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Interference from the vertical variation of soil phosphorus and from water stress on growth in maize, the soybean and sunflower[1]

Interferência da variação vertical de fósforo no solo e do estresse hídrico no crescimento de milho, soja e girassol

Clovis Orlando Da Ros[2]*, Marcia Matsuoka[2], Rodrigo Ferreira da Silva[2] and Vanderlei Rodrigues da Silva[2]

ABSTRACT - The distribution of phosphorus (P) in the soil interferes with the availability of the nutrient and can affect plant growth. The aim of this study was to compare the growth and accumulation of P in maize, soybean and sunflower plants in vertical gradients of the nutrient in the soil, with and without water stress. The design was completely randomised with five replications, in a 3 x 2 factorial scheme: three soil depth gradients of P (decreasing, increasing and nil) and two conditions of soil water availability (with and with no water stress). The depth gradients of P were in decreasing doses of P_2O_5 (300, 200, 100 and 0 mg dm^{-3}), increasing doses (0, 100, 200 and 300 mg dm^{-3}) and equal doses (150 mg dm^{-3}) applied to the intermediate layers between 0.0-5.0, 5.1-10.0, 10.1-15.0 and 15.1-20.0 cm. Height, dry weight and P accumulation in the roots and shoots were quantified. The data were submitted to analysis of variance, and mean values compared by Tukey's test ($p<0.05$). The distribution of P in the soil did not interfere with growth or nutrient accumulation in the soybean. Phosphate fertiliser located in the surface or subsurface layers favoured greater growth and the accumulation of P in the maize and sunflower, compared to the uniform distribution of the nutrient in the 0-20 cm layer. The increase in phosphate fertiliser at depth did not increase growth or P accumulation in the three crops, even under conditions of water stress.

Key words: Soil water. Roots. Dry weight. Nutrient accumulation.

RESUMO - A forma de distribuição do fósforo (P) no solo interfere na disponibilidade do nutriente e pode afetar o crescimento das plantas. O objetivo do trabalho foi comparar o crescimento e a acumulação de P nas plantas de milho, soja e girassol em gradientes verticais do nutriente no solo com e sem estresse hídrico. O delineamento foi o inteiramente casualizado com cinco repetições, no esquema fatorial 3 x 2: três gradientes de P em profundidade no solo (decrescente, crescente e nulo) e duas condições de disponibilidade de água no solo (sem e com estresse hídrico). Os gradientes de P em profundidade foram doses decrescentes de P_2O_5 (300; 200; 100 e 0 mg dm^{-3}); doses crescentes (0; 100; 200 e 300 mg dm^{-3}) e doses iguais (150 mg dm^{-3}), aplicadas nas camadas intermediárias entre 0,0-5,0; 5,1-10,0; 10,1-15,0 e 15,1-20,0 cm. Foi quantificada a altura, a massa seca e o acúmulo de P na parte aérea e nas raízes das plantas. Os dados foram submetidos à análise da variância e as médias comparadas pelo teste de Tukey ($p < 0,05$). A forma de distribuição do P no solo não interferiu no crescimento e no acúmulo do nutriente na soja. A localização da adubação fosfatada na camada superficial ou em subsuperfície favoreceu maior crescimento e P acumulado no milho e girassol em comparação com a distribuição uniforme do nutriente na camada de 0-20 cm. O aumento da adubação fosfatada em profundidade não aumentou o crescimento e o acúmulo de P nas três culturas, mesmo em condições de estresse hídrico.

Palavras-chave: Água no solo. Raízes. Massa seca. Acúmulo de nutrientes.

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INTRODUCTION

Phosphorus (P) is not a very mobile nutrient in the soil, and tends to accumulate in the surface layer, especially in clayey soils of variable load (clay 1:1) and with a high iron oxide content (CHIEN *et al*., 2011; DIEL *et al*., 2014). The high binding energy of the phosphate anion with the positive charges of the colloids forms inner-sphere surface complexes, preventing the P from returning to the soil solution and from being displaced with depth (NOVAIS; SMYTH, 1999).

The method of applying phosphate fertiliser also influences the intensity of the gradient, especially under a no-till system. Broadcast application of the nutrient produces a greater vertical gradient in relation to its incorporation in the furrow when sowing (BARBOSA *et al*., 2015; NUNES *et al*., 2011). Normally, in areas under a no-till system, the highest P content in the soil occurs in the 0.0-2.5 cm layer for broadcast fertiliser, and at 5.0-7.5 cm when applied to the sowing furrow, to the detriment of content that is below the critical level at lower layers (BARBOSA *et al*., 2015).

This condition, inherent to a no-till system, raises the question whether low P availability at depth reduces root growth, and consequently grain production, especially under drought conditions. The greater part of P adsorption occurs through the process of diffusion, in which transport of the phosphate ion to the root surface takes place due to a difference in concentration in the liquid phase of the soil (FINK *et al*., 2016). Applying P at depth may therefore allow greater absorption of the nutrient during periods of drought in relation to surface application, since moisture tends to be higher in the subsurface. In this case, the greater soil moisture becomes the main factor in the supply of P to plants, both in the area where the root surface is in contact with the solution, inducing greater root growth, and in diffusion of the ion to the root surface.

From another perspective, a high concentration of P in the soil surface layer can allow nutrient absorption during periods of adequate soil moisture and translocation to the roots (high mobility in the plant) during drought, provided that moisture does not restrict root growth at depth. Plant root growth at depth will therefore not be affected by a P deficiency, should other factors not limit root growth, such as aeration, compacted layers, toxic elements above tolerance limits, and an adequate availability of nutrients (FARMAHA; FERNÁNDEZ; NAFZIGER, 2012). In this case, the soil phosphorus gradient becomes a factor of less importance to the supply of the nutrient to the plants compared to water availability (BUAH; POLITO; KILLORN, 2000; NUNES *et al*., 2011).

Based on the above ideas, the hypothesis to be assumed is that the vertical soil P depth gradient does not alter growth or the accumulation of the nutrient in plants, even under conditions of water stress. The aim of this work was to compare growth and P accumulation in three grain crops, for different vertical P gradients, in soil with and without water stress.

MATERIAL AND METHODS

The work was carried out in a greenhouse on the Frederico Westphalen campus of the Federal University of Santa Maria, in the State of Rio Grande do Sul, from November 2013 to March 2014, in three experiments with maize (*Zea mays*), soybean (*Glycine Max*) and sunflower (*Helianthus annuus* L.). These were planted in pots made from 200 mm PVC tubes, 270 mm in height, and filled with declumped soil collected from the 0-20 cm layer of an area of annual pasture, air-dried and sieved through a 5 mm mesh.

The soil was classified as a Red Nitosol in brasilian system of soil classification (SANTOS *et al*., 2013), with the following attributes: 560 g kg^{-1} clay, quantified by densometer method; 3.4 and 80.1 mg dm^{-3} of P and K available, respectively, determinated by Mehlich-1 extraction; exchangeable Al, Ca and Mg of 0.0, 10.3 and 3.9 $cmol_c$ dm^{-3} respectively, extracted with a 1.0 mol L^{-1} KCl solution; Cu and Zn of 22.3 and 13.0 mg dm^{-3} respectively, extracted with a 0.1 mol L^{-1} HCl solution; potential CEC of 16.7 $cmol_c$ dm^{-3}; base saturation of 87%; organic matter of 29 g dm^{-3}; pH in water of 6.2 and SMP index of 6.6, as per methodologies described in Silva (2009). The soil physical attributes after filling the pots were, 1.13 kg dm^{-3} of the soil bulk density, a total porosity of 0.53 dm^3 dm^{-3} and a water retention capacity of 0.29 dm^3 dm^{-3} (EMBRAPA, 2011).

The maize hybrid (Pioneer P1630) was planted on 16 October 2013, the soybean cultivar (Brasmax Tornado RR) on 28 November 2013, and the sunflower hybrid (Dow Agrosciences NTC 90) on 02 February 2014, using three seeds per pot. After germination, thinning was carried out, leaving one plant per pot.

A completely randomised experimental design was used, in a 3 x 2 factorial scheme: three soil P depth gradients (decreasing, increasing and zero) and two conditions of soil water availability (with and without water stress), with five replications. The soil P gradients of the experimental units were formed by the application of doses decreasing with depth (300, 200, 100 and 0 mg dm^{-3} of P_2O_5), increasing with depth (0, 100, 200 and 300 mg dm^{-3} of P_2O_5) and of equal doses in the zero gradient (150 mg dm^{-3} of P_2O_5) respectively, applied in the intermediate layers between

0.0-5.0, 5.1-10.0, 10.1-15.0 and 15.1-20.0 cm. A 2.5 cm layer of soil with no fertiliser was placed at the bottom of the pot, to be discarded when evaluating the roots.

The average dose of P in the 0-20 cm layer was the same for all treatments (150 mg dm^{-3} of P_2O_5), based on the recommendation of 300 kg ha^{-1} of P_2O_5. The aim of this high dose of P was to force the formation of a gradient with a single application of fertiliser. The phosphorus dose was equivalent to an expected grain yield of 14 Mg ha^{-1} in the maize, considering this crop to have a higher demand for P under irrigated conditions, as recommended by the SBCS (2016). Together with the phosphate fertiliser, 190 kg ha^{-1} of K_2O were applied to the three crops. Nitrogen fertiliser, equivalent to 200 kg ha^{-1} of N, was applied to the maize and sunflower crops only; in the soybean crop, a peat-type inoculant was used when sowing.

The phosphate fertiliser, in the form of triple superphosphate, and the potassium fertiliser, in the form of KCl, were ground to increase distribution uniformity. The nitrogen fertiliser, in the form of sulfammo, was used as granules to maintain an efficient gradual release of N. The three types of fertiliser were applied to the central part of each soil layer.

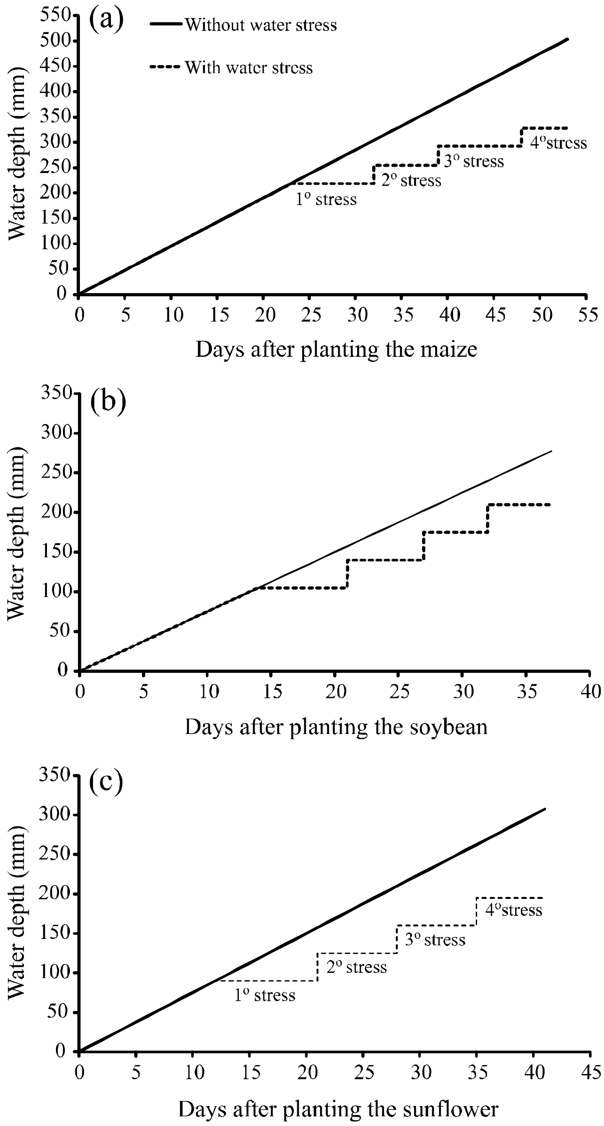
Fifteen days after sowing the sunflower, and 25 days after sowing the maize, a dose equivalent to 100 kg ha^{-1} of N was applied as cover, by the addition of 21 mL per pot of a 1.5% N solution. After application, 20 mm of water were added to incorporate the fertiliser into the soil.

The crops were grown in a greenhouse with an automatic sprinkler irrigation system, and irrigated six times a day, from 08:00 to 18:00, giving a daily average total of 9.5 mm in the maize and 7.5 mm in the soybean and sunflower. This water depth resulted on average in 80% field capacity.

From 24 to 54 days after planting the maize (30 days), from 14 to 37 days in the soybean (23 days) and from 12 to 41 days in the sunflower (29 days), the plants were separated into two groups; in the first group irrigation was normal (no water stress), and in the second irrigation was suspended (with water stress). During this period, the plants were submitted to water stress four times, at average intervals of approximately one week, taking as criterion the beginning of wilting and winding of the leaves at the apex. After each period of water stress, 35 mm of water were added, sufficient to moisten the entire volume of the pot. Figure 1 shows the periods of water restriction for the three crops, and the amount of water applied in the treatments with and without water stress.

After the final period of water stress, the plant growth parameters were quantified, measuring shoot height, and root and shoot dry weight. The shoot dry weight of the plants cut level with the root collar, and of the roots in the 0.0-5.0, 5.1-10.0, 10.1-15.0 and 15.1-20.0 cm layers, was measured after oven drying at 65 °C to constant weight.

Figure 1 - Accumulated water depth for the growing period of maize, soybean and sunflower plants in treatments with and without water stress



The PVC tubes containing the soil and roots were frozen and sliced into 5 cm layers; the roots were separated by water jet, initially over a sieve with mesh a of 4 mm, and then over a sieve with a mesh of 2 mm to remove impurities. Soil samples were collected at these layers, with the P extracted by the Mehlich-1 method, and determined by spectrophotometry. The P was extracted from the shoot and root dry matter using the wet digestion method with sulphuric acid, and determined by spectrophotometry. The methodologies to determine the P in the soil and plants were as described in Silva (2009).

Based on the dry weight (g plant^{-1}) and P content of the shoots and roots (g kg^{-1}), the amount of nutrient accumulated in the plants was calculated in µg plant^{-1}. When necessary, the results were normalised by the transformation $\sqrt{(x+1)}$ and submitted to analysis of variance; the mean values for the treatments were compared by Tukey's test at 5% probability using the Sisvar 5.3 software (FERREIRA, 2015). For soil P levels, a treatment factor (crops) was added, i.e. the statistical analysis was carried out in a 3 x 2 x 3 factorial scheme: three P gradients, two conditions of soil water availability and three crops.

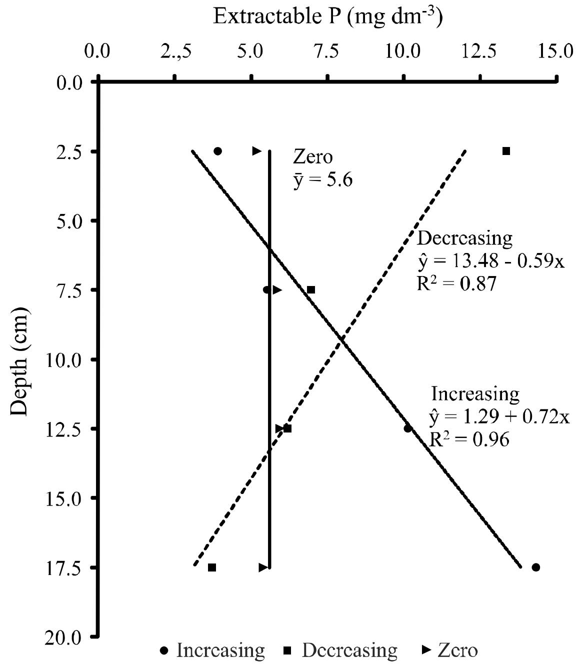
RESULTS AND DISCUSSION

The application of increasing and decreasing doses of P to the soil with depth when planting the maize, soybean and sunflower crops, made possible the formation of a vertical nutrient gradient (Figure 2). In the average of the three crops, and of the treatments with and without water stress, the treatment with the increasing gradient resulted in an increase with depth of 3.9 to 14.3 mg dm^{-3} of P respectively in the 0-2.5 and 15.1-20.0 cm layers. In the decreasing gradient, the P content was reduced from 13.3 to 3.7 mg dm^{-3} for the same layers respectively. In the treatment with a uniform application of P to the four layers (zero gradient), the content remained constant, with a mean value of 5.6 mg dm^{-3} per layer.

It can be seen that the original P content of the soil (3.4 mg dm^{-3}) was not changed in the 15-20 cm layer for the decreasing gradient (3.2 mg dm^{-3}) (Figure 2). As P was applied only to the upper layers in this treatment, this would indicate that there was no displacement of the nutrient at depth. This may characterise the high adsorption of the phosphorus ion to the soil colloids, and explains the ease of gradient formation with the localised application of the fertiliser, especially in soils similar to that used in the present study, as highlighted in soils with predominantly variable-load clay minerals (clay 1:1) and rich in iron oxide (CHIEN *et al*., 2011; DIEL *et al*., 2014).

With the uniform application of phosphate fertiliser to the soil layers (null gradient), the P content did not reach the critical level (Figure 2), which is 12.0 mg dm^{-3} for the soil under study (SBCS, 2016). For the increasing and decreasing gradients, the P content reached a critical level in at least one layer of soil, with values of up to 13.9 mg dm^{-3}, close to the value established for the

Figure 2 - Extractable P content in four layers of soil after the application of fertiliser doses for the formation of increasing, decreasing and zero gradients. Mean value for soil samples in maize, soybean and sunflower crops (with and without water stress)



sunflower crop (14.4 mg dm^{-3}) in soils with 410 to 610 g kg^{-1} of clay (ELTZ *et al*., 2010). Studies show that the amount of P required to raise one unit of nutrient in the soil (mg kg^{-1}) is greater in the 0-20 cm layer than in the 0-10 cm layer, explained by dilution in a larger volume of soil and a greater adsorption of P by the soil colloids (SCHLINDWEIN *et al*., 2013).

The mean quantity of extractable P in the four layers of soil was 8.5 mg dm^{-3} for the increasing gradient, 7.6 mg dm^{-3} for the decreasing gradient and 5.6 mg dm^{-3} for the zero gradient (Figure 2). The greater values of P found in the soil with the increasing and decreasing gradients demonstrate the importance of localising the phosphate fertiliser to increase P availability to the plants, especially in soils with a high adsorption capacity for the nutrient, as reported in several studies (BERGAMIN *et al*., 2008, NUNES *et al*., 2011, ROSOLEM; MERLIN, 2014).

The vertical distribution of the phosphate fertiliser in the 0-20 cm layer interfered in different ways in the growth parameters of the maize, soybean and sunflower plants as a function of water stress. In the soybean crop, water stress significantly reduced plant growth and accumulated P in the same proportion for all P gradients (Table 1).

Table 1 - Plant height, dry weight and accumulated P in the shoots and roots of the soybean crop for phosphorus depth gradient and conditions of water stress

Parameter/layer	Phosphorus depth gradient			Water stress		CV (%)
	Decreasing	Increasing	Zero	Without	With	
	---------- Shoots ----------					
Height (cm)	28.1 a[(1)]	29.4 a	31.0 a	31.3 a	27.7 b	7.8
Dry weight (g plant^{-1})	9.0 a	8.5 a	9.4 a	11.1 a	7.0 b	9.4
Accumulated P (µg plant^{-1})	15.5 a	14.3 a	15.8 a	17.1 a	13.4 b	10.2
	---------- Roots - dry weight (g plant^{-1}) ----------					
0.0 - 5.0 cm	2.10 a	1.67 a	1.73 a	2.31 a	1.36 b	22.6
5.1 - 10.0 cm	0.66 a	0.46 a	0.63 a	0.76 a	0.41 b	48.8
10.1 - 15.0 cm	0.45 a	0.51 a	0.49 a	0.61 a	0.35 b	42.8
15.1 - 20.0 cm	0.56 a	0.60 a	0.50 a	0.73 a	0.37 b	28.2
	---------- Roots - accumulated P (µg plant^{-1}) ----------					
0.0 - 5.0 cm	3.32 a	2.12 b	2.46 a	3.07 a	3.20 b	28.2
5.1 - 10.0 cm	0.81 a	0.52 a	0.71 a	0.84 a	0.51 b	50.6
10.1 - 15.0 cm	0.49 a	0.50 a	0.59 a	0.65 a	0.41 b	46.4
15.1 - 20.0 cm	0.59 a	0.59 a	0.57 a	0.75 a	0.41 b	32.6

[(1)] Mean values followed by the same letter on a line and for gradient and water stress, do not differ by Tukey's test at 5% probability (non-significant interaction between treatment factors)

The reduction of soybean growth in the treatment with water stress was 11.5% in plant height, 36.9% in shoot dry weight and 41.1% in root dry weight for the 0.0-5.0 cm layer (Table 1). Water deficiency, even when moderate, can delay or interrupt cell division and expansion well before water stress becomes severe enough to cause stomatal closure and a decrease in photosynthesis (TAIZ; ZEIGER, 2013).

In relation to the soil P gradients, it can be seen that plant height, dry weight and accumulated P in the shoots and roots of the soybean plants were not affected by the form of distribution of the phosphate fertiliser in the 0-20 cm layer, irrespective of soil water availability (Table 1). In the maize and sunflower crops, the lowest values for growth parameters and accumulated P were found under conditions of water stress and in the zero gradient (Table 2). In these two crops, the effects of water stress were possibly added to that of low soil P availability. In a study with different levels of soil water and phosphorus, Araújo *et al*. (2014) also found less fresh biomass and smaller head diameter in the sunflower, when both factors were limiting.

In the maize and sunflower crops, despite the significant interaction between the two treatment factors under study, it was not possible to see any advantage, under conditions of water stress, from the increasing P gradient in the soil in comparison to the decreasing gradient, for all the parameters under evaluation (Table 2). In these two crops, there was greater plant height, dry matter and accumulated P in the shoots, and greater dry weight and accumulated P in the roots, in the surface layer of the soil (0.0-5.0 cm) for the increasing and decreasing gradients, compared to the zero gradient.

The greater growth and amount of accumulated P in the maize and sunflower plants with the increasing and decreasing gradients show that the two crops were more demanding of phosphorus than the soybean. It can be seen that the P content in the four layers of soil of the zero gradient, even being below the critical level, did not negatively affect soybean growth. Dovale and Fritsche-Neto (2013) report that there is a difference in P use efficiency among maize plants, and even among genotypes. This demonstrates the need for studies into cultivar classification and genotype selection based on requirements of soil P availability. The SBCS (2016) specifies different critical levels of P for crop groups as a function of the demand for the nutrient (very demanding, demanding and slightly demanding), but does not determine critical levels for grain crops.

Under conditions of water stress, the lack of response of root dry weight and accumulated P to the increasing P depth gradient, compared to the decreasing gradient, may be related to the rapid reduction of available water in the soil. Hsiao and Xu (2000) point out that continued root growth at depth under conditions of lower water availability, depends on the maintenance of a minimum turgor pressure in the cells to allow cell wall elongation and cell growth. A soil water deficit tends to stimulate the allocation of photoassimilates to the roots, and increases expansion of the root system to deeper and more humid zones in the soil, especially until the flowering stage of the crops, when the volume of soil exploited by the root system increases and the absorption of water and nutrients is facilitated.

The 0-20 cm layer of soil exploited by the roots was probably insufficient, under conditions of water stress, to make a moisture gradient possible, capable of contributing to greater root growth and of allowing greater phosphorus absorption under greater availability of the nutrient with depth. A difference in P accumulation in the dry matter only occurs when the water stress imposed is sufficient to interfere in the process of nutrient absorption (LEÃO; FREIRE; PAES, 2011). In maize, a minimum amount of 40% of available soil water is necessary for the crop to respond significantly to the doses of phosphorus applied to the soil (ALVES *et al*., 2002).

The greater growth and P accumulation in the maize and sunflower plants with the increasing and decreasing gradients are probably related to the greater availability of P in the soil due to localisation of the phosphate fertiliser, irrespective of layer (Figure 1 and Table 2). These results confirm the importance of localisation of the phosphate fertiliser, especially in soils where the P content is below the critical level, and which

Table 2 - Plant height, dry weight and accumulated P in the shoots and roots of maize and sunflower plants for phosphorus depth gradient and conditions of water stress

Crop	Water stress	Phosphorus depth gradient			CV (%)
		Decreasing	Increasing	Zero	
---------- Height (cm) ----------					
Maize	Without	139.3 aA(1)	126.5 aB	99.2 aC	6.8
	With	113.8 bA	119.2 aA	98.0 aB	
Sunflower	Without	69.4 aA	72.0 aA	62.2 aB	6.4
	With	70.6 aA	63.4 bB	68.2 aAB	
---------- Shoot dry weight (g plant^{-1}) ----------					
Maize	Without	90.6 aA	87.2 aA	49.7 aB	14.3
	With	54.7 bA	55.0 bA	48.9 aA	
Sunflower	Without	20.1 aA	21.0 aA	17.1 aB	12.2
	With	16.7 bA	18.0 bA	9.9 bB	
---------- Accumulated P in the shoots (µg plant^{-1}) ----------					
Maize	Without	118.51 aA(3)	120.34 aA	69.87 aB	19.4
	With	105.04 aA	6.46 aA	86.18 aA	
Sunflower	Without	32.32 aA	35.63 aA	34.11 aA	16.7
	With	27.81 aB	37.29 aA	20.10 bB	
---------- Root dry weight (0.0-5.0 cm) (g plant^{-1}) ----------					
Maize	Without	13.64 aA	11.86 aA	7.41 aB	14.4
	With	6.57 bA	6.43 bA	3.97 bA	
Sunflower	Without	3.57 aA	2.61 aB	1.50 aC	12.6
	With	1.51 bA	1.77 bA	1.42 aA	
---------- Accumulated P in the roots (0.0-5.0 cm) (µg planta^{-1}) ----------					
Maize	Without	13.77 aA(3)	9.52 aB	7.39 aB	23.2
	With	7.37 bA	8.40 aA	4.04 bB	
Sunflower	Without	5.64 aA	4.11 aB	3.61 aB	23.0
	With	3.08 bA	3.81 aA	3.32 aA	

(1) Mean values followed by the same letter, uppercase on a line, lower case in a column, do not differ by Tukey’s test at 5% probability

have a high capacity for adsorption of the nutrient, to increase its availability in the soil and its accumulation in the plant.

In soils with high P availability, studies show that localisation of the phosphate fertiliser in the sowing furrow, distribution on the soil surface or incorporation into the 0-20 cm layer, can affect root growth, but does not influence grain yield (BERGAMIN *et al*., 2008; BUAH; POLITO; KILLORN, 2000; NUNES *et al*., 2011; PAULETTI *et al*., 2010; SÁ; BRIEDS; FERREIRA, 2013).

When comparing the treatments of increasing and decreasing gradients, it was seen that there was no difference in weight production or accumulated P in the roots of the three crops, irrespective of soil layer (Tables 1, 2 and 3). The low demand for P by the plants at the initial growth stage, together with the low soil density, the absence of exchangeable aluminium, and the adequate availability of nutrients and water in the 0-20 cm layer, favoured rapid root growth at depth. In this situation, localising the highest dose of P at the surface or subsurface made no difference to the roots finding the points of greatest nutrient concentration. Subsequently, with the greater demand for P by the plant, supply at the various growth points may have been met by high nutrient mobility in the plant (ZHOU, WANG, 2004).

In a three-year study of the soybean, with four doses of P applied to the surface and at a depth of 15 cm, Farmaha, Fernández and Nafziger (2012) point out that the allocation of phosphate fertiliser at depth when planting has no effect on growth or on nutrient accumulation in the plant tissue, compared to applying the fertiliser to the soil surface. The authors also report that there is no disadvantage to the nutrition of soybean plants with the vertical stratification of soil P under a no-till system, especially when the content is above the critical level.

Opening furrows to place the phosphate fertiliser, conditions improvements in the physical attributes of the soil, mainly with applications at depths of between 15 and 20 cm. The furrow opened by the seeder facilitates the infiltration of water into the soil profile and, in the phase of highest demand by the crop, contributes to greater water availability in the surface layer of the soil, where the largest amount of roots is concentrated (LIPIEC *et al.*, 2006). Under

Table 3 - Root dry weight and accumulated P in the roots of maize and sunflower plants for phosphorus depth gradient and conditions of water stress

Crop	Phosphorus depth gradient			Water stress		CV (%)
	Decreasing	Increasing	Zero	Without	With	
Root dry weight $_{(5.1\text{-}10.0\ cm)}$ (g plant^{-1})						
Maize	3.46 a[(1)]	3.49 a	2.07 b	3.74 a	2.27 b	22.3
Sunflower	0.58 a	0.59 a	0.30 b	0.55 a	0.42 a	37.7
Root dry weight $_{(10.1\text{-}15.0\ cm)}$ (g plant^{-1})						
Maize	2.55 a	2.92 a	2.31 a	3.37 a	1.81 b	27.1
Sunflower	0.46 a	0.34 a	0.38 a	0.44 a	0.36 a	48.7
Root dry weight $_{(15.1\text{-}20.0\ cm)}$ (g plant^{-1})						
Maize	2.80 a	2.78 a	1.87 a	2.54 a	2.45 a	38.2
Sunflower	0.43 a	0.35 a	0.41 a	0.49 a	0.30 b	33.3
Accumulated P in the roots $_{(5.1\text{-}10.0\ cm)}$ (µg plant^{-1})						
Maize	3.20 a	3.52 a	2.03 a	3.45 a	2.39 b	23.4
Sunflower	0.78 a	0.71 a	0.49 a	0.70 a	0.61 a	40.6
Accumulated P in the roots $_{(10.1\text{-}15.0\ cm)}$ (µg plant^{-1})						
Maize	2.25 b	3.06 a	2.27 b	3.10 a	1.96 a	26.3
Sunflower	0.54 a	0.31 b	0.55 a	0.48 a	0.45 a	38.1
Accumulated P in the roots $_{(15.1\text{-}20.0\ cm)}$ (µg plant^{-1})						
Maize	2.25 ab	2.95 a	1.85 b	2.33 a	2.37 a	37.7
Sunflower	0.42 ab	0.39 b	0.57 a	0.51 a	0.41 a	34.9

[(1)] Mean values followed by the same letter on a line and for gradient and water stress, do not differ by Tukey's test at 5% probability (non-significant interaction between treatment factors) such conditions, the indirect benefits of opening the furrow may increase plant growth and grain yield, but should not be confused with the specific effects of the phosphate fertiliser (FARMAHA; FERNÁNDEZ; NAFZIGER, 2012).

The application of phosphate fertiliser to the sowing furrow (5-7 cm) or at depth (15-20 cm) is a practice that is also justified to avoid a high concentration of the nutrient on the soil surface, especially in areas that have a great potential for surface runoff, together with a high risk of eutrophication of water sources (SHIGAKI; SHARPLEY; PROCHNOW, 2007; SMITH *et al*., 2015). Important are areas of low water infiltration, which are associated with low crop residue cover and soil density above the critical limit, and districts where there are no terraces, common in areas of grain cultivation under a no-till system in the southern region of Brazil.

Despite these advantages, the exclusive decision to apply P at depth is not justified by the specific aim of increasing accumulation of the nutrient in plants, and consequently, of increasing the growth and productivity of crops, corroborating the hypothesis of this work.

CONCLUSIONS

1. A vertical soil P gradient does not influence growth or P accumulation in plants of the maize, sunflower or soybean, even under conditions of water stress;
2. Localising the phosphate fertiliser in the surface or subsurface layer provides greater growth and P accumulation in maize and sunflower plants compared to the same dose evenly distributed in the 0-20 cm layer;
3. The method of distribution of the phosphate fertiliser interferes less in the growth of soybean plants compared to the maize and sunflower.

REFERENCES

ALVES, V. M. C. *et al*. Manejo da água disponível no solo e adubação fosfatada: efeito sobre a cultura do milho. **Revista Brasileira de Engenharia Agrícola e Ambiental**, v. 6, n. 2, p. 247-251, 2002.

ARAÚJO, D. L. *et al*. Efeito da adubação fosfatada e estresse hídrico nas características fenológicas do girassol (*Helianthus annuus* L.). **Agropecuária Científica no Semiárido**, v. 10, n. 4, p. 26-31, 2014.

BARBOSA, N. C. *et al*. Distribuição vertical do fósforo no solo em função dos modos de aplicação. **Bioscience Journal**, v. 31, n. 1, p. 87-95, 2015.

BERGAMIN, A. C. *et al*. Resposta de duas cultivares de soja à adubação a lanço e em sulco, no município de Rolim de Moura/RO. **Revista de Ciências Agrárias**, n. 50, p. 155-166, 2008.

BUAH, S. S. J.; POLITO, T.A.; KILLORN, R. No-tillage soybean response to banded and broadcast and direct and residual fertilizer phosphorus and potassium applications. **Agronomy Journal**, v. 92, p. 657-662, 2000.

CHIEN, S. H. *et al*. Agronomic and environmental aspects of phosphate fertilizers varying in source and solubility: an update review. **Nutrient Cycling in Agroecosystems**, v. 89, n. 2, p. 229-255, 2011.

DIEL, D. *et al*. Distribuição horizontal e vertical de fósforo em sistemas de cultivos exclusivos de soja e de integração lavoura-pecuária-floresta. **Pesquisa Agropecuária Brasileira**, v. 49, n. 8, p. 639-647, 2014.

DOVALE, J. C.; FRITSCHE-NETO, R. Genetic control of traits associated with phosphorus use efficiency in maize by REML/BLUP. **Revista Ciência Agronômica**, v. 44, n. 3, p. 554-563, 2013.

ELTZ, L. F. *et al*. Adubação fosfatada para girassol sob sistema plantio direto no Paraguai. **Bragantia**, v. 69, n. 4, p. 899-904, 2010.

EMPRESA BRASILEIRA DE PESQUISA AGROPECUÁRIA. Centro Nacional de Pesquisas de Solos. **Manual de métodos de análises de solo**. 2. ed. revista. Rio de Janeiro: Embrapa Solos, 2011. 230 p.

FARMAHA, B. S.; FERNÁNDEZ, F. G.; NAFZIGER, E. D. Distribution of soybean roots, soil water, phosphorus and potassium concentrations with broadcast and subsurface-band fertilization. **Journal of Environmental Quality**, v. 76. n. 3, p. 1079-1089, 2012.

FERREIRA, D. F. **Sisvar**: sistema de análise de variância. Versão 5.3. Lavras,MG: UFLA, 2015.

FINK, J. R. *et al*. Diffusion and uptake of phosphorus, and root development of corn seedlings, in three contrasting subtropical soils under conventional tillage or no-tillage. **Biology and Fertility of Soils**, v. 52, p. 203-210, 2016.

HSIAO, T. C.; XU, L. K. Sensitivity of growth of roots versus leaves to water stress: biophysical analysis and relation to water transport. **Journal of Experimental Botany**, v. 51, n. 350, p. 1595-1616, 2000.

LEÃO, D. A. S.; FREIRE, A. L. O.; PAES, J. R. Estado nutricional de sorgo cultivado sob estresse hídrico e adubação fosfatada. **Pesquisa Agropecuária Tropical**, v. 41, n. 1, p. 74-79, 2011.

LIPIEC, J. *et al*. Soil porosity and water infiltration as influenced by tillage methods. **Soil and Tillage Research**, v. 89, n. 2, p. 210-220, 2006.

NOVAIS, R. F.; SMYTH, T. J . Fósforo em solo e planta em condições tropicais. Viçosa, MG: Universidade Federal de Viçosa, 1999. 399 p.

NUNES, R. S. *et al*. Distribuição de fósforo no solo em razão do sistema de cultivo e manejo da adubação fosfatada. **Revista Brasileira de Ciência do Solo**, v. 35, n. 3, p. 877-888, 2011.

PAULETTI, V. *et al*. Yield response to fertilization strategies in no-tillage soybean, corn and common bean crops. **Brazilian Archives of Biology and Technology**, v. 53, n. 3, p. 563-574, 2010.

ROSOLEM, C. A.; MERLIN, A. Soil phosphorus availability and soybean response to phosphorus starter fertilizer. **Revista Brasileira de Ciência do Solo**, v. 38, n. 5, p. 1487-1495, 2014.

SÁ, J. C. M.; BRIEDIS, C.; FERREIRA, A. O. No-till corn performance in response to P and fertilization modes. **Revista Ceres**, v. 60, n. 1, p. 96-10, 2013.

SANTOS, H. G. *et al*. **Sistema brasileiro de classificação de solos**. 3. ed. Rio de Janeiro: Embrapa Solos, 2013. 353 p.

SCHLINDWEIN, J. A. *et al*. Phosphorus and potassium fertilization in no till southern Brazilian soils. **Agricultural Sciences**, v. 4, n. 12, p. 39-49, 2013.

SHIGAKI, F.; SHARPLEY, A.; PROCHNOW, L. I. Rainfall intensity and phosphorus source effects on phosphorus transport in surface runoff from soil trays. **Science of the Total Environment**, v. 373, n. 1, p. 334-343, 2007.

SILVA, F. C. **Manual de análises químicas de solos, plantas e fertilizantes**. 2. ed. Brasília: Embrapa Informação Tecnológica, 2009. 627 p.

SMITH, D. R. *et al*. Surface runoff and tile drainage transport of phosphorus in the Midwestern United States. **Science Society of America**, v. 44, n. 2, p. 495-502, 2015.

SOCIEDADE BRASILEIRA DE CIÊNICA DO SOLO. Núcleo Regional Sul. **Manual de calagem e adubação para os Estados do Rio Grande do Sul e de Santa Catarina**. 11. ed. Porto Alegre: Comissão de Química e Fertilidade do Solo, 2016. 376 p.

TAIZ, L.; ZEIGER, E. **Fisiologia vegetal**. 5. ed. Porto Alegre: Artmed, 2013. 918 p.

ZHOU, W.; WANG, K.; LI, H. Phosphorus translocation and distribution in intercropping systems of soybean (*Glycine max*) and citrus (*Citrus poonensis*). **Ying Yong Sheng Tai Xue Bao**, v. 15, n. 1, p. 215-220, 2004.