SEÇÃO IV - FERTILIDADE DO SOLO E NUTRIÇÃO DE PLANTAS

PHOSPHORUS AND ROOT DISTRIBUTION AND CORN GROWTH AS RELATED TO LONG-TERM TILLAGE SYSTEMS AND FERTILIZER PLACEMENT[1]

Sérgio Ely Valadão Gigante de Andrade Costa[2], Edicarlos Damaceno de Souza[3], Ibanor Anghinoni[4], João Paulo Cassol Flores[5], Eduardo Giacomelli Cao[6] & Marquel Jonas Holzschuh[7]

SUMMARY

Soil and fertilizer management during cultivation can affect crop productivity and profitability. Long-term experiments are therefore necessary to determine the dynamics of nutrient and root distribution as related to soil profile, as well as the effects on nutrient uptake and crop growth. An 18-year experiment was conducted at the Federal University of Rio Grande do Sul State (UFRGS), in Eldorado do Sul, Brazil, on Rhodic Paleudult soil. Black oat and vetch were planted in the winter and corn in the summer. The soil management methods were conventional, involving no-tillage and strip tillage techniques and broadcast, row- and strip-applied fertilizer placement (triple superphosphate). Available P (Mehlich-1) and root distribution were determined in soil monoliths during the corn grain filling period. Corn shoot dry matter production and P accumulation during the 2006/2007 growing season were determined and the efficiency of P utilization calculated. Regardless of the degree of soil mobilization, P and roots were accumulated in the fertilized zone with time, mainly in the surface layer (0–10 cm). Root distribution followed P distribution for all tillage systems and fertilizer treatments. Under no-tillage, independent of the fertilizer placement, the corn plants developed more roots than in the other tillage systems. Although soil tillage systems and fertilizer treatments affected P and root distribution throughout the soil profile, as well as P absorption and corn growth, the efficiency of P utilization was not affected.

Index-terms: soil tillage, P fertilization, utilization efficiency.

---

[1] Parte da Dissertação de Mestrado apresentada pelo primeiro autor a Universidade Federal do Rio Grande do Sul – UFRGS. Realizada com recursos da CAPES. Recebido para publicação em fevereiro de 2009 e aprovado em maio de 2009.

[2] MSc. Ciência do Solo – PPGCS, Universidade Federal do Rio Grande do Sul – UFRGS. Av. Bento Gonçalves 7712, CEP 91540-000 Porto Alegre (RS). E-mail: sergioelycosta@hotmail.com

[3] Dr. Ciência do Solo – PPGCS-UFRGS. Aluno de Pósdoc na Universidade Federal de Goiás – UFG. Rua Riachuelo, Caixa Postal 03, CEP 75804-020 Jataí (GO). E-mail: edicarlos@pq.cnpq.br

[4] Professor do PPG – Ciência do Solo, UFRGS. E-mail: ibanghi@ufrgs.br

[5] Dr. Ciência do Solo – PPGCS-UFRGS, Postdoutorando e Associado na Universidade de Virginia Tech. E-mail: joaof09@vt.edu

[6] Aluno de graduação de Agronomia Student, UFRGS. E-mail: duda_cao@yahoo.com.br

[7] Doutorando – PPG Ciência do Solo, UFRGS. E-mail: mjhrs@hotmail.com

RESUMO: *DISTRIBUIÇÃO DE FÓSFORO E RAÍZES E CRESCIMENTO DO MILHO EM SISTEMAS DE MANEJO DO SOLO E MODOS DE APLICAÇÃO DE FERTILIZANTE NO LONGO PRAZO*

O manejo do solo e de fertilizantes ao longo do tempo de cultivo pode contribuir para o rendimento e lucratividade das lavouras. Há, então, a necessidade de se ter e avaliar experimentos de longo prazo para que se consiga entender a dinâmica da distribuição de nutrientes e raízes no perfil do solo e seu efeito na absorção de nutrientes e no crescimento e desenvolvimento da cultura. Foi utilizado um experimento de 18 anos de duração em um Argissolo localizado na Estação Experimental da Universidade Federal do Rio Grande do Sul (UFRGS), no município de Eldorado do Sul, com a sucessão de milho no verão e aveia-preta consorciada com azevém no inverno, sob manejos de solos e modos de aplicação de fertilizantes. Os manejos de solo foram o convencional, plantio direto e cultivo em faixas, e a fertilização fosfatada (superfosfato triplo) foi a lanço, em linha e em faixas. A distribuição do P disponível (Mehlich-1) e das raízes de milho no perfil do solo foi avaliada pela coleta de monólitos de solo no período de enchimento de grãos do milho; a produção da parte aérea seca do milho e o acúmulo de P da safra de 2006/2007 foram determinados, sendo calculada a eficiência de utilização de P. Independentemente do grau de mobilização do solo, o P e as raízes acumularam-se ao longo do tempo na zona fertilizada, principalmente na camada de 0–10 cm. A distribuição de raízes seguiu a distribuição de P, independentemente do manejo de solo e do modo de aplicação do fertilizante fosfatado. No sistema plantio direto, qualquer modo de aplicação de P, o milho apresentou quantidade maior de raízes em relação aos demais manejos. Embora o manejo do solo e os modos de aplicação de P tenham alterado a distribuição do nutriente e das raízes de milho no perfil do solo, a absorção de P e o crescimento do milho, bem como a eficiência de utilização do nutriente pelo milho, não foram influenciados.

Termos de indexação: preparo do solo, adubação fosfatada, eficiência de uso.

INTRODUCTION

Adequate soil tillage is fundamental for profitable and sustainable environmental systems. The degree of soil tilling required in a given situation is directly related to the method of soil management. When the soil is not revolved, organic matter and nutrients can accumulate in the soil surface (Eltz et al., 1989), especially in tropical and subtropical regions. In Brazil, no-tillage systems (NT) have expanded exponentially since the early 1990s, reaching an area of 26 million ha by 2008 (FEBRAPDP, 2008). The use of NT establishes new soil relationships, which are affected by tilling degree and the pattern of nutrient distribution, both acknowledged important characteristics (Anghinoni & Barber, 1980), affecting the volume of fertilized soil, and consequently, the availability of plant nutrients (Anghinoni, 2004).

Phosphorus is most strongly influenced by soil and fertilizer management (Model & Anghinoni, 1992) due to the low nutrient diffusion in the soil (Barber, 1995) and reduced availability in oxidic soils (Novais & Smyth, 1999). Six factors have been reported as highly important in relation to P fertilizer management: initial soil P content, rate of P application, volume of fertilized soil, soil texture, fertilizer characteristics and soil mineralogy (Anghinoni, 2004).

The initial high P availability due to the absence of tilling and the direct application of soluble P fertilizer (i.e., row placement), results in an abundant P supply during the early development stages of a crop (Anghinoni, 1992). It is also expected that when the fertilizer is mixed with an intermediate soil volume (between that of row-application and broadcast treatment methods), and when the fertilizer is incorporated into the soil, the resulting corn grain yields are higher (Barber, 1995; Brown, 1996). However, fertilizer treatment can be less important when a soil already contains adequate P levels for crop growth and production (Bordoli & Mallarino, 1998). An evaluation of the root system is therefore an important characteristic, since root distribution reveals the effects of tillage on the soil physical and chemical conditions. Root distribution near the nutrient-enriched zone favors plant establishment, and in later development stages, the distribution of roots throughout the soil profile becomes very important for nutrient and water absorption, primarily in periods of hydric stress (Gregory, 2006).

Phosphorus accumulation due to local fertilizer applications in NT results in concentrations of roots near the surface and along the rows (Mackay et al., 1987; Klepker & Anghinoni, 1993). On the other hand, extremely high soil P concentrations can cause deleterious effects to plants by increasing the osmotic pressure that damages the root apical meristem (Barber, 1995). Special attention is therefore required when working with soil tillage systems and fertilizer treatments, to prevent high P and root accumulation in a limited soil volume (Klepker & Anghinoni, 1993).

In addition to increasing the degree of soil salinity, local fertilizer treatments can result in higher root concentrations in these micro-regions, reducing water availability. As a result, nutrient diffusion to the roots is reduced, as in the case of P (Davis & Zhang, 1991). In this regard, higher root growth in small fractions of fertilized soil does not necessarily result in increased levels of total root growth. Higher efficiency of P utilization (EPU) can be achieved with broadcast treatment and applications as used in conventional and strip soil tillage (Klepker & Anghinoni, 1993).

It is therefore expected that fertilizer placement and soil tilling affects P distribution which in turn influences root distribution and is, consequently, related to P use efficiency by corn plants.

The present research was conducted to evaluate, primarily, the effect of soil tillage systems and fertilizer treatments, over the course of 18 years, on P and root distribution throughout the soil profile, and how the distribution affected P use efficiency by corn plants.

MATERIALS AND METHODS

The experiment started in 1988 at an Experimental Station of the Federal University of Rio Grande do Sul (Brazil) in Eldorado do Sul, Rio Grande do Sul (Brazil), on a Rhodic Paleudult clay loam soil. The 0–20 cm layer contained: 22, 14, and 64 g kg^{-1} of clay, silt and sand, respectively, and 36, 109 and 720 g kg^{-1} of dithionite-citrate-bicarbonate soluble Fe, ammonium oxalate soluble Fe and caulinite, respectively. The experimental plots were located in hilly to smooth-hilly land formations with mean declivity of 0.03 m m^{-1}. The mean annual rainfall in the region is 1440 mm and the climate subtropical with warm humid summer weather (Cfa), according to the Köppen classification.

The experimental area was maintained as a native field until 1974 and then conventionally tilled in the following two years (1975-1976). Until the beginning of the experiment, in 1988, the fallow period was interrupted only once, in 1985, by the cultivation of black oat (*Avena strigosa*, S.), under conventional tillage.

In May of 1988, lime was applied to the experimental area and was incorporated into the soil by one disk plowing and two diskings. Liming was followed by cultivation of black oat. After harvest, in October of the same year, soil tillage systems and fertilizer treatments were applied prior to corn (*Zea mays* L.) sowing. The initial main soil chemical properties, in the 0–15 cm soil layer, before applying the treatments were: pH_{H_2O} 5.2; P and K (Mehlich-1) 2.5 and 132 mg dm^{-3}, respectively; and 30 g kg^{-1} of organic matter.

The following tillage systems were used: conventional tillage (CT- one-disk plowing at 15 cm depth and 50 cm width; two disk plowings at a depth of 15 cm); strip tillage (ST- by moldboard plowing of a 20 cm wide strip at a depth of 15 cm, in the corn seedling lines) and no-tillage (NT- by opening a row at a depth of 5–8 cm in corn seedling lines). Plowing was performed in opposite directions in alternate years. Triple superphosphate and KCl were applied using various techniques: broadcast (Brd- applied evenly by hand over the surface of the whole plot, mixed with the soil in conventional tillage or left on the soil surface in strip and no-tillage); strip (Stp- in a 20 cm-wide strip in corn sowing rows, with incorporation into the soil in conventional tillage and strip tillage, and left on the surface in no-tillage treatment) and row (Row- at a depth of 5–8 cm and width of 5 cm, with opened rows in seedling lines for all tillage systems).

The experiment was carried out in a randomized block design, in a 3 x 3 bi-factorial scheme, separated by 5 m strips, in split-plot design, with soil tillage systems in the main plots (24 x 12 m) and fertilizer treatments in the split-plots (12 x 8 m), with three replications. From October 1988, the following cropping sequence was used: corn during spring/summer seasons and black oat + vetch (*Vicia sativa*) during autumn/winter seasons, with liming reapplications every four years, after the first application in 1988, aiming at a pH (SMP method) of 6.0. Lime was incorporated in all conventional and strip tillage systems; for the no-tillage system, lime was surface-applied and all crop residues of corn, vetch and black oat, were left on the surface. From 1988 to 2006, 120, 90, and 70 kg ha^{-1} of N, P_2O_5 and K_2O, respectively, were applied annually.

For this study, corn was sown (Pioneer 30R50 hybrid) on October 20, 2006, after the application of tilling and fertilizer treatments, with a seedling density of 5–7 plants m^{-1} and 1 m distance between lines. The corn sowing rows were at the same place as in the previous seasons. Prior to the treatments, the primary soil chemical properties in the 0–15 cm layer were determined as follows: pH in water 5.2; organic matter 30 g kg^{-1}; P and K (Mehlich-1) 8.0 and 130 mg $dm^{-3,}$ respectively, 0.2, 4.0,1.8 $cmol_c$ dm^{-3} of exchangeable (1.0 mol L^{-1} KCl) Al^{3+}, Ca^{2+}, Mg^{2+}, respectively, and 7.0, 1, 1.5, 0.5 and 20 mg dm^{-3} of exchangeable S, Zn, Cu, B and Mn, respectively. Based on these results, there was no need for micronutrient applications, and 60, 150 and 100 kg ha^{-1} of N, P_2O_5 and K_2O, using urea, triple superphosphate and potassium chloride, respectively, were applied evenly, independent of the P fertilizer treatments, aiming at a corn yield of > 8 Mg ha^{-1}, based on recommendations of CQFSRS/SC (2004). Fifteen days after emergence (DAE), plants were selected to maintain a stand of 5 plant m^{-1} (50,000 plants ha^{-1}); at 35 DAE 60 kg ha^{-1} of N in the form of urea were top-dressed. Corn was cultivated with overhead irrigation; in six irrigations, supplying 25 mm of water each, from November to

February, (corresponding to the drought period) (Figure 1), resulting in a total of 150 mm of water in the total cycle. Adding this value to the 721 mm rainfall, the crop was supplied with 871 mm of water throughout the growth cycle.

Soil monoliths were sampled (August 01, 2007) for P and root distribution throughout the soil profile, during the corn grain filling period (drought stage), in two of the three replications, under the following tillage systems and fertilizer placement combinations: CT with lime and fertilizer incorporation in Stp, Brd and Row (3); NT without lime incorporation and fertilizer treatment in Row and Brd (2) and ST with liming and fertilizer incorporation in Stp (1), resulting in 12 sampled plots. These monoliths (10 cm thick) were sampled in pits perpendicular to corn seedling lines cut open with a wooden board (50 x 40 cm) with sharp metal blades (5 x 5 cm), according to the Schuurmman & Goedewagen (1971) method, modified by Pedó (1985). Each monolith (50 x 40 x 10 cm) was subdivided into four depths (0–5, 5–10, 10–15 and 15–20 cm) at four singular different distances from each side of the corn stalk (0–5, 5–10, 10–15 and 15–25 cm) (4 x 8 = 32) and two depths (20–30 and 30–40 cm) with five horizontal stratifications (5–5, 5–15, 15–25, 25–15 and 15–5 cm) (2 x 5 = 10), respectively, resulting in 42 (32 + 10 = 42) soil samples. In each monolith, soil and roots were separated in adjacent layers, so that there was one root sample for each soil sample.

Simultaneously with soil monolith sampling, a plant corresponding to each sample monolith was collected and shoot dry matter production (SDMP) and P content (Tedesco et al., 1995) were determined, allowing the calculation of P shoot accumulation (PA). Following these procedures, efficiency of P utilization was determined ($EPU = SDMP^2 \, PA^{-1}$) as proposed by Siddiqi & Glass (1981). Available P (Mehlich-1) was determined in soil samples collected in the monoliths (Tedesco et al., 1995).

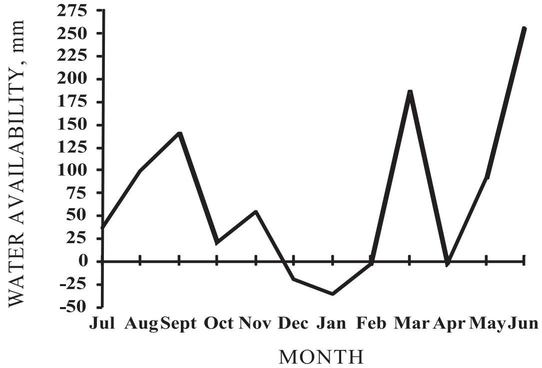

Figure 1. Hydric balance for water storage capacity in the soil 50 mm, in the period in which experiment was held, EEA/UFRGS, 2006/2007 growing season.

Root length was obtained using digital scanned images (Epson CX 4100) followed by the use of SIARCS 3.0 software (Guimarães et al., 1997). Based on the root length, root density was calculated as the ratio of root length/soil volume (cm cm^{-3}). Phosphorus and root distribution throughout the soil profile were obtained by the use of graphs generated from Sigma Plot 10.0® (Systat Software, Inc.), which allowed the elaboration of spatial distribution maps.

For variance analysis of available P and roots in the sampled monolith layers, the following model was used:

$$Y_{ijk} = \mu + S_i + \text{error a (ik)} + D_j + SD_{ij} + \text{error b (i,j,k)}$$

where μ = overall experiment mean; S = soil tillage systems (i = 1,2,3,4,5,6); D= depth (j = 1,2,3,4,5,6) and Error = experimental error.

For evaluation of shoot and total root length in the monoliths, the following model was used:

$$Y = \mu + S_i + \text{error (ij)}$$

where μ = overall experiment mean; S = soil tillage systems (i = 1,2,3,4,5,6); and Error = experimental error. When the variance analysis was significant, the Tukey test ($p < 0.05$) was applied.

RESULTS AND DISCUSSION

Available P content was high down to a depth of 20 cm, according to CQFSRS/SC (2004), despite the adopted soil tillage system (Figure 2a). The initial soil P content and the accumulation that occurred during the previous 18 years under phosphate fertilization could explain such high values. Available P concentrations (Figure 2a) and root density throughout the soil profile (Figure 2b), as expected, were concentrated in the surface layer and decreased with depth. The effects of soil tillage systems and fertilizer treatments on P distribution in the soil profile were observed down to a depth of 15 cm. Such effects on corn root density were only verified in the 0–5 cm layer, as reported by DeMaria et al. (1999) for P and by Rasmussen (1999) for root distribution. Higher corn root density in the surface layers can be due to corn root architecture (Venzke Filho et al., 2004). Although aggregate stability impacts root distribution in soils under no-till system (Manske & Vlek, 2002), it seems that nutrient accumulation in the soil surface layer is of primary importance, especially of nutrients with low soil mobility, such as P.

The P values in the ST/Stp system tended to higher along the soil profile (Figure 2a), followed by CT/Stp and NT/Row. Except for CT/Brd and CT/Row, these contents were higher ($p < 0.05$) in the other tillage systems at a depth of 5 cm. However, higher values occurred in deeper layers, at a depth of 10 cm in the

CT/Stp and NT/Row treatments, and at a depth of 15 cm in the ST/Stp treatment. In relation to root density, lower density values were observed in the CT/Row and CT/Brd systems, following P availability and highlighting the importance of root growth in the NT/Row treatment down to a depth of 40 cm.

Successive fertilization treatments led to P accumulation, mainly in soils with low levels of P adsorption, despite the adopted tillage system (DeMaria et al., 1999). Strip applications, which result in fertilized volumes intermediate between those of the row and broadcast methods, can result in higher surface P values, even with different degrees of soil mobilization (Zerboune, 1996).

The high available P concentration in the 5–10 cm layer (Figure 2a) following localized application without soil tilling (NT) is due to the fertilizer treatment of the seed bed, at a depth of 5 - 8 cm. On the other hand, the weaker and more uniform P distribution in the soil profile when the fertilizer is incorporated indicates a mixing effect in soils with higher P adsorption capacity (Anghinoni, 1992). Available P values below the critical level for this soil (12 mg dm^{-3}) (CQFSRS/SC, 2004), observed in the 20–30 and 30–40 cm layers independent of the adopted tillage system, are a result of the low P mobility, even in soils with low P adsorption capacity (Rheinheimer et al., 2003). In Rhodic Paleudult soils, due to the texture gradient and increased P retention by the clay fraction, P availability in the deeper layers is expected to be lower (Hussain et al., 1999).

Phosphorus accumulation in the soil surface under no-till is also a result of P cycling by crops (Santos & Tomm, 2003). This phenomenon results from decomposition of shoot residues in the soil surface and root decomposition concentrated in the 0–5 cm layer, especially in the NT/Brd and CT/Stp treatments (Figure 2b and Table 1).

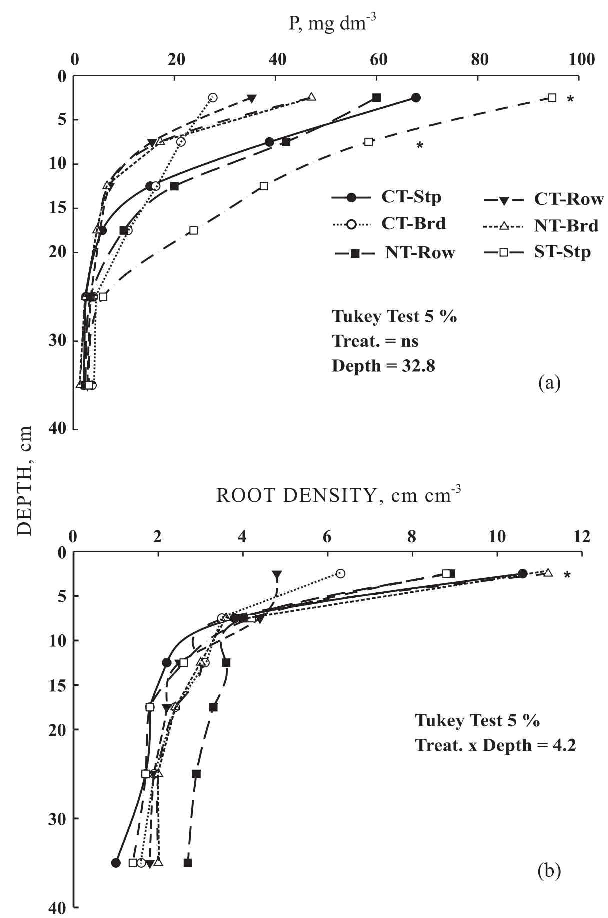

Figure 2. Phosphorus (Mehlich-1) (a) and root density (b) in a Rhodic Paleudult soil profile under different tillage systems for 18 years: Conventional - strip (CT-Stp), conventional – broadcast (CT/Brd), conventional – row (CT/Row), no-tillage – broadcast (NT/Brd), no-tillage – row (NT/Row) and Strip – Strip (ST/Stp), 2006/2007 growing season.

Table 1. Relative root density distribution in a Rhodic Paleudult soil profile under 18 years of different tillage systems - 2006/2007 growing season

Layer	Soil tillage systems (1)					
	CT/Row	CT/Brd	CT/Stp	NT/Row	NT/Brd	ST/Stp
cm	%					
0–5	27 a	34 a	50 a	35 a	47 a	43 a
5–10	25 ab	18 b	18 b	15 b	15 b	20 b
10–15	15 bc	16 b	11 bc	14 b	12 b	13 bc
15–20	12 c	13 b	8 bc	13 b	10 b	9 c
20–30	11 c	10 b	8 bc	12 b	8 b	8 c
30–40	10 c	9 b	5 c	11 b	8 b	7 c

(1) CT: conventional; NT: No-tillage; Row = Row; Brd: broadcast; Stp: strip. Means followed by the same letter in the columns do not differ by Tukey Test ($p < 0.05$).

The higher root density in the NT/Row treatment group, from 10 cm below the soil surface (Figure 2b and Table 1) is a result of both no tilling and fertilizer placement effects. Although physical properties such as macro porosity, pore continuity and soil bulk density can restrict root growth, especially in the case of Rhodic Haplodults (Flores et al., 2008), as used here, the tillage systems and fertilizer placements did not affect these properties to an extent that would restrict root growth (Marcolan & Anghinoni, 2006). Also, this experiment was performed in a well-structured native grassland area where the better initial soil physical conditions contributed to a weaker impact of soil tilling. Thus, long-term no tilling with row fertilizations increased the P levels in depth and also contributed to root growth.

Higher mean available P contents along the soil profile in the ST/Stp treatment did not result in higher root growth (Figure 2b) or distribution in deeper layers (Table 1). This may be due to the fact that available P contents in soil layers do not represent the degree and intensity of fertilizer mixing with the soil, which can vary in both horizontal and vertical directions, as verified in the soil monoliths sampled in the experimental area. Therefore, P (Mehlich-1) and root spatial distribution were influenced by soil tillage and fertilizer treatment (Figures 3 and 4a,b,c,d,e,f). We observed significant spatial variation in the evaluated properties affected by fertilizer treatment, and by the incorporation or not into the soil; by the formation of microsites by fertilizer granules (Sousa & Volkweiss, 1987); by the sampling procedures; and by the high variability of P concentrations and root distribution in the soil (Dwyer et al., 1996).

Although P was applied at the same rate throughout the experiment, the P content varied greatly, when comparing fertilizer treatments in the same tillage system or in different tillage systems with the same fertilizer treatments. In the fertilizer treatments that enrich a small soil volumes (row or band), the available P content, about 100 to 200 mg dm^{-3}, contrasted with the values (~50 mg dm^{-3}) observed in soils treated with P by broadcast application (Figures 3 and 4). High levels of P, reaching 200 mg dm^{-3} in the ST/Stp (Figure 3c), were unexpected since the soil was tilled annually, despite being a 20 cm strip (in contrast to the row placements, which exhibited lower peaks, around 100 mg dm^{-3}). On the other hand, values around 40 mg dm^{-3} in the 0–15 cm layer in the CT/Brd treatment (Figure 4a) reflect the effect of fertilizer incorporation into the soil, assuming the absence of P soil stratification. The extremely high levels of available P observed at certain locations, as revealed by the soil monoliths (Figures 3 and 4), represent the nutrient variability in the soil, as reported by Klepker & Anghinoni (1993) and Schlindwein & Anghinoni (2000a,b).

On average, root distribution followed P fertilizer treatment; however, some root density values varied in relation to the soil tillage system, as seen in the most shallow surface layer (0–5 cm), with values ranging from 25 to 10 cm cm^{-3} for NT/Brd (Figure 3d) and CT/Brd (Figure 4d), respectively. On the other hand, root accumulation in the seed-rows, due to row applications, resulted, in the 0–5 cm layer, in peaks around 25 cm cm^{-3} for the NT/Row (Figure 3e) and CT/Row systems (Figure 4e). This trend, also observed for P distribution, demonstrates that the degree of the fertilized soil volume significantly affects root distribution throughout the soil profile. When the fertilizer was strip-applied, root distribution was deeper. CT/Stp (Figure 4f) seems to have favored a more homogeneous root distribution throughout the soil profile, whereas in ST/Stp (Figure 3f) roots were more concentrated in the zone where the fertilizer was mixed with soil. These results indicate, as suggested by Ball-Coelho et al. (1998), that as the volume of soil mobilization increases, root vertical growth is favored, in contrast to the no-tilling system where this distribution occurs mainly horizontally.

Fertilizer treatments in this study resulted in more variable P availability when compared to the results observed by Klepker & Anghinoni (1993), whereas root density values were similar. The higher values observed in our study can be explained by the remaining P after the successive P applications in the 18 years of this study.

Higher root length values occurred in NT, in both Brd and Row placements, regardless of the fertilizer treatment (Table 2). However, the different root length values did not affect shoot dry matter production (SDMP) or P shoot accumulation. Higher root length values in soils under well-established NT system (> 10 years) were also observed by Wang et al. (1986) and Rasse & Smucker (1998). Where the NT system had been used for < 10 years, however, lower (19 %) values were observed in soils under NT than CT (Qin et al., 2005).

Higher SDMP and PA values were observed in the CT/Brd and ST/Stp systems, with more uniform P and root distribution in the soil profile (Table 2), as reported by Klepker & Anghinoni (1993). However, these authors found higher EPU values than those observed here. Extremely high levels of available P, under row and strip fertilizer treatments, could limit P absorption due to excessive root growth and reduced water availability in these root-rich zones. Soil salinity effects, as a consequence of simultaneous potassium chloride application with P fertilization, may have contributed to these differences.

For the soil in this study, with low P sorption capacity and intermediate initial available P values, P availability near corn roots has great relevance for early crop development. According to Havlin et al. (2005), the importance of local fertilization for initial crop development can be summarized as two main effects: (1) increased root-P contact, reducing the

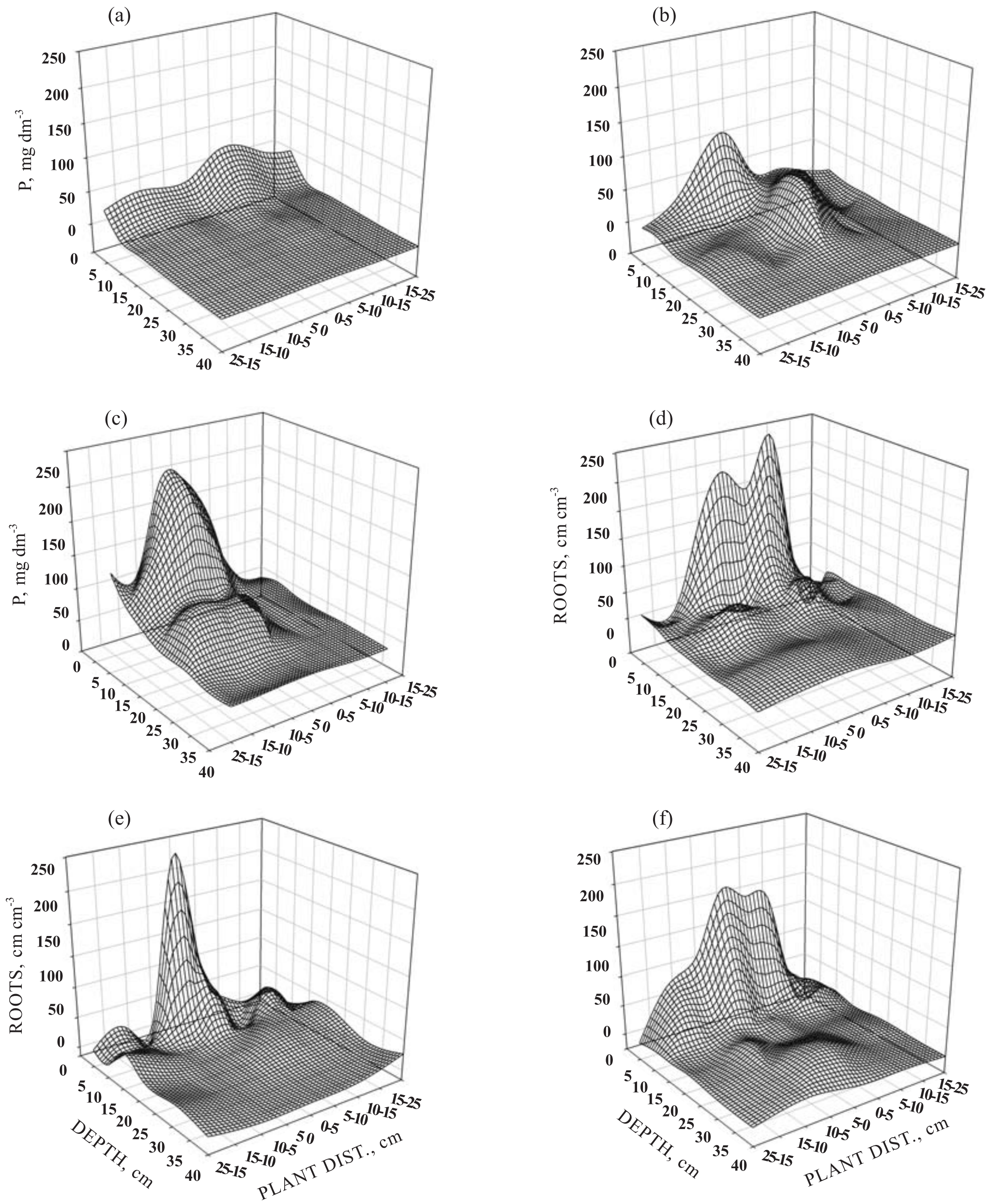

Figure 3. Phosphorus (a, b and c) and root (d, e and f) distribution at corn grain filling period, in a Rhodic Paleudult soil profile under tillage systems: no tillage-broadcast, no-tillage-row and strip-strip, respectively, for 18 years, 2006/2007 growing season (Representative monolith of the plot).

effects of P sorption by the soil; (2) increasing P concentrations in this region ameliorate absorption conditions. The latter effect appears to have been most relevant in the present study. The 150 kg P_2O_5 applied is equivalent to a concentration of 1,450 mg kg^{-1} of P in the soil [considering 5 cm wide and 7 cm deep rows and 1m between rows: P applied in row (66 kg)/ fertilized volume (10 000 x 0.05 x 0.07 m = 35 m^3) $\rightarrow$ considering an average soil density in this layer of 1,300 kg m^3 : 66 kg of P in (35 x 1,300) = 1450 mg kg^{-1} of P in the soil]. Phosphorus levels of 500 mg kg^{-1} (Peryea, 1990) and 400 mg kg^{-1} (Klepker & Anghinoni, 1993), in the context of row fertilization, limited root growth. For the first case, the authors attributed the reduced growth to apical meristem damage; in the latter case, restricted root growth was attributed to both soil drying and salinity in the root-rich zone. This effect could have been enhanced by the application of KCl together with superphosphate fertilization.

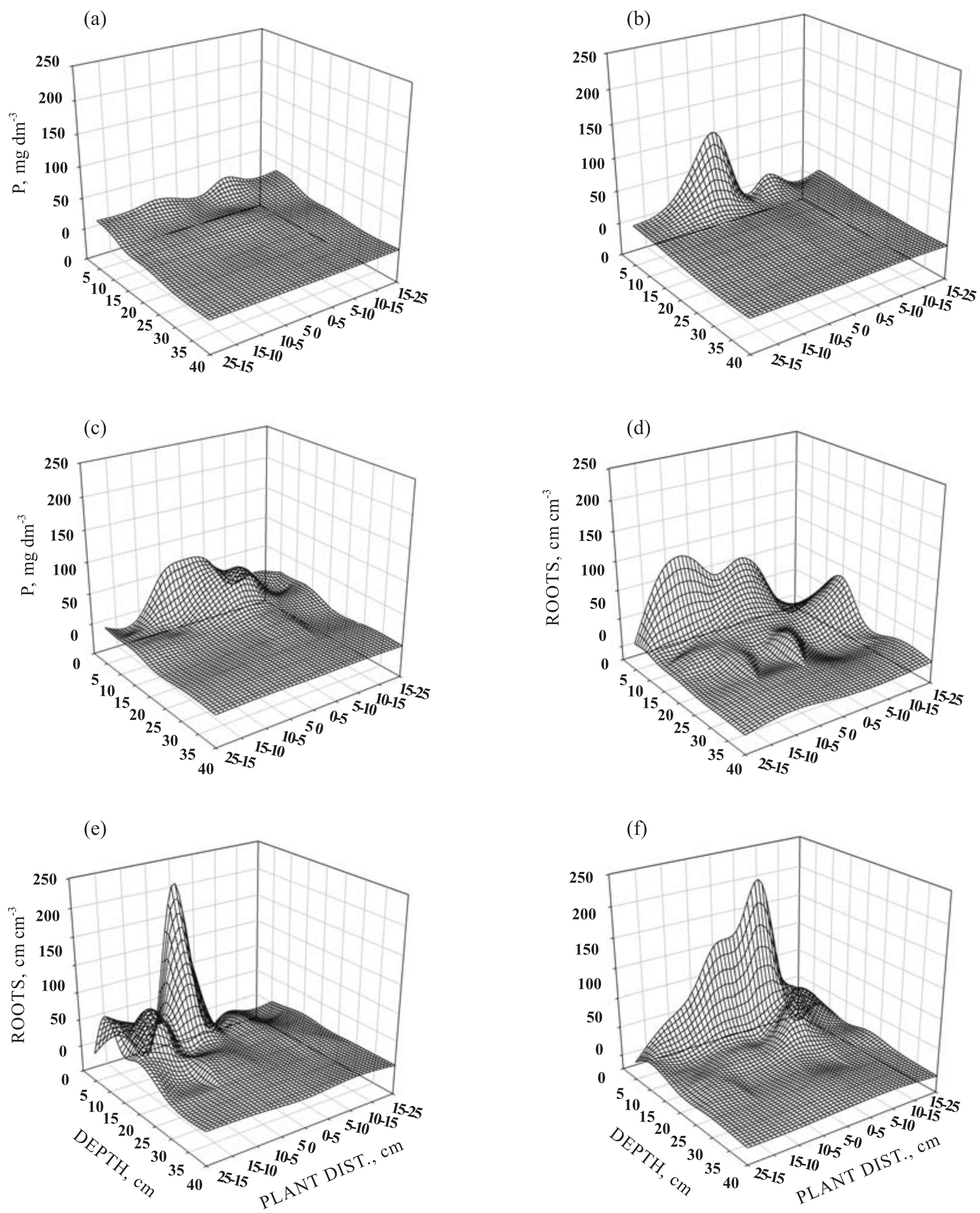

Figure 4. Phosphorus (a, b and c) and root (d, e and f) distribution at corn grain filling period, in a Rhodic Paleudult soil profile under tillage systems: conventional-broadcast, conventional-row and conventional-strip, respectively, for 18 years, 2006/2007 growing season (Representative monolith of the plot).

Although high root density values were observed in response to elevated P concentrations, P absorption by corn did not seem to be affected in the same way. Despite the adopted tillage system or fertilizer placement, after 18 years, soil has reached a high P status. Thus, in such highly fertile soil, nutrient transport to the root surface does not limit uptake by the crop, even low concentrations in the soil solution are adequate to ensure supply by diffusion (Barraclough, 1989). The concentration of P in the soil solution is of primary importance for P root supply and is affected by microbial activity and other physical properties such as aeration and soil moisture (Barber, 1995). The need of measuring other properties, as already stated, is crucial for a more concrete discussion on the P-root-shoot-soil interactions, especially considering that continuous temperature, hydric and atmospheric oscillations induce alterations, both in root and shoot growth, so the root-shoot relation in field conditions is variable (Qin, 2003).

Table 2. Root length, phosphorus accumulation, shoot dry matter production (SDMP) and efficiency of phosphorus utilization (EPU) by corn plants in the soil monoliths sampled at corn grain filling period, in a Rhodic Paleudult soil under different tillage systems and fertilizer placements, 2006/2007 growing season

Soil tillage system[(1)]	Root length	Phosphorus	SDMP	EPU
	m	mg/plant	g/plant	g mg $^{-1}$
CT/Brd	288 bc[(2)]	951 a	227a	54,4 a
NT/Brd	353 a	763 b	202 abc	53,3 a
CT/Row	220 d	596 c	190 bc	60,3 a
NT/Row	339 a	559 c	178 c	56,7 a
CT/Stp	265 bcd	639 c	183 c	52,5 a
ST/Stp	257 cd	853 ab	219 ab	56,4 a

[(1)] CT: conventional; NT: no-tillage; Row: row; Brd: broadcast; Stp: strip. [(2)] Means followed by the same letter in the columns do not differ by Tukey Test ($p < 0.05$).

Studies that evaluate root and corn growth require special attention, to find a specific approach since the different soils properties are key to the observation of mechanisms involved in nutrient availability and use efficiency. This long-term study provided insights into how, regardless of the tillage system, P distribution in the soil affects root distribution. It seems reasonable that other studies, approaching other soil physical (i.e. aeration), chemical (i.e. speciation) and biological (i.e. phosphatase activity) properties will also obtain important results related to P supply and how it affects corn growth and, consequently, the efficiency of P utilization.

CONCLUSIONS

1. Despite the degree of soil mobilization, superphosphate resulted in the accumulation of P and root density in the fertilized soil volume in the long term, particularly in the 0–10 cm layer.

2. Soil under no-tillage system resulted in more roots than in other tillage systems, except for those involving fertilizer treatments.

3. Although tillage system and fertilizer treatments affected P absorption and corn growth, the efficiency of P utilization was not affected.

ACKNOWLEDGEMENTS

The authors express special thanks to Adão Luís Ramos dos Santos, for his contribution in the field trials and laboratory analysis; to the Agronomic Experimental Farm of the Federal University of Rio Grande do Sul State (UFRGS) for the permission to carry out the field trials, to Dirceu Klepker, researcher with Embrapa, for granting access to data from previous experimental years, and for the financial support provided by CAPES.

LITERATURE CITED

ANGHINONI, I. Fatores que interferem na eficiência da adubação fosfatada. In: YAMADA, T. & ABDALLA, S.R.S., eds. Fósforo na agricultura brasileira. Piracicaba, Potafos, 2004. p.537-562.

ANGHINONI, I. Uso de fósforo pelo milho afetado pela fração do solo fertilizada com fosfato solúvel. R. Bras. Ci. Solo, 16:349-353, 1992.

ANGHINONI, I. & BARBER, S.A. Phosphorus application rate and distribution in the soil and phosphorus uptake by corn. Soil Sci. Soc. Am. J., 44:1041-1044, 1980.

BALL-COELHO, B.R.; ROY, R.C. & SWANTON, C.J. Tillage alters corn root distribution in coarse-textured soil. Soil Till. Res., 45:237-249, 1998.

BARBER, S.A. Soil nutrient bioavailability. New York: John Wiley & Sons, 1995. 414p.

BARRACLOUGH, P.B. Root growth, macronutrient uptake dynamics and soil fertility requirements of a high-yielding winter oilseed rape crop. Plant Soil, 119:59-70, 1989.

BORDOLI, J.M. & MALLARINO, A.P. Deep and shallow banding of phosphorus and potassium as alternatives to broadcast fertilization for no-till corn. Agron. J., 90:27-33, 1998.

BROWN, R. Evaluating residual value of band applied fertilizer phosphorus. Manhattan, Kansas State University, 1996. 134p. (Tese de Doutorado)

COMISSÃO DE QUÍMICA E FERTILIDADE DO SOLO – CQFRS/SC. Manual de adubação e de calagem para os Estados do Rio Grande do Sul e Santa Catarina. Porto Alegre, Sociedade Brasileira de Ciência do Solo - Núcleo Regional Sul, 2004. 400p.

DAVIES, W.J. & ZANG, J. Roots signals and the regulation of growth and development of plants in drying soil. Ann. Rev. Plant Physiol., 42:55-76, 1991.

DeMARIA, I.C.; NNABUDE, P.C. & CASTRO, O.M. Long-term tillage and crop rotation effects on soil chemical properties of a Rhodic Ferralsol in Southern Brazil. Soil Till. Res., 51:71-79, 1999.

DWYER, L.W.; MA, B.L.; STEWART, D.W.; HAYHOE, H.N.; BALCHIN, D.; CULLEY, J.L.B. & McGOVERN, M. Root mass distribution under conventional and conservation tillage. Can. J. Soil Sci., 76:23-28, 1996.

ELTZ, F.L.F.; PEIXOTO, R.T.G. & JASTER, F. Efeito de sistemas de preparo de solo nas características físicas e químicas de um Latossolo Bruno álico. R. Bras. Ci. Solo, 12, 259-267, 1989.

FEBRAPDP. Expansão do sistema plantio direto em território nacional. Available in: <http://www.febrapdp.com.br.> Access on May 06, 2008.

FLORES, C.A.; REINERT, D.J.; REICHERT, J.M.; ALBURQUERQUE, J.A. & PAULETTO, E.A. Recuperação da qualidade estrutural, pelo sistema plantio direto, de um Argissolo Vermelho. Ci. Rural, 38:2164-2172, 2008.

GREGORY, P. Plant roots - growth, activity and interaction with soils. Oxford, Blackwell Publishing, 2006. 318p.

GUIMARÃES, M.F.; JORGE, L.A.C.; DE MARIA, I.C.; TAVARES FILHO, J.; BICUDO, S.J. & CRESTANA, S. Três metodologias de avaliação de raízes: Descrição, limitações e vantagens. In: SIMPÓSIO NACIONAL DE INSTRUMENTAÇÃO AGROPECUÁRIA, São Carlos, 1997. Anais. São Carlos, Empresa Brasileira de Pesquisa Agropecuária - Centro Nacional de Pesquisa e Desenvolvimento de Instrumentação Agropecuária, 1997. p.295-304

HAVLIN, J.L.; BEATON, J.D.; TISDALE, S.L. & NELSON, W.L. Soil fertility and fertilizers. 7.ed. Nova York, Macmillan, 2005. 515p.

HUSSAIN, I.; OLSON, K.R. & EBELHAR, S.A. Long-term tillage effects on soil chemical properties and organic matter fractions. Soil Sci. Soc. Am. J., 63:1335-1341, 1999.

KLEPKER, D. & ANGHINONI, I. Phosphate uptake and corn root distribution as affected by fertilizer placement and soil tillage. Agronomy (Trends Agric. Sci.), 1:111-115, 1993.

MACKAY, A.D.; KLADIVKO, E.J.; BARBER, S.A. & GRIFFITH, D.R. Phosphorus and potassium uptake by corn in conservation tillage systems. Soil Sci. Soc. Am. J., 51:970-974, 1987.

MANSKE, G.G.B. & VLEK, P.L.G. Root architecture - Wheat as a model plant. In: WAISEL, Y.; ESHEL, A. & KAFKAFI, U. Plant roots. 3.ed. The Hidden Half, 2002. p.249-259.

MARCOLAN, A.L. & ANGHINONI, I. Atributos físicos de um Argissolo e rendimento de culturas em função do revolvimento do solo em plantio direto. R. Bras. Ci. Solo, 30:163-170, 2006.

MODEL, N.S. & ANGHINONI, I. Respostas do milho a modos e técnicas de preparo do solo. R. Bras. Ci. Solo, 16:55-59, 1992.

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

PEDÓ, F. Rendimento e distribuição de raízes de seis espécies de plantas em dois níveis de compactação do solo. Porto Alegre, Universidade Federal do Rio Grande do Sul, 1985. 92p. (Tese de Mestrado)

PERYEA, F.J. Phosphate - fertilizer-induced salt toxicity of newly planted apple trees. Soil Sci. Soc. Am. J., 54:1778-1783, 1990.

QIN, R. Morphology and distribution of fully developed root systems of wheat and maize as affected by tillage systems. Zürich, Swiss Federal Institute of Technology, 2003. 101p. (Tese de Doutorado)

QIN, R.; STAMP, P. & WALTER, R. Impact of tillage and banded starter fertilizer on maize root growth in the top 25 centimeters of the soil. Agron. J., 97:674-683, 2005.

RASMUSSEN, K.J. Impact of ploughless soil tillage on yield and soil quality: A Scandinavian review. Soil Till. Res., 53:3-14, 1999.

RASSE, D.P. & SMUCKER, A.J.M. Root recolonization of previous root channels in corn and alfafa rotations. Plant Soil, 204:203-212, 1998.

RHEINHEIMER, D.S.; ANGHINONI, I.; CONTE, E.; KAMINSKI, J. & GATIBONI, L.C. Dessorção de fósforo avaliada por extrações sucessivas em amostras de solo provenientes dos sistemas plantio direto e convencional. Ci. Rural, 33:1053-1059, 2003.

SANTOS, H.P. & TOMM, G.O. Disponibilidade de nutrientes e teor de matéria orgânica em função de sistemas de cultivo e de manejo de solo. Ci. Rural, 33:477-486, 2003.

SCHLINDWEIN, J.A. & ANGHINONI, I. Variabilidade horizontal de atributos de fertilidade e amostragem do solo no sistema plantio direto. R. Bras. Ci. Solo, 24:85-91, 2000a.

SCHLINDWEIN, J.A. & ANGHINONI, I. Variabilidade vertical de fósforo e potássio disponíveis e profundidade de amostragem do solo no sistema plantio direto. Ci. Rural, 30:611-617, 2000b.

SCHUURMAN, J.J. & GOEDEWAAGEN, M.A.J. Methods for the examination of root systems and roots. Wageningen, Pudoc, 1965. 86p.

SIDDIQI, M.Y. & GLASS, A.D. Utilization index: A modified approach to the estimation and comparison of nutrient efficiency in plants. J. Plant Nutr., 4:289-302, 1981.

SOUSA, D.M.G & VOLKWEISS, S.J. Reações do superfosfato triplo em grânulos com solos. R. Bras. Ci. Solo, 11:133-140, 1987.

TEDESCO J. M.; GIANELLO C.; BISSANI C. A.; BOHNEM H. & VOLKWEISS, S.J. Análise de solo, plantas e outros materiais. 2.ed. Porto Alegre,Universidade Federal do Rio Grande do Sul, 1995. 174p. (Boletim Técnico de Solos, 5)

VENZKE FILHO, S.P.; FEIGL, B.J.; PICCOLO, M.C.; FANTE JR, L.; SIQUEIRA NETO, M. & CERRI, C.C. Root systems and soil biomass under no-tillage system. Sci. Agríc., 61:529-537, 2004.

WANG, J.; HESKETH, J.D. & WOOLLEY, J.Y. Preexisting channels and soybean rooting patterns. Soil Sci. Soc. Am. J., 141, 432-437, 1986.

ZERBOUNE, M.A. Residual P from single and repeated bands in no-till systems as evaluated by crop response and sampling strategies. Lincoln, University of Nebraska, 1996. (Doctorate Thesis)