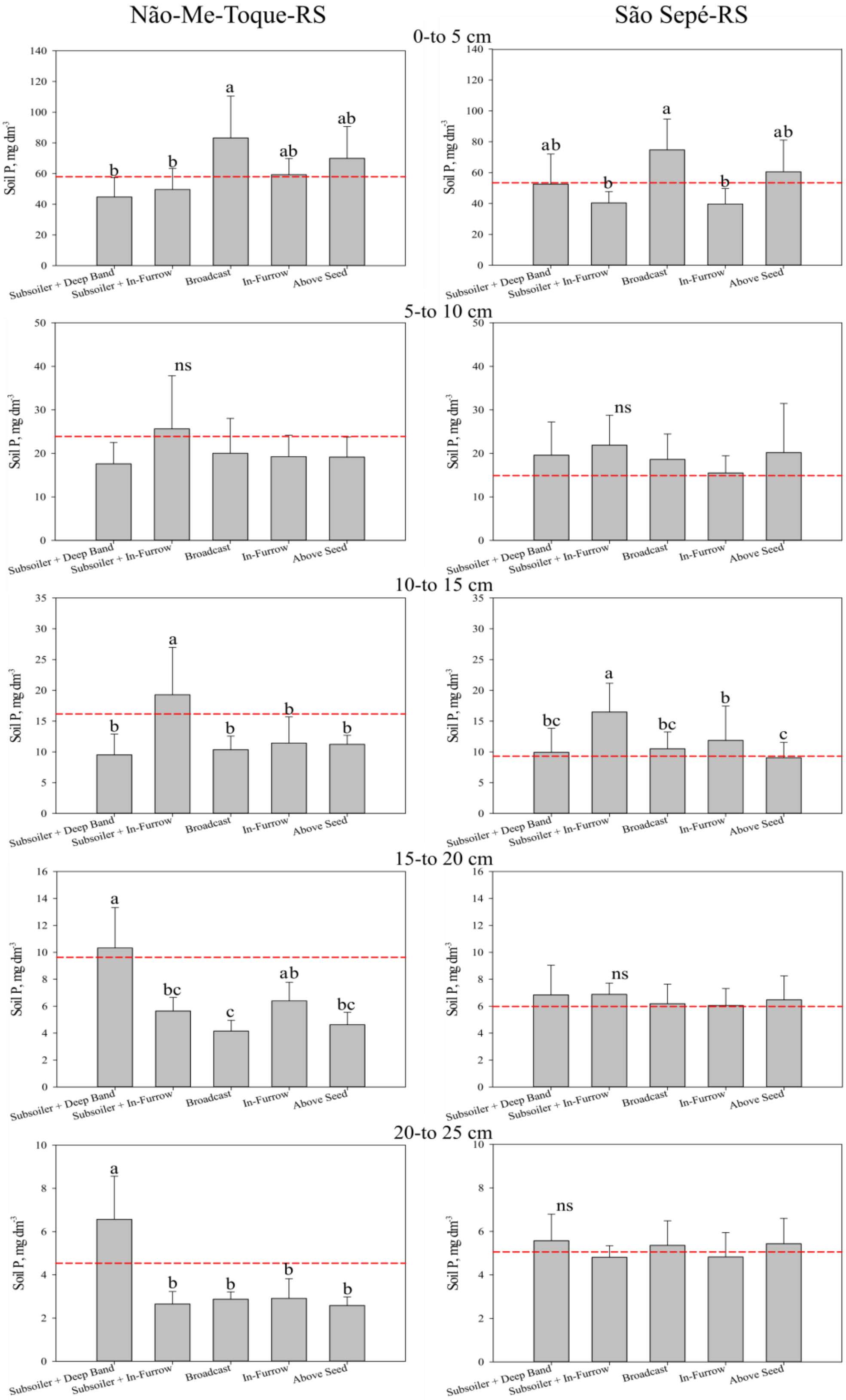

Figure 4. Residual soil P levels after soybean crop season under different P placement treatments in Não-Me-Toque, RS and São Sepé, RS, 2015. The red line represents the initial soil P level before study was established. *Values followed by same letter indicate no significant difference at the *p*≤ 0.05 probability level. ^{ns} no significance.

4 ARTIGO 3: Phosphorus placement as a strategy to mitigate soybean (*Glycine max L.*) drought stress in no-till systems

4.1 ABSTRACT

Drought events have often occurred in the last years and have been considered the main limiting factor to crop yields worldwide. Phosphorus fertilizer placement under no-till system (NT) could affect root distribution into soil profile affecting nutrient uptake and water supply, mainly in drought periods, impacting crop yields. A field study was conducted at the cities of Não-Me-Toque, RS (Field 1) and São Sepé, RS (Field 2), Brazil, to investigate the effect of phosphorus placement on root distribution in soil profile and the impact on the soybean grain yield over an induced drought situation. Treatments consisted of phosphorus placements: subsoiler plus deep band (DB), subsoiler plus in-furrow (SF), broadcast (B), in-furrow (F), and above seed (AS). Analyzed parameters were root distribution, soybean grain weight, and soybean grain yield in natural condition and over an induced drought situation. There was yield response to phosphorus placement ($p<0.001$) in Field 2 and no response in Field 1 under natural precipitation. Deep band placement promoted a better roots distribution in the soil profile in both sites, with an increase of root length in the 20- to 25 cm layer, where P was placed. In DB, 28 and 30% of the total root length are in the 15- to 25 cm layer in Field 1 and Field 2, respectively. Management practices that promote high concentration of phosphorus in furrow showed larger proportion of roots near the surface. Deep band treatment reduced grain yield loss to 9% in Field 1 and to only 0.3% in Field 2 under an induced drought, promoting greater capacity for the plant to support water deficit, when compared to other P management strategies. Root growth distribution had direct impact on soybean grain yield under induced drought, showing the same tendency in both sites.

4.2 INTRODUCTION

Extreme weather events related with recent climate change have been occurring with more frequency in last years (Wilbanks et al. 2015). As a consequence, the precipitation regime can be altered, which tends to provide scenarios of water excess or drought stress (Marengo et al. 2013), reflecting on agriculture production.

Water availability has been considered the main factor that limits crop yield worldwide (Dilley, 2005; Helmer and Hilhorst, 2006) and drought is the major player in the high year-to-year yield variability in rainfed and dryland agriculture (Purcell et al., 2000). United States and Brazil, 1st and 2nd greatest soybean growers and exporters in the world (USDA, 2015), are subjected to re-occurring annual drought events in several regions (Torres et al., 2013). These drought events correspond to a total of $199 Billion* in losses in the US alone, due to water deficit stress (Smith and Matthews, 2015).

Several studies have explored strategies to mitigate water stress on crops. Phosphorus fertilizer management, for example, could alter root system architecture (Williamson et al. 2001) providing an increased or reduced explored soil volume, therefore altering the water support capacity to the plant. Recent studies have demonstrated that deep root systems have important role in exploring soil stored water, whereas roots near the soil surface become important when plant water supply is mainly provided by rainfall events (Tron et al. 2015). Therefore, the correct fertilizer management has the potential to provide better root growth conditions which may contribute to improve P use-efficiency and drought mitigation by greater exploration of the soil volume.

Thus, the objective of this study was to evaluate the impact of P fertilizer placement on soybean root distribution into soil profile and consequent damage caused by drought stress in grain yield under NT.

4.3 MATERIAL AND METHODS

This study is a comprehensive appraisal of the effect of P placement and other variables that can interfere P fertilization efficiency, and consequently, grain yield. In order to perform this research, a field study in two different sites was conducted to evaluate the induced drought impact on soybean yield submitted to different P placement. Furthermore, data from 62 studies will be presented, comparing soybean yield under P placement strategies in different soil chemical and physical characteristics.

Site Description

Two field experiments were conducted near Não-Me-Toque, RS (Field 1) and São Sepé, RS (Field 2), southern Brazil, in the 2014/2015 crop season. These sites have similar climate, incident solar radiation and other characteristics (Table 1), as well as different soil chemical and physical composition (Table 3).

The soil management adopted in both experimental areas is long-term no-tillage. Areas have been under no-till for 5 yr in São Sepé and 30 yr in Não-Me-Toque, which corresponds to a transition and a maintenance phase of this system (Sá et al., 2001), respectively.

Treatments

The experimental design was a randomized complete block with four replicates and five treatments. Individual plot size was 15 m wide by 200 m long. Treatments consisted of five phosphorus placements: subsoiler plus deep band (DB), subsoiler plus in-furrow (SF), broadcast (B), in-furrow (F), and above seed (AS). The phosphorus source used was triple surperphosphate (0-42-0) at seeding at the rate of 70 kg P_2O_5 ha^{-1}. The equipment used to apply the fertilizer in treatment DB was developed from a previously existing commercial subsoiler FOX® (STARA®, Nao-Me-Toque, RS). This equipment has 9 straight knifes by 30 cm wide and has a fertilizer tank attached to the chassis. Thus, the P application in DB was 20 cm deep spaced each 30 cm wide. The same subsoiler used in DB was utilized in SF, but without deep fertilizer application. In SF the fertilizer was applied with planter shank (~10 cm), in planting, in order to isolate the P placement effect of DB. Broadcast treatment (B) was performed immediately prior to planting, and was not incorporated. The planting in B was realized using planter shank system without fertilizer application. In-furrow treatment was established with planter shank (fertilization on row) applying fertilizer around 10 cm deep. Treatment AS has been used in large scale by farmers in southern Brazil. It is a disk rippled coulter system coupled after fertilizer has been applied in row but above the surface. In this system the P fertilizer is slightly incorporated and lies above the seed.

Soybean planting was performed with a Victória DPS 4050 planter (STARA®, Não-Me-Toque, RS) total 4.5 m wide spacing (10 sowing lines x 45 cm wide). Thus, P placement in DB not necessary fit with planting rows. Broadcast placement was performed with a self-propeller spreader Hércules 5.0 (STARA®, Não-Me-Toque, RS) with 27 m width spread.

The soybean varieties used were the NA 5909 RG in Field 1 and Monsoy 5917 IPRO in Field 2 in the plant populations of 330,000 and 300,000 plants ha^{-1}, respectively. Varietal characteristics are given in Table 2. This study was performed on commercial areas lent by farmers, where soybean varieties, plant populations, and planting date followed agronomic recommendations to each region aiming higher yields.

Case study

A case study was conducted to evaluate the effect of different P placement in the soybean yield under induced drought condition. For this purpose, rainfall shelters were installed in DB, B, F and AS. The rainfall shelters were 3x4 m built in wood structure and plastic cover, excluding 100% of the rainfall during 25 days starting at grain filling stage.

Yield samples were collected from inside and outside the rainfall shelters. Drains were made around rainfall shelters to prevent water run-in from outside.

Measurements

Phosphorus placement treatments were evaluated for effects on root distribution on the soil profile, drought stress, and grain yield. Soybean root growth was evaluated at flowering stage using the Needleboard Monolith method and rooting profile (Böhm, 1979), adapted by Pedó (1986). The monoliths were 30x40x10 cm with nails spaced every 5 cm, with a total soil volume collected of 8.75 dm^3. The soil monolith was cut in layers of 5 cm depth increments to obtain root distribution in the profile. After wash the roots, images were generated exposing the roots from the collected soil volume to a digital scan with Epson 11000XL scanner. The generated images were analyzed by the software WinRhizo Pro 2013 to determine total root length.

Grain yield was obtained by hand harvest with subsamples of 8 m^2, each 50 m, in each plot, a total of 3 subsamples per plot that composes one replicate. Grain weight and moisture were measured in each plot, corrected to 13% and calculated to kg ha^{-1}.

Literature review

A literature review was performed showing a wide amount of published information (62 experiments) using Google Scholar. The key words used in the search were: phosphorus placement, phosphorus broadcast, phosphorus in row, phosphorus management, soybean phosphorus. The target parameters were: soybean yield, soil P level, soil pH, soil clay content, organic matter content, and soil Al. Some parameters were not shown in all articles.

Statistical analysis

Phosphorus placement effects on soybean yield and root length were examined using a general ANOVA with Treatment as factor using SAS Studio (version 9.4; SAS, Cary, NC). A

Tukey post-hoc comparison of means test were done using the LSMEANS and SLICE options for PROC GLIMMIX at $p < 0.05$.

4.4 RESULTS AND DISCUSSIONS

There was yield response to phosphorus placement ($p<0.001$) in Field 2 and no response in Field 1 (Table 4) under natural rainfall conditions (Figure 2). Differences can be related to the environmental conditions, as there was 94 mm precipitation in Field 1 and 31 mm precipitation in Field 2 (Figure 1), and possibly the period which the no-till system was established, which can be partially explaining the results measured in Field 1 (30 yr. no-till) versus Field 2 (5 yr. no-till). According to Nunes et al. (2011), phosphorus placement can influence yields in the beginning of the establishment of the no-till system, fading yield responses over the years. The reason for that could be realated with changes in soil conditions promoted by no-tillage, which will increase P availability in soil. In general, five factors are responsible for drive P availability in soil: soil P concentration, soil texture, soil organic matter, soil management and microrganisms. Except soil texture, all factors are improved with the established of no-till system, reducing the energy of P absorption in soil and increasing P availability (dos Santos et al., 2008).

Several studies exploring phosphorus placement have been conducted in the last decades (Table 5), encompassing a wide range of soil types, climate conditions, initial P levels, soil texture, soil organic matter content, soil pH, aluminum, etc. Still, results don’t allow for firm conclusion of the most efficient and productive P management strategy (Figure 3). In our review, 62 studies were gathered and grouped by statistical response of soybean yield to P placement. Approximately 9.8% of the studies resulted in higher soybean yields when P was placed in furrow as compared to broadcast placement (5%). Still, most of the studies (85.2%) showed no difference between P placement strategy on soybean yield. In many cases, different responses to P placement were found even within the same range of a given soil parameter. For instance, yield was increased by both broadcast and in-furrow P at pH ranging from 6- to 6.5 and from 5- to 5.5, with no clear trend of yield benefit from any treatment.

A direct parameter that is indicative of the plant's ability to explore the soil for fertilizer and soil moisture is the root system architecture. Although the root system analysis is usually very difficult and time consuming, the information generated can help to explain the reason why there is so much variability in field studies results. Phosphorus management can alter root system distribution (Williamson et al. 2001) indicating how susceptible plants are to adverse environmental condition.

Total root length and root distribution in each soil layer under different P placement is shown in Table 6. Deep band placement promoted a better distribution of roots on the soil profile in both sites, with an increase of root length in the 20- to 25 cm layer, where the P was placed. Deep banding P had 28 and 30% of the total root length in the 15- to 25 cm layer in Field 1 and Field 2, respectively. Management practices that promote high concentration of phosphorus in furrow showed large proportion of roots near the surface. For instance, F resulted in 55 and 37% of the total root length concentrated in the 0- to 5 cm layer in Field 1 and Field 2, respectively, as much as 80 and 59% of the total roots were in the 0- to 10 cm layer. The worst root growth scenario was found in the AS, where 58% of total roots were found in the 0- to 5 cm layer in Field 1 (78% considering the 0- to 10 cm layer) and 38% of the total roots is in the 0- to 5 cm layers in Field 2 (63% considering the 0- to 10 cm layer).

Broadcast treatment showed less amount of roots in the 0- to 5 cm layer and more in the 10- to 15 cm layer when compared to F.

Nutrient uptake depends on the amount of nutrient in soil and mainly on the water content in the fertilized soil layer, which is needed as carrier to root cells (Kutílek and Nielsen, 2015; Barber, 1995). A shallower root system become plants more responsive to rainfall and/or drought events, mainly during the reproductive phase to support the plant water demand. On the other hand, a deeper root system provides wider explored soil volume, and consequently more water and nutrients support to plants (Dardanelli et al. 1997).

Induced drought- A Case research

Deep band treatment showed high capacity to support the plant in a drought stress situation in both sites (Figure 5) with lower impact in grain yield, compared with other managements. In Field 1 there was a reduction of 9% of the grain yield and in Field 2 just 0.3% due to drought. Broadcast P treatment showed intermediate impact with 20 and 2% reduction on grain yield over a drought situation in Field 1 and Field 2, respectively. Managements that showed higher percentage of root lengths on surface had greatest reduction in grain yield on a drought situation. The reduction in grain yield in F was as much as 28 and 4% in Field 1 and Field 2, respectively. Above seed treatment showed reduction of 30 and 13% in grain yield in Field 1 and Field 2, respectively, under drought as compared to natural precipitation. This results illustrate the drastic effect of drought in grain yield in treatments that induced higher percentage of root length in the 0- to 5 cm layer.

Soybean plants demand about 7 to 9 mm of water per day during flowering through seed fill stage (Embrapa, 2011). The plants need to have the capacity to support this water demand (transpiration process) even in a drought event, which will guarantee enough photosynthates to be produced during the reproductive phase (Ribas-Carbo et al. 2005). The reduction of net photosynthesis can reach up to 40 and 70% over moderate to severe drought stress, respectively (Ribas-Carbo et al. 2005). This water support will provide a constant amount of photoassimilates to the grain, influencing grain weight, and consequently crop yield (Kutílek and Nielsen, 2015).

Water deficit at the beginning of seed-fill had the greatest detriments' effect on grain weight (Muchow and Sinclair, 1986). Thereby, Figure 4 shows the reduction of soybean grain weight as the main factor impacting soybean grain yield under an induced drought situation in different phosphorus placement.

4.5 CONCLUSIONS

Deep band treatment showed high capacity to support the plant in a drought stress situation with lower impact in grain yield, compared with other managements. In this treatment, 28 and 30% of the total root length is in the 15- to 25 cm layer in Field 1 and Field 2, respectively. On the other hand, management practices that promote high concentration of phosphorus in furrow showed large proportion of roots near the surface. For instance, in-furrow placement resulted in 55 and 37% of the total root length concentrated in the 0- to 5 cm layer in Field 1 and Field 2, respectively, as much as 80 and 59% of the total roots were in the 0- to 10 cm layer. In Field 1 there was a reduction of 9% of the grain yield and in Field 2 only 0.3% due to drought conditions. The results showed the importance of wide root systems to support plant requirements throughout growth stages.

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FIGURES

Figure 1. Precipitation during the experimental period. a) Não-Me-Toque, RS; and b) São Sepé, RS. Rainfall shelters have been installed on field for 25 days in flowering stage.

Figure 2. Soybean grain yield under rainfall normal condition in: a) Não-Me-Toque, RS; and b) São Sepé, RS. *Values followed by same letter indicate no significant difference at the $P \leq 0.05$ probability level.

Figure 3. Comparison between in-furrow and broadcast P placement and the effect on soybean yield. Data from 62 were gathered covering wide range of soil characteristics. †percentage of experiments with more responsible to P placement to yield. Red squares represent studies where in-furrow treatments resulted in statistical greater yield; Blue triangles represent studies where broadcast treatment resulted in statistical greater yields; and solid circles means no yield difference between treatments. Some information was not showed in all the papers.

Figure 4. Soybean grain weight in different phosphorus placement under drought stress and normal condition. a) Não-Me-Toque, RS; and b) São Sepé, RS. The bar means standard deviation.

Figure 5. Soybean grain yield in different phosphorus placement under drought stress and normal condition. a) Não-Me-Toque, RS; and b) São Sepé, RS. The bars mean standard deviation.

Table 1. Climate characterization for the study locations of Não-Me-Toque, RS and São Sepé, RS, Brazil.

Parameters	**Site**	
	Não-Me-Toque, RS	**São Sepé, RS**
Latitude	28º30’S	30º15’S
Longitude	52º46’W	53º46’W
Mean annual precipitation (mm)	1950	1600
Mean annual temperature (ºC)	18	19
Elevation (m)	475	202
Incident solar radiation (MJ m^{-2} day^{-1})	16	14
Köppen climate classification	Cfa†	Cfa

†Subtropical climates.

Table 2. Soil chemical and physical characteristics at the experiment sites in Não-Me-Toque, RS and São Sepé, RS.

Location	Chemical									Physical	
	Depth	pH_{H20}	P[#]	K	Ca	Mg	Al	Al[§]	Clay	Depth	PR
	cm		- mg dm^{-3} -		-- cmol$_c$ dm^{-3} --			%	%	cm	MPa[¶]
São Sepé, RS[†]	0-1	6.1	153	466	11.4	3.4	0	0	40		
	0-5	6.0	55	251	9.4	3.6	0	0	30	0-20	2.4
	5–10	5.4	15	194	6.1	3.2	0.1	1	28		
	10-20	4.6	7	130	4.5	2.2	0.5	7	30		
	20-30	4.2	5	88	4	1.8	1.3	18	32	20-40	2
	30-40	4.2	3	59	3.7	1.5	1.3	20	35		
Não-Me-Toque, RS[‡]	0-1	5.1	78	259	7	2.1	0.2	2	37		
	0-5	5.4	58	306	7.3	2.7	0.2	2	42	0-20	1.6
	5-10	5.2	25	268	6.7	2.6	0.2	2	50		
	10-20	5.0	13	157	6.1	2.6	0.2	3	57		
	20-30	5.2	2	100	5.6	2.4	0.3	3	80	20-40	1.9
	30-40	4.9	1	57	4.5	2.1	0.4	6	84		

[†] Paleudalf; [‡] Haplortox; [§] Percentage of Al in the effective CEC; [¶] Penetration resistance (PR).
[#] P-Mehlich 1.

Table 3. Soybean variety characteristics, NA 5909 RG and Monsoy 5917 IPRO.

Characteristics†	**NA 5909 RG‡**	**Monsoy 5917 IPRO§**
Maturity group	5.9	5.9
Cycle (days)	(115-130)	(105-120)
Growth habit	Indeterminate	Indeterminate
Fertility requirement	High	Medium/High
Lodging	Resistant	Resistant

†Information obtained from companies in Brazil. ‡Não-Me-Toque, RS; §São Sepé, RS.

Table 4. Significance of F values for the effects of grains yield over natural precipitation and induced drought condition, treatments (e.g, phosphorus placement), depth, classes and interaction.

Effect	P>F	
	Não-Me-Toque, RS	São Sepé, RS
Grain yield		
	ns	<0.001
Root distribution		
Treatment (T)	<0.001	<0.001
Depth (D)	<0.001	<0.001
T × D	<0.001	<0.001

[ns] no significance at $p \leq 0.05$.

Table 5. Reference of literature review.

Reference	**Country**	**Site/Years**
Barbosa et al. (2014)	Brazil	1
Bergamin et al. (2008)	Brazil	2
Borges and Mallarino (2000)	US	21
Buah et al. (2000)	US	11
Farmaha et al. (2011)	US	3
Guareschi et al. (2008)	Brazil	1
Guareschi et al. (2011)	Brazil	1
Jerke et al. (2012)	Brazil	8
Lana et al. (2003)	Brazil	3
Moterle et al. (2009)	Brazil	1
Motomiya et al. (2004)	Brazil	2
Nunes et al. (2011)	Brazil	14
Olibone and Rosolem (2010)	Brazil	5
Pauletti et al. (2010)	Brazil	7
Rosolem and Merlin (2014)	Brazil	3
Salvagiotti et al. (2013)	Argentina	11
Teixeira et al. (2013)	Brazil	1

Table 6. Total root length (cm dm^{-3}) and percentage by layer of soil.

Depth	Root length									
	Deep Band		In-furrow + Tillage		Broadcast		In-furrow		Above seed	
cm	cm dm^{-3}	%†	cm dm^{-3}	%	cm dm^{-3}	%	cm dm^{-3}	%	cm dm^{-3}	%
					<u>Não-Me-Toque, RS</u>					
0-5	176.9 Ba‡	31	189.8 Ba	38	213.1 ABa	49	221.7 ABa	55	246.8 Ba	58
5-10	110.5 ABCbc	19	137.4 Ab	27	112.3 ABb	26	101.3 BCb	25	85.0 Cb	20
10-15	119.0 Ab	21	81.2 Bc	16	63.2 Bc	14	38.4 Cc	10	36.6 Cc	8
15-20	66.1 Ad	12	42.1 Bd	8	26.1 CDd	6	22.0 Dd	5	30.8 BCc	7
20-25	90.5 Ac	16	51.3 Bd	10	21.7 Dd	5	20.4 Dd	5	30.1 Cc	7
Total	563.2	100	502.0	100	436.6	100	404.0	100	429.5	100
					<u>São Sepé, RS</u>					
0-5	154.8 ABa	28	186.5 Aa	30	106.3 Ca	32	167.2 ABa	37	148.2 Ba	38
5-10	126.7 Bb	23	189.2 Aa	31	66.3 Db	20	102.8 BCb	22	100.6 Cb	25
10-15	106.2 Abc	19	103.1 Ab	17	67.2 Bb	20	48.0 Cd	11	54.2 BCc	14
15-20	79.1 Ad	14	87.1 Ab	14	50.1 Bc	15	78.1 Ac	17	59.3 Bc	15
20-25	87.7 Acd	16	47.4 BCc	8	40.7 CDc	13	57.3 Bd	13	32.3 Dd	8
Total	554.7	100	613.4	100	330.8	100	453.5	100	395.0	100

†Percentage of total root length. ‡Upper case letters compare treatments by depths. Lower case letters compare depths within each treatment. Values followed by same letter indicate no significant difference at the $p \leq 0.05$ level.

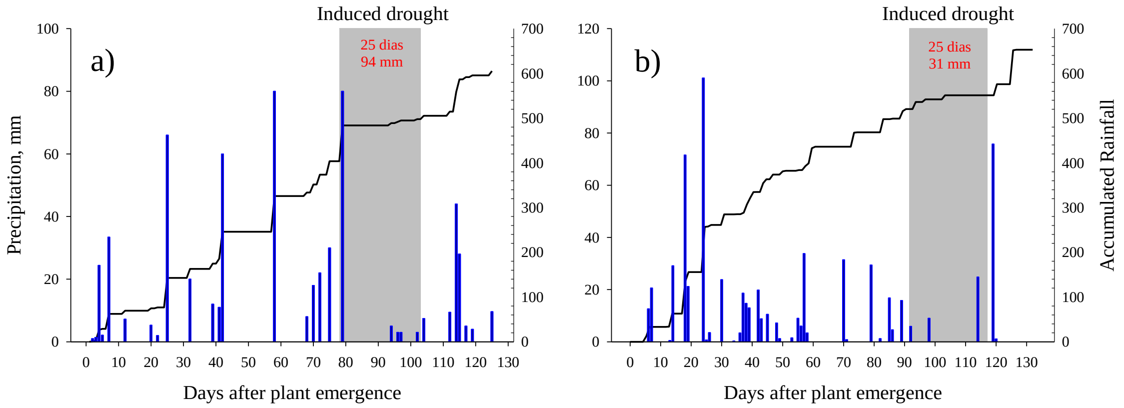

Figure 1. Precipitation during the experimental period. a) Não-Me-Toque, RS; and b) São Sepé, RS. Rainfall shelters have been installed on field for 25 days during grain filling stage.

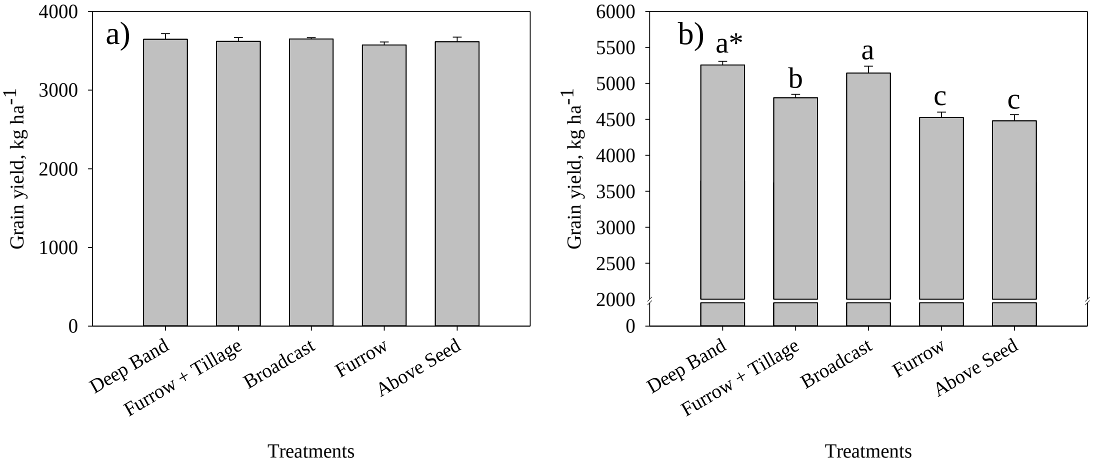

Figure 2. Soybean grain yield under normal rainfall condition in a) Não-Me-Toque, RS; and b) São Sepé, RS. *Values followed by same letter indicate no significant difference at the *p*≤ 0.05 level.

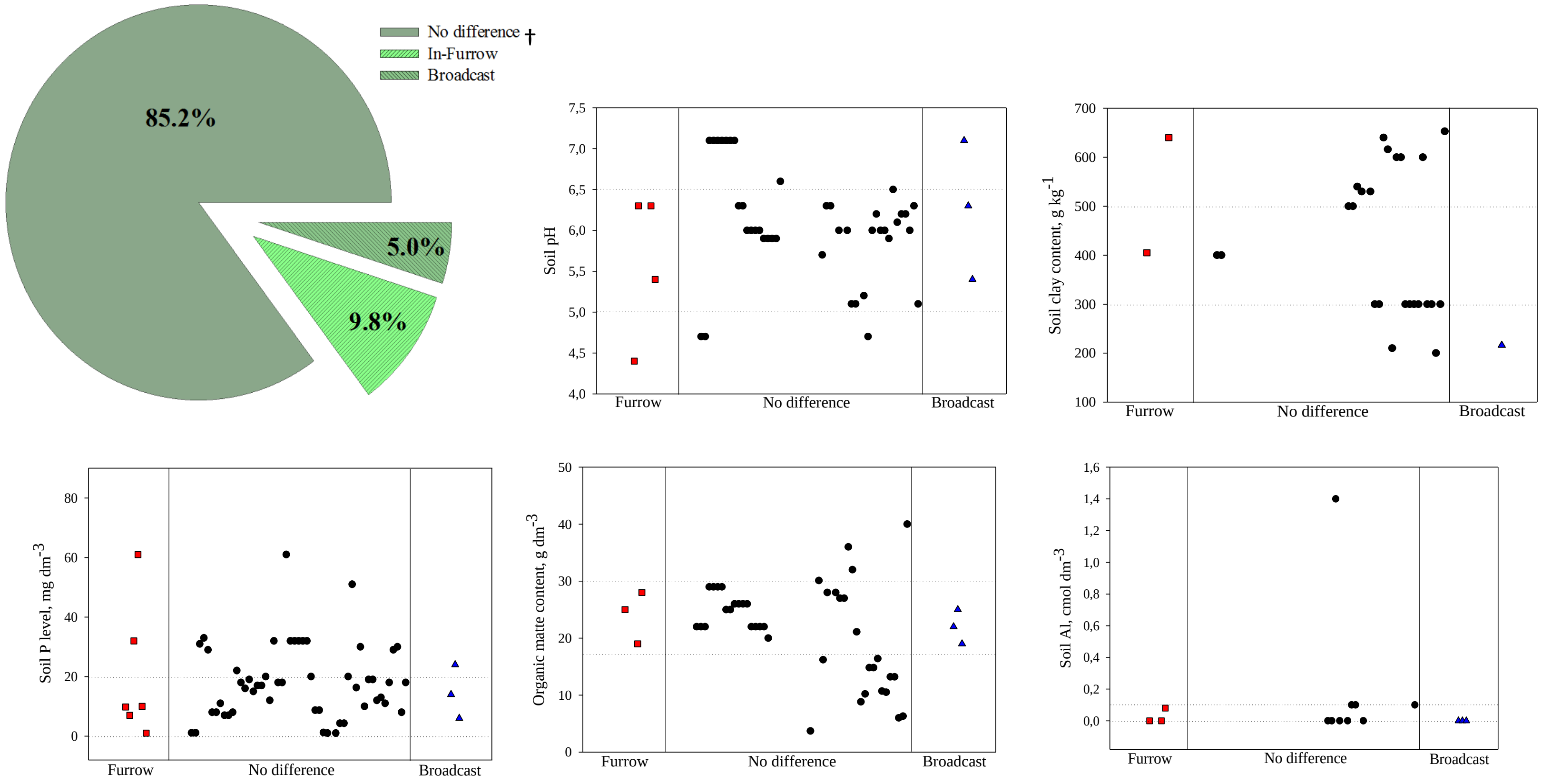

Figure 3. Comparison between in-furrow and broadcast P placement and the effect on soybean yield. Data from 62 were gathered covering wide range of soil characteristics. †percentage of experiments with more responsible to P placement to yield. Red squares represent studies where in-furrow treatments resulted in statistical greater yield; Blue triangles represent studies where broadcast treatment resulted in statistical greater yields; and solid circles means no yield difference between treatments. Some information was not showed in all the papers.

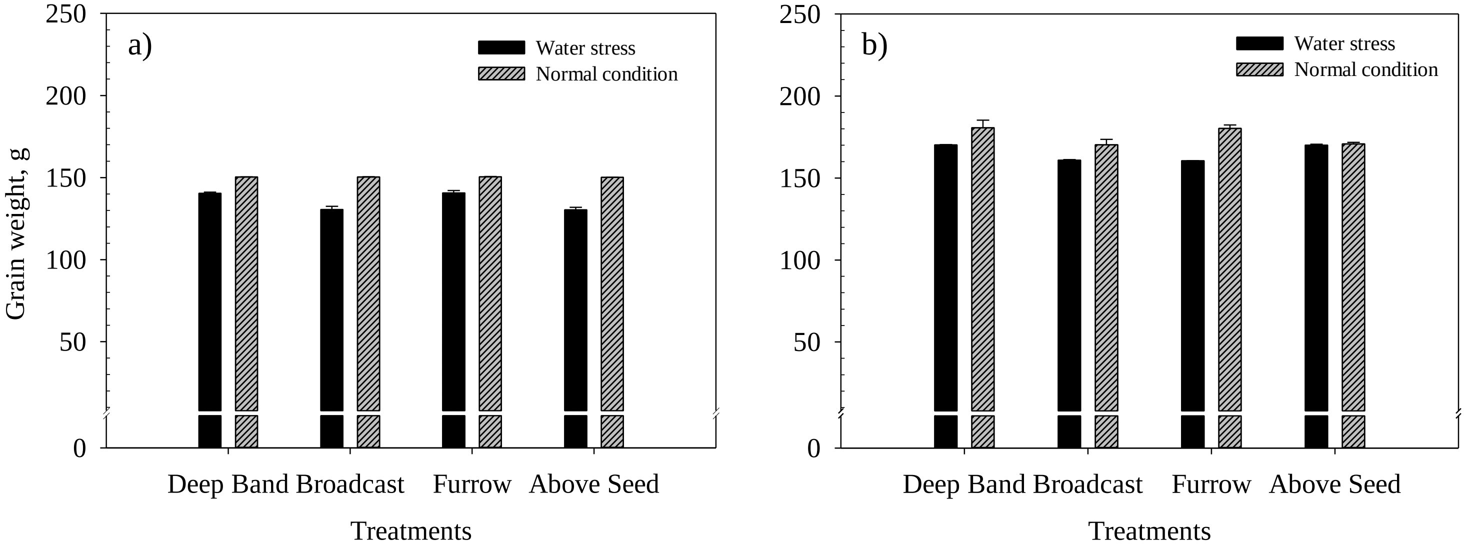

Figure 4. Soybean thousand-grain weight in different phosphorus placement under drought stress and normal precipitation condition. a) Não-Me-Toque, RS; and b) São Sepé, RS. The bar means standard deviation.

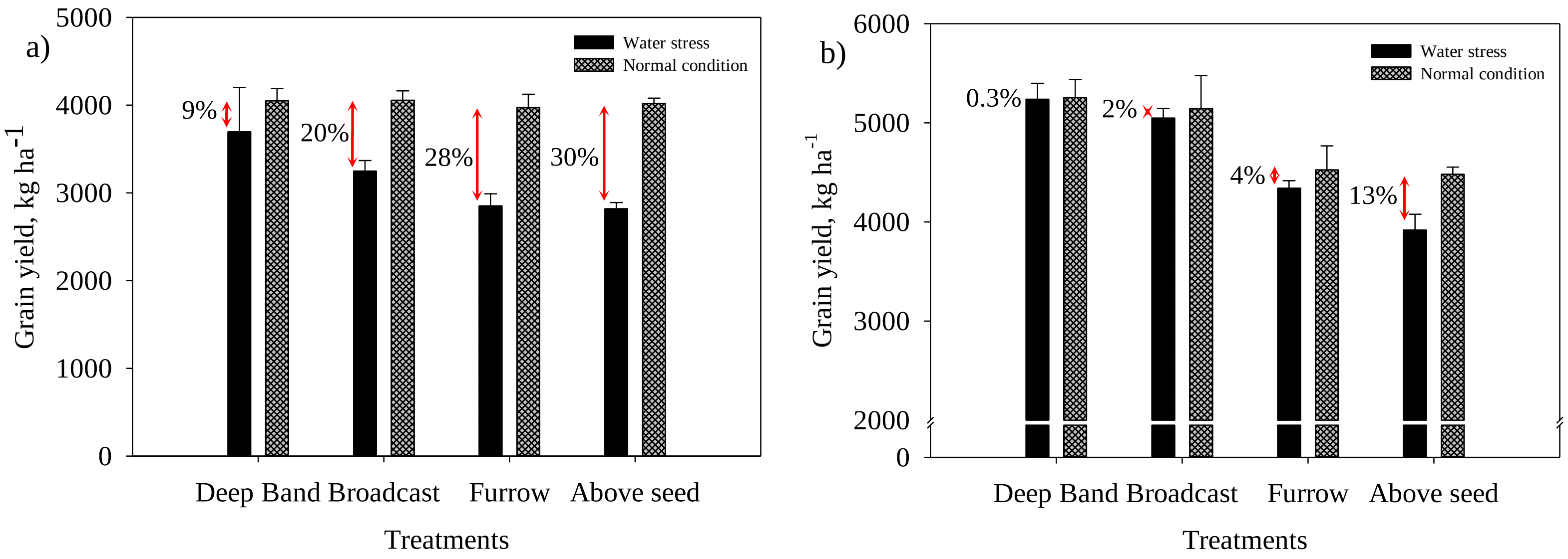

Figure 5. Soybean grain yield in different phosphorus placement under drought stress and normal condition. a) Não-Me-Toque, RS; and b) São Sepé, RS. The bars means standart desviation

5 DISCUSSION

This work is composed by 3 chapters aiming to explore a world concern which is P fertilizer management as well as P use-efficiency by plants, with focus on a better understanding of how plants react to a particular modification in the environment and alter the whole nutrition system of the plant.

Root is the plant organ that is in direct contact with soil, and is responsible for water and nutrients uptake, in addition to anchorage. Naturally, greatest proportion of the root system is in shallow layers, which is a genetic trait of adaption in plants. P placement modifies root growth and changes the adaptability of soybean plant to the environment. Thus, changes in root system interfere directly in plant-soil interactions, which will alter the whole plant energy balance, nutrients and water support in the plants. All changes in soil fertility will be detected by roots and can build crop yield.

In our results, we observed that deep band P promoted a deeper root growth, and in-furrow managements tended to provide a localized root growth around fertilized area. Broadcast showed no increase in shallow root growth and showed increase in lateral roots. The first observed effect was that there were different stimulus phases for root growth considering the same P management. One same P strategy can promote an initial P starvation and then P supplementation, or *vice-versa*, inducing modification in root architecture. Hormonal or sugar signs are activated, inducing root growth and controlling this process. The reason for this behavior is related to the cost of building root growth and a more efficient balance of energy in the plant, developing roots only when and where they are needed. Plant does not need to produce a great amount of roots, and spend energy in the process of doing so, if there are enough roots to supply the nutrient demand. Thereby, plant can direct the energy provided from photosynthesis to organs with higher energetic demands.

The plant response to P uptake under different P placement strategies was as expected. There was an increase in P uptake when there was greater volume of roots in the fertilized area. In-furrow treatments promoted greater amount of total P in initial growth phase, but in so far as there is an improvement of plant growth and a wider volume of soil that can be explored by roots, P placement lost relevance to P uptake. Physical and chemical conditions promoted by soil management and P placement altered root growth dynamics, affecting the interaction soil-root, and consequently, total P uptake.

A wider root system will provide a greater contact with volume of soil improving soil-plant interaction. Consequently, the plant has more water and nutrients uptake and possibly, greater symbiosis interaction between roots and microorganisms. This indirect effect of P placement strategy under N synthesized by rhizobium is still rarely addressed in the literature, requiring future studies.

Based on the balance of inputs/outputs of P, higher amount of P removed with grain (output) was observed, exceeding the input rate applied by fertilizer. Despite there was a greater concentration of P in the grain than what is reported in the literature, the great amount of removed P can be attributed to the higher yields observed in the study. In average, Não-Me-Toque, RS (Field 1) and São Sepé, RS (Field 2) showed total soybeans grain yield of 3989 kg ha^{-1} and 4841 kg ha^{-1}, respectively. These results showed great potential of modern varieties to produce higher amount of biomass and provide greater P accumulation and removal. Results also show that treatments that develop deeper root systems presented greater partial P balance.

Several studies exploring phosphorus placement have been conducted in the last decades with wide range of soil types, climate, initial P levels, soil texture, soil organic matter content, soil pH, aluminum, etc. Still, the results do not allow a definite conclusion of the most efficient and productive P management strategy. In many cases, different responses to P placement were found even within the same range of a given soil parameter. A direct parameter that is an indicative of the plant’s ability to explore the soil for fertilizer and soil moisture is the root system architecture. Nutrient uptake depends on the amount of nutrient in soil and mainly on water content in the fertilized soil layer, which is needed as the carrier to root cells.

Deep band treatment showed higher capacity to support the plant in a drought stress situation with lower impact in grain yield, compared to other managements. In this treatment, 28 and 30% of the total root length is in the 15- to 25 cm layer in Field 1 and Field 2, respectively. On the other hand, management practices that promote higher concentration of phosphorus in furrow showed large proportion of roots near the surface. For instance, in-furrow placement resulted in 55 and 37% of the total root length concentrated in the 0- to 5 cm layer in Field 1 and Field 2, respectively, as much as 80 and 59% of the total roots were in the 0- to 10 cm layer. In Field 1 there was a reduction of 9% of the grain yield and in Field 2 only 0.3% due to drought conditions. The results showed the importance of deep root systems to support plant requirements throughout growth stages.

Our results showed soybean physiologic performance and the P efficiency through the P balance between P input, P uptake and P removal. Other aspects related to P losses to the system and the environmental impact are extremely important, and must be considered in addition to grain yield, in the cropping system. Still, the relationship between a deeper root system and supplementation of other nutrients (not addressed in this work) could be very relevant to crop yields. The influence of P management on root growth may be altering the uptake of other nutrients e.g N, Ca, S, etc.

There is a need to physiologically evaluate the impact of any soil management, and also possible changes occurring in different plant organs. These could present effects in extreme climates and environments. Moreover, industry of agricultural machinery, soil fertility and plant physiology cannot be evaluated separately.

6 CONCLUSÃO

O manejo da fertilização fosfatada induziu alterações no crescimento radicular de forma a aumentar a absorção do nutriente e respeitando o balanço e eficiência energética da planta. Como consequência, a dinâmica de absorção de P e a capacidade adaptativa da planta ao ambiente sofreram alterações. A fertilização fosfatada profunda apresentou promissores resultados de forma a contribuir com o aumento da eficiência no uso do P e propiciar de forma indireta, melhores condições adaptativas para aplanta.

A fertilização fosfatada profunda propiciou um maior crescimento radicular em profundidade, fornecendo maior suporte hídrico para a soja e aumentando a área explorada de solo de forma a incrementar a capacidade absortiva da planta. Em soma, outros benefícios decorrentes ao favorecimento do crescimento radicular, os quais não foram abordados neste trabalho, podem apresentar grande importância para a obtenção de altas produtividades. Por exemplo, a maior interação rizóbio-sistema radicular propiciado por um mais amplo sistema radicular com consequente aumento no fornecimento de nitrogênio pela simbiose é possível. Da mesma forma, há a possibilidade do aumento indireto na absorção de outros nutrientes tais como cálcio, enxofre, etc.

A aplicação de P superficialmente não induziu maior crescimento radicular na superfície, porém verificou-se aumento no crescimento lateral. Dentre os tratamentos estudados, a aplicação a lanço obteve o segundo melhor resultado, tanto para o aumento da eficiência na recuperação de P do solo quanto em situação de estresse hídrico. Cabe aqui ressaltar que não foram avaliados nesse trabalho perdas pelo sistema solo e impacto ambiental gerado pelos métodos de fertilização de P, reconhecendo-se a grande importância desses fatores para um manejo sustentável da fertilização.

Na fertilização em linha de semeadura maiores valores iniciais de acúmulo de P no tecido vegetal não refletiram em aumentos na produtividade. As mudanças provocadas no crescimento do sistema radicular pela deposição do fertilizante fosfatado nessa profundidade tornaram a planta mais suscetível às condições ambientais, podendo assim apresentar maiores instabilidades produtivas de acordo com as características climáticas do ano agrícola.

Outros estudos são necessários para aprofundar as informações sobre este tema. Porém, há a necessidade da observação de fatores indiretos ligados ao manejo da fertilização fosfatada. O aumento sustentável da produção agrícola se deverá ao entendimento multidisciplinar dos fatores que regem a produtividade das culturas.