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VANDERSON MODOLON DUART

SURFACE APPLICATION OF LIME AND FERTILIZATION WITH PHOSPHORUS AND SULFUR IN A WHEAT-SOYBEAN CROPPING SYSTEM UNDER NO-TILL

APLICAÇÃO SUPERFICIAL DE CALCÁRIO E ADUBAÇÃO COM FÓSFORO E ENXOFRE EM UM SISTEMA DE CULTIVO DE TRIGO-SOJA SOB PLANTIO DIRETO

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Advisor: Professor Dr. Eduardo Fávero Caires

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ABSTRACT

DUART, V.M. **Surface Application of Lime and Fertilization with Phosphorus and Sulfur in a Wheat-Soybean Cropping System under No-till.** 2023. Thesis of doctorate degree in Agronomy - University State of Ponta Grossa.

Brazil plays a pivotal role in global food production and food security as the world's largest producer of soybean, which contributes to the global protein production. In Southern Brazil, wheat is a crop of significant importance in the wheat-soybean rotation, cultivated during the fall-winter season. Despite Brazil's large agricultural production, which is largely based on no-till systems, there is potential to increase crop yield through more appropriate management practices. Brazil, as it is located in regions with a tropical and subtropical climate, has highly weathered soils characterized by high acidity, low levels of exchangeable bases (Calcium (Ca), magnesium (Mg), and potassium (K)), high phosphorus (P) fixation by iron and aluminum hydroxide-oxides, and low levels of sulfur (S) mainly due to the frequent use of fertilizers without S. In no-till systems, the correcting soil acidity in subsurface layers can be challenging due to the low solubility and slow reaction of lime in the soil. Surface application of lime and fertilization with P and S in a wheat-soybean cropping system under no-till were studied in this thesis in four chapters. In the first two chapters, alternatives to improve the reaction of lime applied to the soil surface and the plant nutrition and grain yields of wheat and soybean in a no-till farming system were analyzed. In chapter 1, the effects of surface lime (SL) combined with the use of monoammonium phosphate (MAP) and elemental sulfur (ES) were investigated on soil acidity, root growth, nutrition, and grain yield of a wheat-soybean rotation under a no-till farming system. Fertilization with MAP and MAP + ES in combination with SL did not improve the response of surface liming in correcting soil acidity in the soil profile and showed similar effects compared to SL alone. The improvement of soil fertility with SL favored wheat root growth more than soybean, although it increased the grain yield of both crops. Lime resulted in an average increase in wheat grain yield of about 40% when applied alone and 74% when combined with MAP + ES. The average soybean grain yield increased by 36% with SL, regardless of the use of MAP, and MAP + ES. In chapter 2, it was investigated whether combining SL with application of single superphosphate (SSP) in broadcast (SSP_B) and in-furrow (SSP_F) or phosphogypsum (PG) could improve the action of lime in alleviating acidity in the soil profile, plant nutrition and grain yield of wheat and soybean under a no-till system. In this study, it was found that SL under a no-till system effectively increased soil pH, Ca and Mg contents, and base saturation, and reduced Al content and Al saturation in the soil profile up to 1 m deep in the short- and -medium term. However, SL alone was superior or equivalent to the treatments with SL + SSP_B, SL + SSP_F, and SL + PG. The application of SSP_B, SSP_F, and PG in combination with liming increased P content in the soil surface layer (0–0.10 m), with a more pronounced increase observed with the SSP_B application. In the short term, 1 year after liming, the addition of PG combined with SL increased the SO_4-S content in the subsoil layers (from 0.10 m to 1 m), while at 3 and 5 years after liming, there was an increase in SO_4-S content with both SSP (SSP_B and SSP_F) and PG use, with a more pronounced effect observed with SSP_B application. The cumulative wheat grain yield from five harvests increased by 40% with SL, 54% with SL + SSP_F, and 70% with SL + SSP_B and PG. Meanwhile, the cumulative soybean grain yield from five harvests increased by 36% with SL, regardless of the addition of SSP_B, SSP_F, and PG. In chapter 3, questions related to the mode of application (broadcast or in the sowing furrow) of phosphate fertilizers (MAP and SSP) in maintaining P content in the soil and responses of wheat and soybean in a no-till system were addressed. The hypothesis to be tested was that in soil with a high P level, the mode of application of phosphate fertilizers does not affect the availability of P in the soil as well as the P-leaf content and grain yields of wheat and soybean crops. The results showed that the P content in the soil surface decreased over time in plots without P addition. The annual application of phosphate fertilizers at 100 kg P_2O_5 ha^{-1} in the wheat crop, regardless of the mode and source of application, was sufficient to maintain a high level of P in the soil after 5 years, similar to the initial level. This resulted in high P-leaf content and high grain yields in a wheat-soybean crops sequence.

Furthermore, the results indicated that the application of phosphate fertilizers in the sowing furrow or by broadcast in wheat, using MAP or SSP as sources, is a strategy that should be encouraged to minimize P fixation on soil particles, improve P-leaf content, and increase wheat and soybean grain yields in highly weathered soils under no-till systems. In chapter 4, the focus was on analyzing the efficiency of various S sources (SSP, PG, and ES) in increasing wheat and soybean grain yields and maintaining an adequate level of S in the soil. The results showed that the SO_4-S content in the soil profile increased with the applied S sources (SSP, PG, and ES). Additionally, the S-leaf content of wheat increased with ES and PG applications, and the S-leaf content of soybean increased with PG application. Although a trend was observed for S sources to increase cumulative wheat grain yield by 2% to 13%, there was no significant influence of the application of S-fertilizers on wheat and soybean grain yields. The results also indicated that a soil SO_4-S level of 13 mg dm^{-3} in the 0–0.20 m depth was sufficient to supply the demand for S by a wheat-soybean succession under no-till. Overall, the chapters highlight the importance of proper management practices, such as surface liming, and P and S fertilization in improving soil fertility, crop nutrition, and grain yields under a no-till farming in Southern Brazil. The findings have important implications for the success of sustainable agriculture for food production in Brazil and other regions with similar climatic and soil conditions.

Keywords: Soil fertility; Soil acidity; Single superphosphate; Sulfate; Phosphogypsum; Elemental sulfur.

RESUMO

DUART, V.M. **Aplicação de calcário na superfície e adubação com fósforo e enxofre na sucessão trigo-soja em sistema plantio direto.** 2023. Tese de doutorado em Agronomia – Universidade Estadual de Ponta Grossa.

O Brasil desempenha um papel fundamental na produção global de alimentos e na manutenção da segurança alimentar como maior produtor mundial de soja, contribuindo para a produção global de proteínas. No Sul do Brasil, o trigo é uma cultura de grande importância na sucessão trigo-soja, sendo cultivado na estação de outono-inverno. Apesar da grande produção agrícola no Brasil, a qual é amplamente baseada no sistema plantio direto, é possível elevar os rendimentos das culturas por meio de práticas de manejo mais adequadas. O Brasil, por estar localizado em regiões de clima tropical e subtropical, possui solos altamente intemperizados caracterizados por alta acidez, baixos teores de bases trocáveis (cálcio (Ca), magnésio (Mg) e potássio (K)), alta fixação de fósforo (P) pelos óxidos-hidróxidos de ferro e alumínio, e baixos teores de enxofre (S) devido ao frequente uso de fertilizantes sem S. Em sistema plantio direto, a correção da acidez do solo em camadas subsuperficiais pode ser um desafio devido à baixa solubilidade e lenta reação do calcário no solo. A aplicação superficial de calcário e a adubação com P e S em uma sucessão trigo-soja sob plantio direto foram estudadas nesta tese em quatro capítulos. Nos dois primeiros capítulos, foram analisadas alternativas para melhorar a reação do calcário aplicado na superfície do solo, a nutrição das plantas e os rendimentos de grãos de trigo e soja em sistema plantio direto. No capítulo 1, foram investigados os efeitos da calagem superficial (SL) combinada com o uso de fosfato monoamônico (MAP) e enxofre elementar (S^0) sobre a acidez do solo, o crescimento radicular, a nutrição das plantas e o rendimento de grãos de uma sucessão trigo-soja sob sistema plantio direto. A adubação com MAP e MAP + S^0 em combinação com SL não melhorou a resposta da calagem superficial na correção da acidez no perfil do solo e apresentou efeitos semelhantes à SL isoladamente. A melhoria da fertilidade do solo com SL favoreceu mais o crescimento radicular do trigo do que o da soja, embora tenha aumentado o rendimento de grãos de ambas as culturas. O calcário na superfície resultou em um aumento médio no rendimento de grãos de trigo de cerca de 40% quando aplicado sozinho e de 74% quando combinado com MAP + S^0. O rendimento médio de grãos de soja aumentou 36% com SL, independentemente do uso de MAP e MAP + S^0. No capítulo 2, foi investigado se a combinação de SL com aplicação de superfosfato simples (SSP) à lanço (SSP_L) e em sulco (SSP_B) ou fosfogesso (PG) poderia melhorar a ação do calcário na redução da acidez no perfil do solo, na nutrição das plantas e nos rendimentos de grãos de trigo e soja em sistema plantio direto. Neste estudo, verificou-se que a SL em plantio direto aumentou efetivamente o pH do solo, os teores de Ca e Mg e a saturação por bases, e reduziu o teor de Al e a saturação por Al no perfil do solo até 1 m de profundidade em curto e médio prazos. No entanto, a SL sozinha foi superior ou equivalente aos tratamentos com SL + SSP_L, SL + SSP_B e SL + PG. A aplicação de SSP_L, SSP_B e PG em combinação com a calagem aumentou o teor de P na camada superficial do solo (0–0,10 m), com aumento mais pronunciado observado com a aplicação de SSP_L. Em curto prazo, 1 ano após a calagem, a adição de PG combinada com SL aumentou o teor de $S\text{-}SO_4$ nas camadas do subsolo (de 0,10 m até 1 m), enquanto aos 3 e 5 anos após a calagem, houve aumento no teor de $S\text{-}SO_4$ com o uso de SSP (SSP_L e SSP_B) e PG, com efeito mais pronunciado observado com a aplicação de SSP_L. O rendimento acumulado de grãos de trigo em cinco safras aumentou em 40% com SL, 54% com SL + SSP_B e 70% com SL + SSP_L ou PG. Enquanto isso, o rendimento acumulado de grãos de soja em cinco safras aumentou 36% com SL, independentemente da adição de SSP_L, SSP_B e PG. No capítulo 3, foram abordadas questões relacionadas ao modo de aplicação (à lanço ou no sulco de semeadura) de fertilizantes fosfatados (MAP e SSP) para a manutenção do teor de P no solo e nas respostas do trigo e da soja em sistema plantio direto. A hipótese testada foi que em solo com alto teor de P, o modo de aplicação dos fertilizantes fosfatados não afeta a disponibilidade de P no solo, bem como o teor foliar de P e os rendimentos de grãos de trigo e soja. Os resultados mostraram que o teor de P na superfície do solo diminuiu ao longo do tempo em parcelas sem adição de P. A aplicação anual de fertilizantes fosfatados na dose de 100 kg P_2O_5 ha^{-1} na cultura do trigo, independentemente do modo e da fonte, foi suficiente para manter o nível de P no solo elevado após 5 anos, semelhante ao nível inicial. Isso resultou em alto teor foliar de P e alto rendimento de grãos em uma sequência de cultivos de trigo e soja. Além disso, os resultados indicaram que a aplicação de fertilizantes fosfatados no sulco de semeadura ou à lanço no trigo, usando MAP ou SSP como fontes, é uma estratégia que deve ser incentivada para minimizar a fixação de P nos colóides do solo, melhorar o teor foliar de P e aumentar os rendimentos de grãos de trigo e soja em solos altamente intemperizados sob plantio direto. No capítulo 4, o foco foi analisar a eficiência de várias fontes de S (SSP, PG e S^0) em aumentar os rendimentos de grãos de trigo e soja e manter um nível adequado de S no solo. Os resultados mostraram que o teor de $S\text{-}SO_4$ no perfil do solo aumentou com as fontes de S aplicadas (SSP, PG e S^0). Além disso, o teor foliar de S do trigo aumentou com as aplicações de S^0 e PG, e o teor foliar de S da soja aumentou com a aplicação de PG. Embora tenha sido observada tendência de as fontes de S aumentarem o rendimento cumulativo de grãos de trigo de 2% a 13%, não houve influência significativa da aplicação de fertilizantes com S nos rendimentos de grãos de trigo e soja. Os resultados também indicaram que o nível de $S\text{-}SO_4$ no solo de 13 mg dm^{-3} na profundidade de 0-0,20 m foi suficiente para suprir a demanda de S pela sucessão trigo-soja em sistema plantio direto. No geral, os capítulos destacam a importância de práticas de manejo adequadas, como calagem superficial e adubação com P e S para melhorar a fertilidade do solo, a nutrição das plantas e os rendimentos de grãos em sistema plantio direto no Sul do Brasil. As descobertas têm implicações importantes para o sucesso da agricultura sustentável visando a produção de alimentos no Brasil e em outras regiões com condições climáticas e de solo semelhantes.

Palavras-chave: Fertilidade do solo; Acidez do solo; Superfosfato simples; Sulfato; Fosfogesso; Enxofre elementar.

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SUMMARY

PRESENTATION

This thesis was written according to "Manual de normatização bibliográfica para trabalhos científicos, UEPG (2019)" and is composed of the following chapters:

Strategies to Improve Surface Lime Efficiency in Correcting Soil Acidity in a No-till Wheat-Soybean Cropping System.

Surface Lime Combined with Phosphogypsum or Single Superphosphate in a Wheat-Soybean Cropping System under No-Till.

Sources and Application Modes of Phosphorus in a No-till Wheat–Soybean Cropping System.

Comparing Various Sulfur Sources for a Wheat–Soybean Cropping System under No-till.

All the chapters reproduce literally the text submitted to the journals and despite interconnections one chapter is independent of the others (the read of any chapter do not presume the read of the others and the acronyms, equations, figures, tables, and references refers only to the current chapter). Preceding the first chapter there is a general introduction, and the last item is composed by the general conclusions.

GENERAL INTRODUCTION

The issue of global food security is a major challenge in the current century (FAO, 2022), as the global population continues to grow (DESA, 2015; POPULATION MATTERS, 2022) and crop failures caused by environmental disasters such as droughts or excessive rainfall affect food production in many countries around the world (FAO, 2022). To address this challenge, it is important to ensure that global food production keeps pace with population growth. However, this requires the implementation of adequate management practices, such as surface liming, and phosphorus (P) and sulfur (S) fertilization, to improve soil fertility, crop nutrition, and grain yield.

Brazil is one of the world's largest grain producers (FAO, 2021), and soybean [*Glycine max* (L.) Merrill] is a crucial crop for the commercial balance of Brazilian agriculture (CONAB, 2023). In Southern Brazil, soybean is grown in the spring-summer season, often in rotation with wheat (*Triticum aestivum* L.) which is grown in the autumn-winter season. Because Brazil is located in tropical and subtropical climate areas, Brazilian soils commonly have high acidity and low nutrient reserves (FAGERIA, 2001; van RAIJ, 2011). Calcium (Ca) deficiency and toxicity caused by aluminum (Al) and manganese (Mn) are the factors that have most limited crop yield in acidic soils of tropical and subtropical regions. In addition, they have a low level of available P due to their strong adsorption/fixation force caused by the abundant iron and aluminum oxide-hydroxides contents in the clay fractions (LYNCH, 2011; van RAIJ, 2011; FINK et al., 2016; WITHERS et al., 2018). Another nutrient that has been gaining importance because it is easily leached and has often been neglected in crop fertilization is S.

No-till systems have been frequently used as a sustainable management practice in agricultural areas in Brazil (FEBRAPDP, 2022). This system provides several benefits to the physical, chemical, and biological parameters of the soil (SCHICK et al., 2017; WEIL; BRADY, 2017; COOPER et al., 2021). As a result, no-till lands have shown improved value of between 10% and 22% compared to plots with conventional tillage (TELLES et al., 2022).

To control soil acidity and increase crop yield in this cropping system, lime is commonly applied to the soil surface without incorporation (CAIRES et al., 2005; 2006; 2011; JORIS et al., 2016; CRUSCIOL et al., 2019). The reaction of surface-applied lime under no-till is slow, resulting in a correction front in the soil profile, with the surface layer corrected in the short and medium term, while the subsurface layer requires a longer period and higher rates to react and reduce acidity (CAIRES et al., 2005; 2011).

This study aimed to test sources of P with low amounts of nitrogen (N) in the ammoniacal form, as well as sources of S, as alternatives to improve the effect of surface application of lime in alleviating acidity in the soil profile under no-till management. The application of low rates of ammoniacal-N via phosphate fertilization with monoammonium phosphate (MAP) over time could have a promising effect on subsurface acidity amelioration after surface lime. Additionally, the use of elemental S on soil with surface lime could contribute to improving subsoil fertility and mitigating Al toxicity. This is because the oxidation of elemental S causes acidification in the surface layer, generating sulfate in the soil (HOROWITZ and MEURER, 2006). Continued use of elemental S could facilitate the movement of the $CaSO_4^0$ ion pair in the soil profile, releasing Ca^{2+} and forming $AlSO_4^+$ in subsurface layers. Although the use of elemental S in agriculture is increasing, studies supporting this hypothesis are scarce, making this a topic of great research interest. It was also investigated whether combining surface lime with application of single superphosphate (SSP) in broadcast and in-furrow or phosphogypsum (PG) could improve the action of lime in alleviating acidity in the soil profile.

This study also evaluated the efficiency of various sources of P and S to improve soil fertility and plant nutrition, and increase wheat and soybean grain yields under a no-till system. Moreover, this study offers significant insights into the management of P sources, addressing concerns that have arisen from the need for P applications that are typically broadcast to expedite sowing operations (FINK et al., 2016). These concerns pertain to P retention in the soil and crop responses over the years resulting from P application in the sowing furrow and broadcast.

In conclusion, the study highlights the importance of soil management under a no-till system, and explores alternatives to alleviate subsoil acidity, improve plant nutrition, and increase grain yields in regions with acidic and low-fertility soils, such as those found in Brazil. Research suggests the use of phosphate sources with low content of ammoniacal-N and S-fertilizers sources as potential alternatives, although the effectiveness of these practices for subsoil improvement remains uncertain.

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CHAPTER 1. STRATEGIES TO IMPROVE SURFACE LIME EFFICIENCY IN CORRECTING SOIL ACIDITY IN A NO-TILL WHEAT-SOYBEAN CROPPING SYSTEM

Abstract: Tropical and subtropical soils typically exhibit low natural fertility, excessive acidity, and limited availability of basic cations and phosphorus. Calcium (Ca) deficiency, as well as aluminum (Al) and manganese (Mn) toxicity, are the primary factors that limit crop yield potential in acidic soils of tropical and subtropical climate. They limit root growth at depth and hinder the uptake of water and nutrients by plants, thus impairing overall crop performance. In a no-till system, soil acidity correction is achieved by surface application of lime without incorporation. Significant progress has been made in Brazil, particularly in recent years, in studying soil acidity correction in no-till systems. However, there is limited understanding of how the application of ammoniacal nitrogen fertilizers and elemental sulfur (S) influences the efficiency of surface lime for acidity correction in no-till systems. The study presents findings from a field experiment that examined the effects of surface lime in conjunction with the use of monoammonium phosphate (MAP) and elemental sulfur (S) on soil acidity correction, root growth, nutrition, and grain yield in a wheat-soybean rotation under a no-till system. The hypothesis is that the combined application of surface lime, MAP, and elemental S will enhance the root environment throughout the soil profile, leading to improved plant nutrition and higher grain yields for both soybean and wheat in a no-till system. The experiment was established in 2016 and conducted over a five-year period with a crop rotation of wheat and soybean. The experimental design utilized a complete randomized block trial with four treatments and four replicates. The treatments included: Control (no amendments), surface lime (SL), SL + MAP, and SL + MAP + elemental S. The application of dolomitic lime on the soil surface of an acid latosol under a no-till system in a region with an average annual rainfall of approximately 1550 mm resulted in a reduction of soil acidity up to a depth of 100 cm. The correction of soil acidity through surface liming was most prominent in the 0-10 cm layer and less pronounced in the 10-100 cm layer. The effects of surface liming were noticeable after one year, increased in magnitude after three years, and remained evident for up to five years following application. The addition of MAP and MAP + elemental S in conjunction with surface liming did not enhance the effectiveness of surface liming in correcting soil acidity throughout the soil profile, and their effects were similar to or less than those of surface liming alone. The improvement of soil fertility in the soil profile through surface lime had a more favorable impact on wheat root growth compared to soybean, although it resulted in increased grain yield for both crops. The length of roots per unit of soil surface area up to a depth of 100 cm exhibited a strong correlation with wheat grain yield, but not with soybean grain yield. This phenomenon may be attributed to the fact that the wheat crop was more adversely affected by insufficient rainfall during its development compared to the soybean crop. Surface liming, when applied alone, led to an average increase in wheat grain yield of approximately 40%. However, when combined with MAP + elemental S, the increase was even more pronounced, reaching up to 74%. For soybean, surface liming resulted in an average yield increase of around 36%, regardless of the use of MAP and MAP + elemental S. The wheat crop demonstrated a stronger response to the addition of soil P and S compared to the soybean crop. The increase in leaf Mg content could have been one of the key factors contributing to the improved soybean grain yield observed with surface liming.

Key-words: *Triticum aestivum* L., *Glycine max,* root growth, monoammonium (MAP), elemental Sulphur.

1.1 INTRODUCTION

In a no-till system, soil acidity can be corrected by applying lime on the surface without incorporation, as mentioned in studies by Caires et al. (2002), Rheinheimer et al. (2018), and Crusciol et al. (2019). Lime application increases the availability of nitrogen (N), P, sulfur (S), and molybdenum (Mo) in the soil. It also provides Ca and magnesium (Mg) for plants, and reduces toxic levels of Al and Mn, creating more favorable conditions for root growth and plant uptake of water and nutrients. However, it's important to note that lime has low water solubility, so correcting soil acidity by surface application of lime is slow, and its effect is limited to the surface layer in the short term, as mentioned in studies by Caires et al. (2005), Ferrari Neto et al. (2021), and Ritchey et al. (1980). Soil acidity in the subsurface layers can still affect rooting and plant nutrition, especially in the presence of toxic Al and/or Ca deficiency, as highlighted by Ritchey et al. (1980).

Studies on the correction of soil acidity in no-till systems have been advancing in Brazil, particularly in recent years, as evidenced by research conducted by Caires et al. (2015), Crusciol et al. (2016; 2019), Joris et al. (2016), Vargas et al. (2019), and Bossolani et al. (2022). However, there is limited knowledge about the effect of ammoniacal nitrogen fertilizer and elemental sulfur (S) application on the efficiency of surface lime to correct soil acidification in a no-till system. In a study by Caires et al. (2015), it was observed that the annual application of relatively high doses of nitrogen (N) in the form of ammonium nitrate (60, 120, and 180 kg N ha^{-1} $year^{-1}$) to a soil that had been surface limed reduced the levels of exchangeable Ca^{2+} and Mg^{2+} in the surface soil layers, but did not reduce subsoil acidity. It is possible that the application of lower doses of ammoniacal N over time through phosphate fertilization with MAP could have a more promising effect on correcting subsoil acidity in conjunction with surface liming. Further research may be needed to explore this possibility and better understand the interactions between N fertilization, elemental S application, and surface liming for soil acidity correction in no-till systems.

During the solubilization of MAP, which contains about 11% nitrogen (N) in the form of ammonium (NH_4^+), nitrification can occur, leading to the formation of nitrate (NO_3^-) and release of protons (H^+) (MOREIRA e SIQUEIRA, 2006). This acidification at the surface can potentially increase the solubility of lime, leading to higher Ca and Mg content in the soil. The Ca^{2+} and Mg^{2+} ions released at the surface can potentially form complexes with NO_3^-, such as $Ca(NO_3)_2$ and $Mg(NO_3)_2$, which are neutral and can move along the soil profile. These complexes can potentially dissociate at depth, releasing NO_3^-, Ca^{2+}, and Mg^{2+}. When plant roots absorb N-NO_3^-, they release hydroxide ions (OH^-) to maintain equilibrium, which can result in an increase in pH in the rhizosphere. Furthermore, increasing the Ca and Mg content in the soil profile can reduce aluminum (Al) saturation, creating a more favorable environment for deep root growth. This hypothetical scenario suggests that the application of MAP in no-till systems could potentially enhance the efficiency of surface liming for soil acidity correction by promoting the movement of Ca, Mg, and NO_3^- ions along the soil profile, improving pH conditions in the rhizosphere, and reducing Al saturation. However, it is important to note that the effectiveness of this approach may be influenced by various factors such as soil type, climate, and management practices, and further research may be needed to validate these hypotheses in field conditions.

Elemental S needs to be oxidized to sulfate (SO_4^{2-}) before it can be taken up by plants (HOROWITZ and MEURER, 2006; TAIZ et al., 2017). The oxidation of elemental S to SO_4^{2-} produces protons (H^+) in the surface layer, resulting in soil acidification (HOROWITZ and MEURER, 2006). The acidification caused by the continued use of elemental S can help dissolve the applied lime on the surface and increase the content of Ca and Mg in the soil. Cations (Ca^{2+} and Mg^{2+}) released on the surface can react with SO_4^{2-} and form complexes with Ca^{2+} ($CaSO_4^0$) and Mg^{2+} ($MgSO_4^0$). These complexes are neutral and can move along the soil profile. In deeper layers, these complexes can help reduce Al phytotoxicity by forming $AlSO_4^+$ and reducing Al saturation, similar to the effect of using gypsum to improve plant root environments (CAIRES and GUIMARÃES, 2018; CRUSCIOL et al., 2019; ZOCA and PENN, 2017).

This study reports on a field experiment investigating the effects of surface liming associated with the use of MAP and elemental S on soil acidity correction, root growth, nutrition, and grain yield of a wheat-soybean rotation under a no-till system. We hypothesize that surface lime application with MAP and elemental S is an efficient strategy to improve the root environment along the soil profile, resulting in improved plant nutrition and grain yield of soybean and wheat in rotation in a no-till system.

1.2 MATERIAL AND METHODS

1.2.1 Site and soil description

The study was carried out at the "Capão da Onça" Farm School of the State University of Ponta Grossa, in the Center-South region of Paraná (southern latitude 25°05'35" and western longitude 50°02'49"). The climate of the region is classified as Subtropical Humid

Mesothermal, type cfb, according to the Köppen classification. The soil, classified as dystrophic Red Latosol of medium texture, has been cultivated by no-till, with no lime or S-containing fertilizer applied for at least five years before the experiment was conducted. Table 1.1 shows the results of chemical analysis (PAVAN et al., 1992) and granulometric analysis (EMBRAPA, 2011) of the soil before the establishment of the experiment.

Table 1.1 - Results of soil chemical and particle-size distribution analyses for different depths, before the establishment of the experiment. Ponta Grossa-PR, 2016.

Depth	**pH**[1]	**Al**	**Ca**	**Mg**	**K**	**CTC**[2]	**V**[3]	**m**[4]	**P**[5]	**SO_4-S**	**C**	**Clay**	**Silt**	**Sand**
cm		------- mmol$_c$ dm^{-3} ---------					--- % ---		--- mg dm^{-3}--		g dm^{-3}	------- g kg^{-1} --------		
0–10	4.5	6.0	16.0	6.0	1.4	92,8	25	20	45.5	3.7	17	260	57	683
10–20	4.0	12.0	5.0	3.0	1.1	99,2	9	57	6.7	5.7	12	260	51	689
20–40	4.1	9.0	6.0	3.0	0.9	100,0	10	48	0.8	9.9	9	279	45	676
40–60	4.3	7.0	7.0	3.0	0.8	77,7	14	39	1.3	8.8	9	280	79	641
60–80	4.5	4.0	9.0	5.0	0.4	70,0	18	24	0.3	9.4	10	320	75	605

[1]pH in 0,01 mol L^{-1} $CaCl_2$; [2] Cation exchange capacity (H+Al + Ca + Mg + K); [3]V: base saturation; [4]m: Al saturation; [5]Phosphorus extracted by Mehlich-1.

1.2.2 Experimental design and treatments

The experiment was installed in 2016 and conducted for five years with a wheat-soybean crop rotation (Figure 1.1). The experimental design used was a complete randomized block trial with four treatments and four replications. The plot size was 15 m × 6 m (90 m^2). The treatments were (Table 1.2): Control (no amendments), surface lime (SL), SL + MAP, and SL + MAP + elemental S.

Table 2.2 – Treatments and doses of lime, MAP and elemental S for the establishment of the experiment. Ponta Grossa-PR, 2016-2021.

Treatments	Lime (t ha^{-1})	MAP (kg P_2O_5 ha^{-1}) [a]	Elemental S (kg S ha^{-1}) [a]
1. Control	0	0	0
2. Surface lime	5,4	0	0
3. Surface lime + MAP	5,4	100	0
4. Surface lime + MAP + S	5,4	100	65

[a] The P_2O_5 applied annually in each sowing wheat crop.

The control treatment received no application of lime, MAP, and elemental S. In the surface lime treatments, lime was applied on June 3, 2016, at a dose calculated to increase the base saturation of the soil in the 0-20 cm deep layer to 70% (5.4 t ha^{-1}) (CAIRES et al., 2005). Dolomitic lime with 327 g kg^{-1} CaO, 206 g kg^{-1} MgO, and 95% of total relative neutralizing power (ECCE) was used. The lime was applied manually by pouring it onto the soil surface, without incorporation, in a single dose at the beginning of the experiment. MAP (11-52-00, N-

P_2O_5-K_2O) was applied mechanically in the wheat sowing furrow at a dose of 100 kg ha^{-1} P_2O_5 to provide P for wheat-soybean succession. Elemental S (Sulfurgran®, containing 90% S) was broadcast on the surface of the plots just before wheat seeding to provide 65 kg ha^{-1} S dose to wheat-soybean succession.

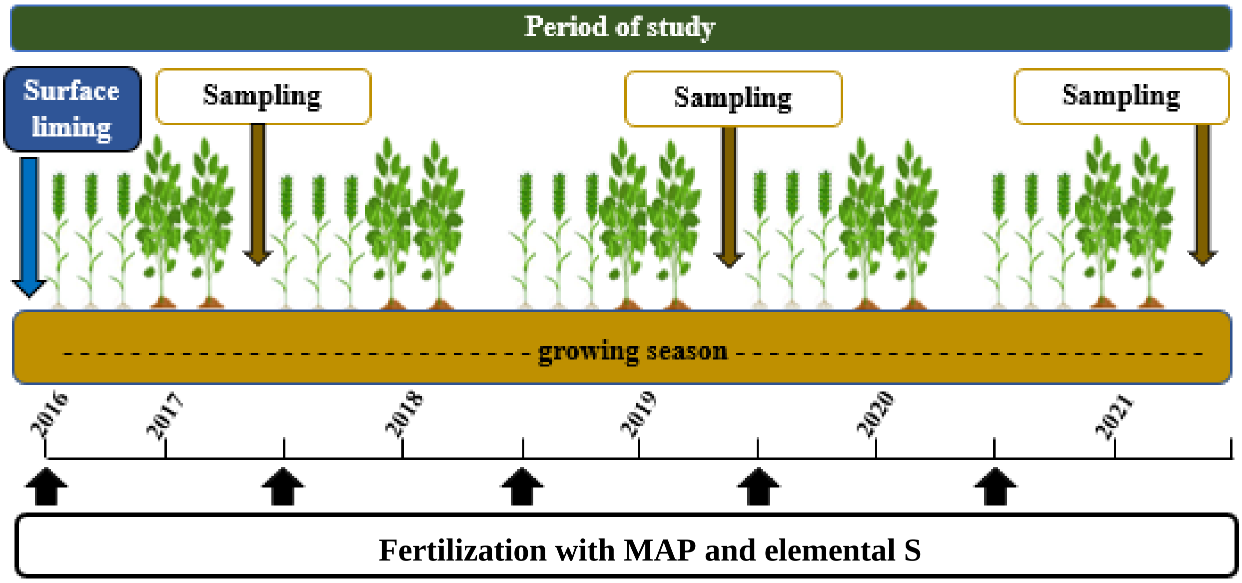

Figure 1.1 - Schematic representation of the wheat–soybean cropping system used in experiment, including the chronological sequence of surface application of lime, fertilization with MAP and elemental S, and soil sampling.

Top dressing nitrogen fertilization in the wheat crops was done by applying 100 kg ha^{-1} N (60 kg ha^{-1} at the beginning of tillering and 40 kg ha^{-1} at the end of sprouting) in the form of urea (45% N), in all plots. Potassium fertilization was carried out by applying broadcasting 84 kg ha^{-1} K_2O in the form of potassium chloride (KCl) for wheat and 84 kg ha^{-1} K_2O for soybean in all plots on the same day of wheat and soybean sowing.

1.2.3 Crop sowing and establishment

Wheat was sown on June 3, 2016 (cv. TBio Toruk), June 28, 2017 (cv. TBio Iguaçu), July 4, 2018 (cv. Quartzo), June 28, 2019 (cv. TBio Toruk), and June 6, 2020 (cv. TBio Ponteiro). Soybean seeds were sown on December 5, 2016 (cv. NIDERA 5909 IPRO), November 24, 2017 (cv. NIDERA 5445 IPRO), December 5, 2018 (cv. LG 60158 IPRO), December 3, 2019 (cv. NIDERA 5445 IPRO), and November 24, 2020 (cv. NIDERA 5445 IPRO). Soybean seeds were inoculated with *Bradyrhizobium japonicum* (SEMIA 5079) using a commercial inoculant shortly before sowing. Row spacing was 0.17 m for wheat and 0.50 m for soybean. Phytosanitary management was carried out according to the needs of the wheat and soybean crops to achieve adequate plant health during the development cycle.

1.2.4 Rainfall

After surface lime application, which was carried out in June 2016, the accumulated rainfall (Table 1.2) was 2057 mm after one year (first soil sampling), 5687 mm after three years (second soil sampling), and 8042 mm after five years (third soil sampling).

The wheat crop was more affected than the soybean crop by the lack of rain during its development (Table 1.3). Wheat cultivated in 2016 had excellent monthly rainfall throughout the development period, above the historical average, which favored crop development and set the stage for high grain yield. However, in subsequent wheat crop years (2017, 2018, 2019, and 2020), rainfall after seeding and close to the flowering was below the historical average for the region; July and September were the driest months and hindered crop development. Rainfall was relatively well distributed during the soybean crops. The most severe drought during soybean development occurred in February 2018, which must have affected crop grain yield.

Table 1.3 - Monthly rainfall (mm) for the duration of the experiment (2016-2021) and the 47-yr (1954–2001) average monthly rainfall (mm) in Ponta Grossa, southern Brazil.

Month	**Year**						**Long-term (47 yr) Average**
	2016	**2017**	**2018**	**2019**	**2020**	**2021**	
January	139	370	444	204	102	223	186
February	310	181	73	140	136	87	161
March	122	104	288	178	30	203	138
April	91	81	16	185	60	4	101
May	221	152	38	289	62	14	116
June	161	175	143	48	187	118	118
July	109	4	14	29	35	39	96
August	227	113	48	50	176	60	79
September	77	53	53	100	42	48	135
October	201	354	271	49	85	214	153
November	178	201	32	256	123	102	119
December	217	193	122	107	150	57	151
Total	2052	1980	1542	1633	1187	1169	1553

Source: Monthly rainfall data obtained from BASF's meteorological station, located on the "Capão da Onça" farm. Historical average rainfall data (1954–2001) obtained from the meteorological station of the Agronomic Institute of Parana (IAPAR, 2021).

1.2.5 Soil sampling and chemical analysis

Soil samples were collected shortly after the soybean harvest in 2017, 2019, and 2021, approximately 1, 3, and 5 years after surface liming. Soil samples were stratified in layers of 0-10, 10-20, 20-40, 40-60, 60-80, and 80-100 cm depth. Ten subsamples were collected per plot to form a composite sample up to a depth of 20 cm, and five subsamples for strata from 20 to 100 cm depth. In these samples, the pH in $CaCl_2$ and the contents of Al, Ca, Mg, and K were determined. Soil pH was determined in a suspension of 0.01 mol L^{-1} $CaCl_2$ (1:2.5 soil/solution, v/v). Exchangeable Al, Ca, and Mg contents were extracted with a 1 mol L^{-1} neutral KCl solution, and K was extracted with a Mehlich-1 solution (0.05 mol L^{-1} H_2SO_4 + 0.05 mol L^{-1} HCl), in a soil/solution ratio of 1:10 (v/v). Exchangeable Al (exchangeable acid with KCl) was determined by titration with a 0.025 mol L^{-1} NaOH solution, Ca and Mg by titration with a 0.025 mol L^{-1} ethylenediaminetetraacetic acid solution, and K by flame photometry. Base saturation (BS, in %) and Al saturation (m, in %) in the soil were calculated using the following equations:

$$BS (\%) = (Ca + Mg + K)/(H + Al + Ca + Mg + Al + K) \times 100;$$

$$m (\%) = Al/(Ca + Mg + Al + K) \times 100.$$

1.2.6 Root sampling and root length determination

Samples of wheat roots in 2018 and 2020 and soybean in 2018-2019 and 2020-2021 were collected at the time of plant flowering. Using a 3.5 cm diameter root extraction auger, six subsamples were collected to form one sample from each plot, three in the seeding line (centered between two plants) and three between rows (approximately 5 cm adjacent to plants), at depths of 0-10, 10-20, 20-40, 40-60, 60-80, and 80-100 cm. Shortly after, the roots were separated from the soil by washing with water in a sieve with a mesh size of 0.5 mm. Roots were then scanned in a bench scanner coupled to a computer to determine length and mean radius using WinRHIZO software. Root length density (cm cm^{-3}), root relative distribution (%), and root length to 100 cm depth per soil area (cm cm^{2}) were determined.

1.2.7 Leaf sampling and chemical analysis

At flowering of wheat and soybean crops, leaves of 30 plants per plot were collected for foliar diagnosis in the five crops. The flag leaf was removed from the top of the plants in the wheat crop and the third leaflet in the soybean crop apex. Samples were washed with deionized water, dried in a forced circulation oven at 60°C until they reached a constant mass, and then ground. Chemical analysis of leaf tissue was performed by sulfur digestion for N and nitric acid-perchloric digestion for P, K, Ca, Mg, and S. Leaf nutrient concentrations were determined by the Kjeldahl method for N, metavanadate colorimetry for P, flame photometry for K, atomic absorption spectrophotometry for Ca and Mg, and turbidimetry as barium sulfate for S (Malavolta et al., 1997).

1.2.8 Crop grain yield

Grain yields of wheat and soybean were determined after physiological maturity of the plants by mechanized harvesting in the middle rows of each plot with a useful area of 20.8 m^2. Grain moisture was corrected to 130 g kg^{-1} water, and yield data (kg) per plot were converted to yield (kg ha^{-1}). Cumulative grain yield of wheat and soybean was determined by summing the productivity of the five wheat and soybean crops.

1.2.9 Statistical analysis

Soil chemical properties data were subjected to analysis of variance using the randomized complete block model in a split-plot design, with treatments as the main plot and soil depth as the subplot. Root growth, leaf diagnosis, and grain yield results of wheat and soybean were subjected to analysis of variance according to the randomized complete block model. The mean values of treatments were compared using the 5% LSD test. Pearson correlation was performed between grain yield and root length to 100 cm depth by soil surface area and between soil chemical properties and root length to 100 cm depth by soil surface area and grain yield. Statistical analyzes were performed using Sisvar software (FERREIRA, 2011) and R, version 3.0.2 (R CORE TEAM, 2015).

1.3 RESULTS AND DISCUSSION

1.3.1 Amendment effects on soil chemical properties

Analysis of variance revealed a significant interaction between treatments and sampling depth for pH ($CaCl_2$), base saturation, exchangeable Ca, Mg, Al contents, and Al saturation at the three-time points of soil sampling (1, 3, and 5 years after lime). As shown in Figure 1.2, lime increased the pH ($CaCl_2$) and base saturation of the soil to a depth of 100 cm over the 5 years after the application of the dolomitic lime.

In the first year after lime, soil pH ($CaCl_2$) increased significantly with lime at the surface to a depth of 100 cm, and there was no significant effect only in the 20-40 cm deep layer (Figure 1.2a). In the third year after lime, surface lime significantly increased soil pH ($CaCl_2$) along the soil profile to a depth of 100 cm (Figure 1.2b), and the residual effect of surface lime on the increase in soil pH persisted throughout the analyzed profile until the fifth year after lime (Figure 1.2c). The increase in pH ($CaCl_2$) was accompanied by an increase in soil base saturation. Soil base saturation increased with surface lime throughout the analyzed profile to a depth of 100 cm after one year of lime application (Figure 1.2a), and this effect persisted in the third (Figure 1.2b) and fifth (Figure 1.2c) years after lime application. The response of the lime applied to the surface, evaluated by the increase in pH ($CaCl_2$) and base saturation of the soil, was slow and gradual up to a depth of 20 cm, but was relatively rapid and sustained when the acidity of the subsoil (20-100 cm) was corrected. The results clearly show that the application of MAP or MAP + elemental S did not accelerate or intensify the response of surface lime to subsoil acidity correction. Isolated surface application of dolomitic lime showed a response in the soil profile that was equal to or greater than that observed in the SL + MAP and SL + MAP + S treatments, indicating that the addition of MAP and MAP + elemental S did not help the reaction of lime in correcting subsoil acidity.

Soil exchangeable Ca and Mg contents increased in the treatments with SL, SL + MAP and SL + MAP + elemental S, and more expressively in the surface layer at 0-10 cm depth (Figure 1.3). Surface lime treatment increased the exchangeable Ca and Mg contents in the layers 0-10 and 10-0.20 cm depth after one year of application (Figure 1.3a) and in the entire soil profile up to 100 cm depth after three years of application (Figure 1.3b). The effect of surface lime further increased exchangeable Ca to 80 cm depth and exchangeable Mg to 100 m depth after five years of application (Figure 1.3c). The increases in exchangeable Ca and Mg in the soil profile with surface lime were equal to or greater than those with the SL + MAP and SL + MAP + elemental S treatments. This indicates that fertilisation with MAP and MAP +

elemental S associated with surface lime was not able to cause greater solubilization and movement of Ca and Mg in the soil profile.

Exchangeable Al content and soil Al saturation in the 0-10 cm layer were reduced to zero in the surface lime treatment (Figure 1.4). The surface lime treatment reduced exchangeable Al content to a depth of 40 cm and Al saturation to a depth of 60 cm after one year of application (Figure 1.4a). Reductions in Al content and Al saturation from surface lime were significant throughout the soil profile to a depth of 100 cm after three years of application (Figure 1.4b), and the effects persisted after five years of application (Figure 1.4c). The surface lime application was as effective or more effective than the SL + MAP and SL + MAP + elemental S treatments in reducing Al content and Al saturation to a depth of 100 cm. This confirms the inefficiency of MAP and MAP + elemental S in improving soil profile acidity.

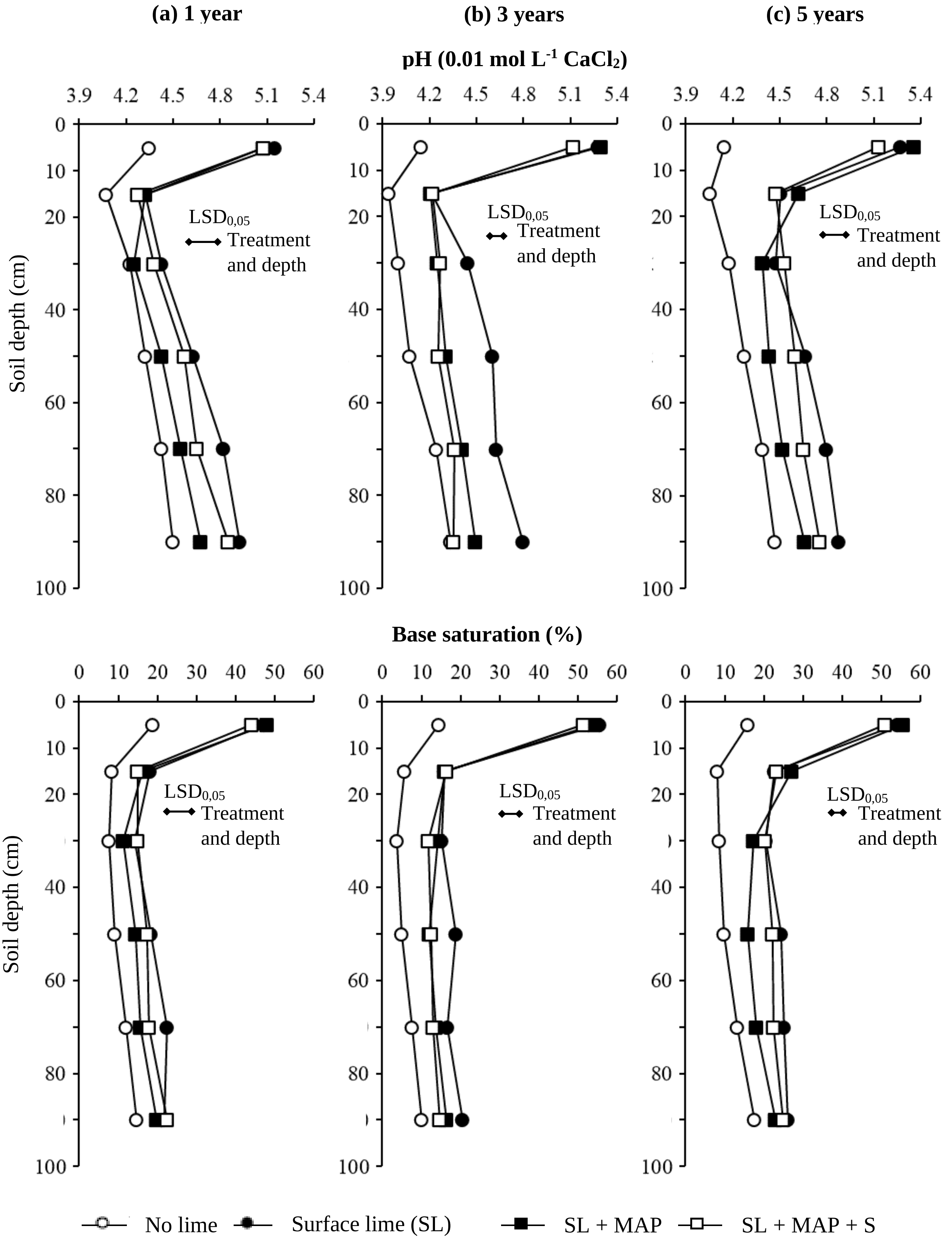

Figure 1.2 - Soil pH (0.01 mol L^{-1} $CaCl_2$) and base saturation in soil profiles of the treatments with no lime addition and with surface lime (SL), SL + MAP, and SL + MAP + elemental S. Lime was surface-applied in June 2016 and soils were sampled after (a) 1, (b) 3, and (c) 5 years of application. Horizontal bars represent the least significant difference (LSD) by the t-test (LSD) at *P* = 0.05.

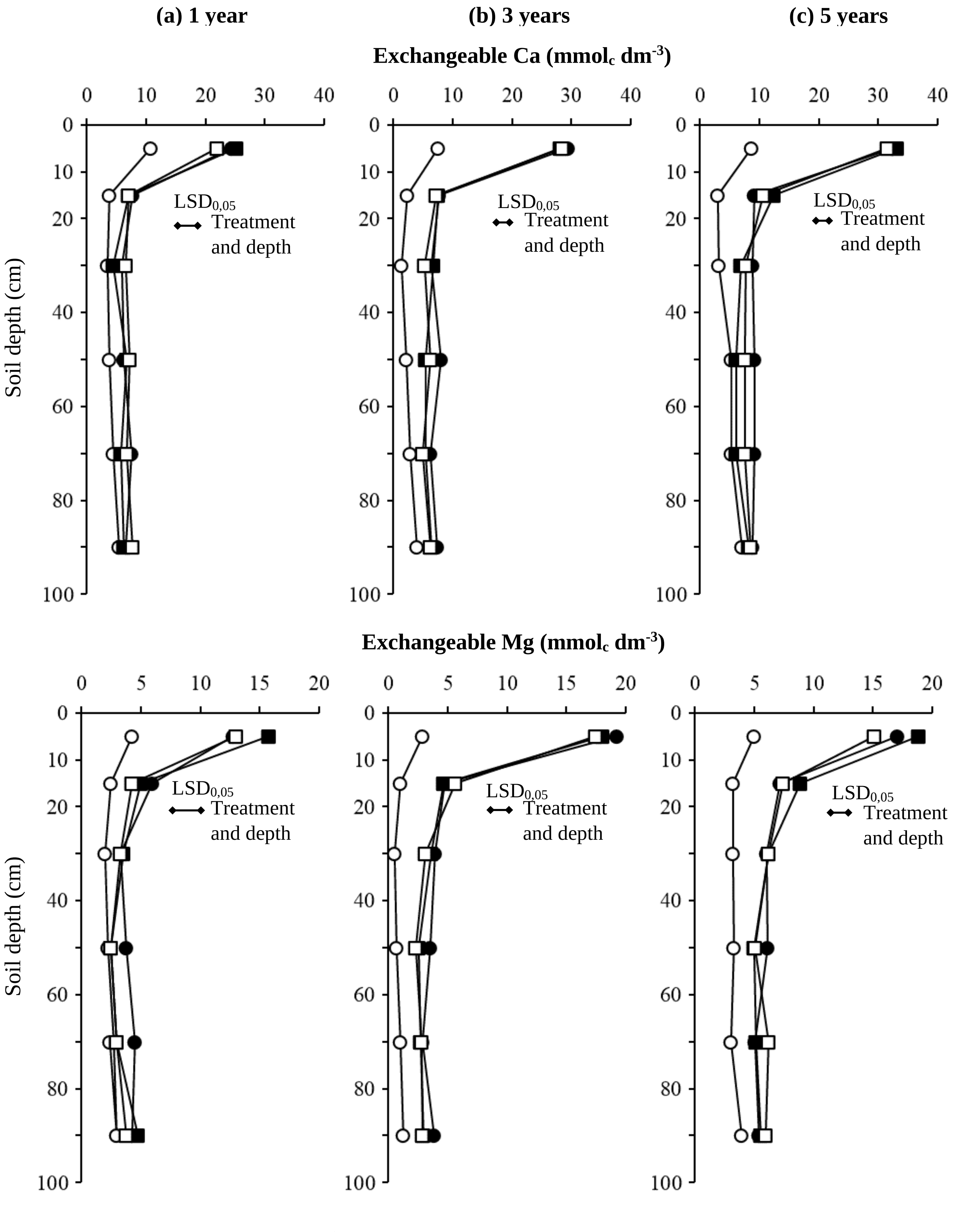

Figure 1.3 - Exchangeable Ca and Mg contents in soil profiles of the treatments with no lime addition and with surface lime (SL), SL + MAP, and SL + MAP + elemental S. Lime was surface-applied in June 2016 and soils were sampled after (a) 1, (b) 3, and (c) 5 years of application. Horizontal bars represent the least significant difference (LSD) by the t-test (LSD) at *P* = 0.05.

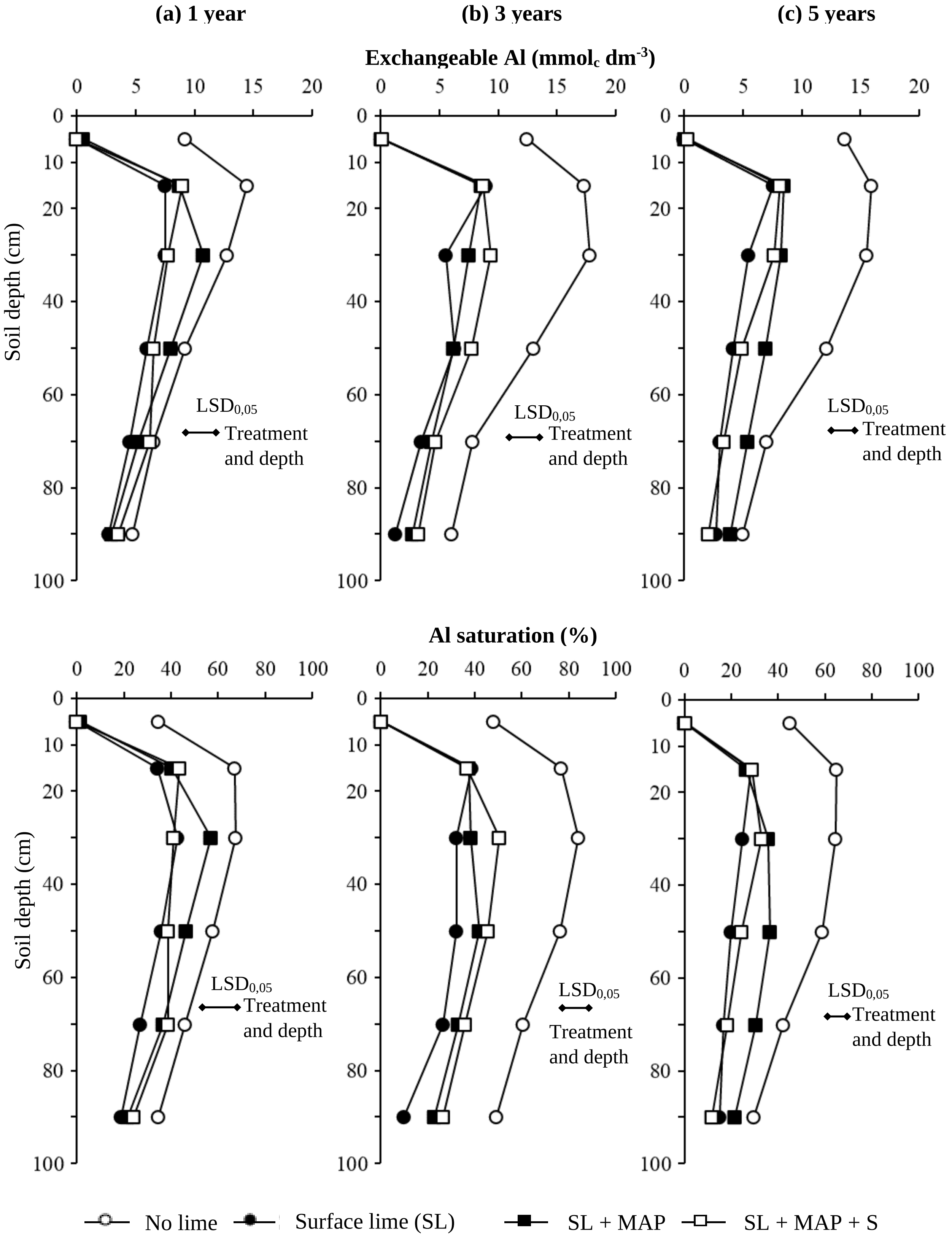

Figure 1.4 - Exchangeable Al content and Al saturation in soil profiles of the treatments with no lime addition and with surface lime (SL), SL + MAP, and SL + MAP + elemental S. Lime was surface-applied in June 2016 and soils were sampled after (a) 1, (b) 3, and (c) 5 years of application. Horizontal bars represent the least significant difference (LSD) by the t-test (LSD) at *P* = 0.05.

With the implementation of MAP, it was expected that during the solubilization of MAP, which contains about 11% nitrogen (N) in the form of ammonium (NH_4^+), nitrification can occur, leading to the formation of nitrate (NO_3^-) and release of protons (H^+) (MOREIRA e SIQUEIRA, 2006). This acidification at the surface can potentially increase the solubility of lime, leading to higher Ca and Mg content in the soil. The Ca^{2+} and Mg^{2+} ions released at the surface can potentially form complexes with NO_3^-, such as $Ca(NO_3)_2$ and $Mg(NO_3)_2$, which are neutral and can move along the soil profile. These complexes can potentially dissociate at depth, releasing NO_3^-, Ca^{2+}, and Mg^{2+}. When plant roots absorb N-NO_3^-, they release hydroxide ions (OH^-) to maintain equilibrium, which can result in an increase in pH in the rhizosphere. Furthermore, increasing the Ca and Mg content in the soil profile can reduce aluminum (Al) saturation, creating a more favorable environment for deep root growth. This hypothetical scenario suggests that the application of MAP in no-till systems could potentially enhance the efficiency of surface liming for soil acidity correction by promoting the movement of Ca, Mg, and NO_3^- ions along the soil profile, improving pH conditions in the rhizosphere, and reducing Al saturation. However, it is important to note that the effectiveness of this approach may be influenced by various factors such as soil type, climate, and management practices, and further research may be needed to validate these hypotheses in field conditions.

With the dynamics of elementary S in the soil, elemental S needs to be oxidized to sulfate (SO_4^{2-}) before it can be taken up by plants (HOROWITZ and MEURER, 2006; TAIZ et al., 2017). The oxidation of elemental S to SO_4^{2-} produces protons (H^+) in the surface layer, resulting in soil acidification (HOROWITZ and MEURER, 2006). The acidification caused by the continued use of elemental S can help dissolve the applied lime on the surface and increase the content of Ca and Mg in the soil. Cations (Ca^{2+} and Mg^{2+}) released on the surface can react with SO_4^{2-} and form complexes with Ca^{2+} ($CaSO_4^0$) and Mg^{2+} ($MgSO_4^0$). These complexes are neutral and can move along the soil profile. In deeper layers, these complexes can help reduce Al phytotoxicity by forming $AlSO_4^+$ and reducing Al saturation, similar to the effect of using gypsum to improve plant root environments (CAIRES and GUIMARÃES, 2018; CRUSCIOL et al., 2019; ZOCA and PENN, 2017).

However, the attributes related to soil acidity (pH, Al, Al saturation, Ca, Mg, and base saturation) were positively affected by surface lime but not improved when surface lime was associated with MAP and MAP + elemental S applications. Therefore, our hypothesis that surface lime with MAP and elemental S is an efficient strategy to improve the root environment along the soil profile under no-till was rejected.

The chemical changes observed in the soil during surface lime were consistent with other research findings, such as those of Churka Blum et al. (2013), who found an increase in soil pH and a decrease in exchangeable Al content to 80 cm depth, a movement and increase in exchangeable Ca to 80 cm depth, and exchangeable Mg to 200 cm depth after 13 years of surface lime application of 6 t ha^{-1}. Indeed, the surface application of lime in no-till effectively corrected the soil acidity below the application site (CAIRES et al., 2004, 2005, 2008, 2011; SORATTO and CRUSCIOL, 2008; VARGAS et al., 2019).

The movement of lime in the soil profile depends on several factors, such as the applied lime dose, reaction time, application method and frequency, climatic conditions, soil type, the addition of ammonia fertilizer, and cropping system (CAIRES et al., 2008). The main mechanisms of action of surface lime in correcting subsoil acidity mentioned in the literature for the no-till system (OLIVEIRA and PAVAN, 1996; AMARAL et al., 2004; BLEVINS et al., 1977; CAIRES et al., 2002; GASSEN and KOCHHANN, 1998; PEARSON et al., 1962; PETRERI and ANGHINONI, 2001; RHEINHEIMER et al., 2000), are the following: (i) vertical displacement of fine lime particles by continuous porosity in the soil profile; (ii) presence of canaliculi formed by dead roots and mesofauna galleries; (iii) formation and migration of $Ca(HCO_3)_2$ and $Mg(HCO_3)_2$ in the soil profile; (iv) formation of organic compounds released by the decomposition of plant residues; and (v) formation and migration of cation pairs (Ca^{2+} and Mg^{2+}) with organic or inorganic anions (NO_3^- and SO_4^{2-}).

Because the no-till system provides for accumulation of crop residues at the soil surface (FRANCHINI et al., 2003) and improves aggregation and aggregate stability, the finer lime particles can actually move inward and downward in the profile together with water infiltration and alleviate of subsoil acidity (AMARAL et al. 2004). It is worth noting that our study was conducted in a medium-texture Oxisol (260 to 320 g kg^{-1} clay along the profile) and that there was a lot of rainfall after surface lime application, with a cumulative rainfall of 2057 mm, 5687 mm, and 8042 mm after one, three, and five years of surface lime application, respectively (Table 1.3).a Although it is not possible to define the mechanism responsible for the improvement of acidity in the subsurface layers when surface lime is applied, our study confirms that surface lime causes a reduction of acidity not only in the surface layers but also in the subsurface layers, and excludes the possibility of including fertilizers with MAP and elemental S as a strategy to improve the efficiency of surface lime in correcting the acidity of the soil profile in a no-till system.

1.3.2 Wheat and soybean root growth

Wheat root length density was higher in 2018 in the SL and SL + MAP + S treatments at depths of 0-10 cm (P = 0.014), 20-40 cm (P = 0.019), and 80-100 cm (P = 0.087) (Table 1.4). In 2020, wheat root length density was higher in the SL + MAP + S treatment compared to the no lime treatment at a depth of 40-60 cm (P = 0.082) and in the SL and SL + MAP + S treatments compared to the no lime treatment at a depth of 80-100 cm (P = 0.053) (Table 1.4).

Soybean root length density, in 2018-2019, was higher in the SL + MAP + S treatment than in the without lime treatment only at the depth of 80-100 cm (P = 0.113) (Table 1.4). In 2020-2021, soybean root length density was higher in the SL + MAP + S treatment than in the no lime treatment at depths of 0-10 cm (P = 0.108), 10-20 cm (P = 0.067), 20-40 cm (P = 0.085), 40-60 cm (P = 0.082), and 60-80 cm (P = 0.053).

Surface lime alone and in combination with the application of MAP + elemental S stimulated root length density of wheat and soybean in the soil profile, and in soybean, root growth was most strongly stimulated by the treatment with SL + MAP + elemental S. Root growth of wheat may have been favored by increases in soil pH, base saturation, and exchangeable Ca and Mg content (Figures 1.2 and 1.3), and decreases in exchangeable Al and Al saturation (Figure 1.4). Soybean root growth may also have been favored by the increased availability of SO_4-S in the soil. In another study conducted in a no-till system, it was also observed that surface lime increased the root length density of wheat but did not change the root length density of soybeans (CAIRES et al., 2008).

Table 1.4 - Root length density of wheat (2018 and 2020) and soybean (2018–2019 and 2020–2021) grown in soil profiles of the treatments with no lime addition and with surface liming (SL), SL + MAP, and SL + MAP + elemental S.

Treatment	**Root growth density (cm cm^{-3})**			
	Wheat		**Soybean**	
	2018	**2020**	**2018–2019**	**2020–2021**
		0–10 cm		
No lime	8.07 b	9.77	8.19	6.31 b
Surface lime (SL)	12.45 a	10.44	7.91	6.57 ab
SL + MAP	7.56 b	11.71	8.62	7.83 ab
SL + MAP + S	11.34 a	12.90	9.34	8.88 a
P* > *F	0.014	0.384	0.422	0.108
CV (%)	14.6	23.2	14.3	19.6
		10–20 cm		
No lime	1.00	2.27	1.38	1.02 b
Surface lime (SL)	1.22	1.27	1.26	1.31 ab
SL + MAP	1.61	1.80	1.52	1.57 ab
SL + MAP + S	1.11	1.91	2.60	2.02 a
P* > *F	0.345	0.422	0.278	0.067
CV (%)	32.1	44.9	59.3	31.3
		20–40 cm		
No lime	0.27 b	0.49	0.70	0.56 b
Surface lime (SL)	0.68 a	0.92	0.61	0.65 b
SL + MAP	0.30 b	0.94	0.78	0.84 ab
SL + MAP + S	0.60 a	0.85	0.89	1.15 a
P* > *F	0.019	0.299	0.737	0.085
CV (%)	28.2	43.9	49.6	37.4
		40–60 cm		
No lime	0.39	0.66 b	0.70	0.69 b
Surface lime (SL)	0.47	1.26 ab	0.55	0.90 ab
SL + MAP	0.43	1.32 ab	0.79	1.01 ab
SL + MAP + S	0.42	1.50 a	0.75	1.30 a
P* > *F	0.495	0.082	0.858	0.082
CV (%)	15.0	35.2	60.7	29.8
		60–80 cm		
No lime	0.19	0.46	0.47	0.50 b
Surface lime (SL)	0.31	0.79	0.46	0.60 b
SL + MAP	0.23	0.77	0.67	0.71 ab
SL + MAP + S	0.20	0.86	0.74	1.07 a
P* > *F	0.709	0.268	0.141	0.053
CV (%)	54.7	39.1	31.8	35.8
		80–100 cm		
No lime	0.07 b	0.25 b	0.21 b	0.53
Surface lime (SL)	0.19 a	0.83 a	0.40 ab	0.53
SL + MAP	0.16 ab	0.65 ab	0.38 ab	0.62
SL + MAP + S	0.22 a	0.92 a	0.52 a	0.92
P* > *F	0.087	0.053	0.113	0.194
CV (%)	36.7	46.4	39.8	41.5

CV: coefficient of variation. Values followed by the same letter in a column within each growing season and depth are not significantly different at $P < 0.05$ (LSD test).

Wheat root relative length increased in 2018 in the 10-20 cm deep layer with the SL + MAP treatment compared with the SL + MAP + S treatment (Table 1.5). In 2020, the relative length of wheat roots was shorter ($P = 0.092$) in the treatment with SL compared with the treatment without lime at a depth of 10-20 cm and greater ($P = 0.087$) at a depth of 80-100 cm; at a depth of 40-60 cm, the relative length of wheat roots was greater in the treatments with SL, SL + MAP, and SL + MAP + S compared with the treatment without lime ($P = 0.050$).

In 2019-2020, the relative length of soybean roots along the soil profile was greater in the SL treatment than in the no-lime treatment at the 60-80 cm ($P = 0.056$) and 80-100 cm ($P = 0.067$) depths, and at the 80-100 cm depths the SL + MAP + S treatment along with the SL treatment also resulted in greater relative root length (Table 1.5). In 2020-2021, the relative length of soybean roots was not affected by the treatments.

On average, for both wheat and soybean crops, about 64% of the wheat root length was in the 0-10 cm layer and 36% in the 10-100 cm layer; in the case of soybean, about 54% of the root length was in the 0-10 cm layer and 46% in the 10-100 cm layer (Table 1.5). Although surface lime resulted in a slight improvement in the distribution of wheat and soybean root length along the soil profile, probably as a result of the softening of soil acidity in deeper layers (Figures 1.2, 1.3, and 1.4), wheat and soybean roots were mainly concentrated in the surface soil layer (0-10 cm).

Table 1.5 - Relative root length of wheat (2018 and 2020) and soybean (2018–2019 and 2020–2021) throughout the soil profile as affected by treatments with no lime addition and with surface lime (SL), SL + MAP, and SL + MAP + elemental S.

Treatment	**Relative root length (%)**			
	Wheat		**Soybean**	
	2018	**2020**	**2018–2019**	**2020–2021**
		0–10 cm		
No lime	72.46	61.75	59.89	53.90
Surface lime (SL)	72.82	54.19	57.90	49.46
SL + MAP	66.41	55.66	58.37	49.20
SL + MAP + S	74.00	56.55	59.89	45.54
P* > *F	0.253	0.678	0.790	0.640
CV (%)	6.2	16.0	16.1	18.1
		10–20 cm		
No lime	7.42 ab	14.33 a	9.80	8.37
Surface lime (SL)	7.44 ab	6.59 b	9.11	9.91
SL + MAP	14.15 a	8.91 ab	9.72	10.20
SL + MAP + S	7.05 b	8.08 ab	14.52	10.19
P* > *F	0.104	0.092	0.514	0.749
CV (%)	37.8	45.6	51.3	28.2
		20–40 cm		
No lime	4.87	6.18	10.25	9.39
Surface lime (SL)	8.02	9.51	8.85	9.75
SL + MAP	5.31	8.97	10.43	10.50
SL + MAP + S	7.77	7.28	10.07	11.55
P* > *F	0.363	0.352	0.950	0.770
CV (%)	38.4	34.5	43.0	30.0
		40–60 cm		
No lime	6.94	8.14 b	10.06	11.29
Surface lime (SL)	5.76	12.96 a	8.33	13.84
SL + MAP	7.51	12.71 a	10.20	12.67
SL + MAP + S	5.64	12.90 a	8.14	13.06
P* > *F	0.289	0.050	0.875	0.798
CV (%)	19.4	20.6	50.2	28.9
		60–80 cm		
No lime	3.47	6.19	6.86 b	8.37
Surface lime (SL)	3.61	8.16	9.90 a	9.03
SL + MAP	3.85	7.52	6.13 b	9.39
SL + MAP + S	2.58	7.29	8.07 ab	10.61
P* > *F	0.858	0.644	0.056	0.760
CV (%)	55.1	29.6	22.2	32.0
		80–100 cm		
No lime	1.34	3.40 b	3.14 b	8.67
Surface lime (SL)	2.35	8.59 a	5.91 a	8.01
SL + MAP	2.77	6.23 ab	5.14 ab	8.05
SL + MAP + S	2.96	7.90 ab	5.68 a	9.05
P* > *F	0.240	0.087	0.067	0.957
CV (%)	39.3	43.9	27.6	37.7

CV: coefficient of variation. Values followed by the same letter in a column within each growing season and depth are not significantly different at $P < 0.05$ (LSD test).

Root length of wheat and soybean per soil surface area up to a depth of 100 cm was significantly affected by treatments (Figure 1.5). For wheat grown in 2018, treatments with SL and SL + MAP + S increased root length per area by about 43% compared to treatments without lime and with SL + MAP. In wheat grown in 2020, treatments with SL + MAP and SL + MAP + S increased root length per area by about 40% compared to treatments without lime (Figure 1.5a). In soybean, the SL + MAP + S treatment increased root length per area by about 30% compared to treatments without lime and SL in 2018-2019. For soybeans grown in 2020-2021, root length per area was about 33% greater for the SL + MAP treatment and 67% greater for the SL + MAP + S treatment compared to the no lime treatment (Figure 1.5b).

In general, the root length of wheat and soybean per soil surface area up to a depth of 100 cm was always greater when treated with surface lime combined with fertilization with MAP + elemental S. In addition to lime softening soil acidity and promoting root growth, applications of MAP and elemental S may have promoted root growth due to the effect of the fertilizers on N, P, and S availability.

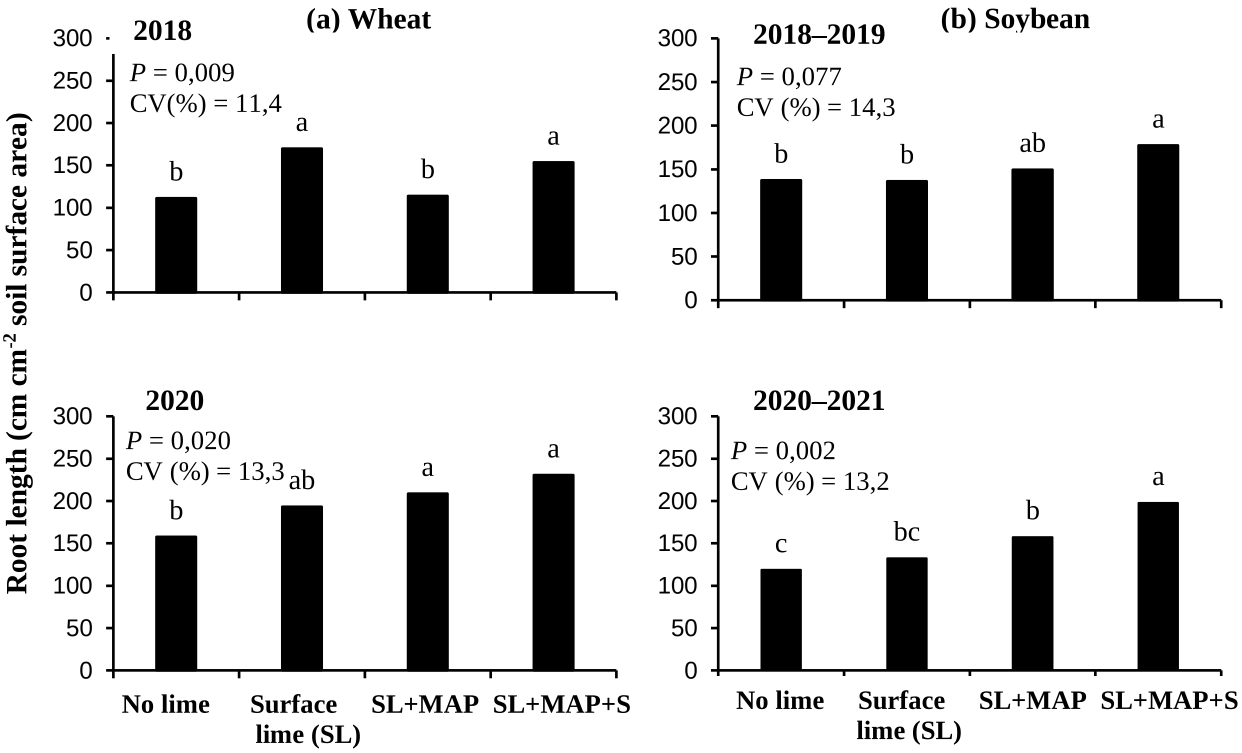

Figure 1.5 - Wheat (a) and soybean (b) root length per unit soil surface area to a depth of 100 cm as affected by treatments with no lime addition and with surface lime (SL), SL + MAP, and SL + MAP + elemental S. Values followed by the same letter in columns within each growing season are not significantly different at $P < 0.05$ (LSD test).

1.3.3 Plant nutritional status

The contents of N, P, K, Ca, Mg, and S in wheat leaf tissue remained within or slightly above the range considered adequate for the crop (Table 1.6). Only leaf K content in the 2016 season, Ca content in 2020, and Mg content in all seasons in the no-lime treatment was below the adequate range (van RAIJ, 2011).

In the 2016 season, treatment with SL provided higher levels of Mg in wheat leaf tissue compared to treatment without lime, regardless of the application of MAP and elemental S (Table 1.6). Treatment with SL + MAP + S resulted in higher S concentrations in wheat leaves compared to treatments without lime and SL + MAP (P = 0.089).

In wheat grown in 2017, the SL treatment provided higher leaf tissue N concentration than the SL + MAP treatment (Table 1.6). Mg content in leaf tissue was higher in the treatment with SL than in the treatment without lime, regardless of the association with MAP and MAP + elemental S. Treatment with SL + MAP + elemental S resulted in higher leaf S content compared to treatments without lime and with SL and SL + MAP.

In 2018, Ca concentration in wheat leaf tissue was higher in treatments with SL + MAP and SL + MAP + elemental S than in treatments without lime and with SL (Table 1.6). Compared with the treatment without lime, SL increased the Mg content in leaves, and the Mg increase was even greater when MAP and MAP + elemental S were added. The S content in leaves was higher in the treatment with SL + MAP + elemental S than in the other treatments.

In the 2019 wheat crop, there was no significant change in foliar diagnosis in treatments with SL, SL + MAP, and SL + MAP + elemental S (Table 1.6).

MAP fertilization increased the leaf P content of wheat grown in 2020 (Table 1.6). SL combined with the applications of MAP and MAP + elemental S resulted in higher Ca and Mg contents in leaves compared with the treatment without lime.

The increase in Ca and Mg concentrations in wheat leaf tissue with SL was certainly due to the increase in exchangeable Ca and Mg content in the soil caused by the application of dolomitic lime (Figure 1.6). SL also decreased soil acidity (Figure 1.1), and this effect may have caused an increase in leaf N concentration. Throughout the 2019 wheat crop development cycle, monthly rainfall was well below the historical average for the region (Table 1.2), and the lack of rain may have altered the response of leaf nutrient levels.

Table 1.6 - Nutrient concentrations in wheat leaves as affected by treatments with no lime addition and with surface lime (SL), SL + MAP, and SL + MAP + elemental S under a no-till system in southern Brazil.

Treatment	**Leaf nutrient concentrations of wheat (g kg^{-1})**					
	N	**P**	**K**	**Ca**	**Mg**	**S**
	------------------- g kg^{-1} -------------------					
	- - - - - - - - - - Wheat 2016 - - - - - - - - - -					
No lime	37.94	4.21	12.19	3.58	1.19 b	2.63 b
Surface lime (SL)	38.36	3.81	11.69	4.71	1.72 a	2.87 ab
SL + MAP	42.21	4.13	11.69	4.67	1.75 a	2.51 b
SL + MAP + S	41.93	3.84	11.06	4.73	1.83 a	3.17 a
$P > F$	0.584	0.279	0.132	0.085	0.008	0.089
CV (%)	13.7	8.2	5.1	14.6	13.1	12.2
	- - - - - - - - - - Wheat 2017 - - - - - - - - - -					
No lime	34.37 ab	4.00	20.53	3.62	1.21 b	1.89 b
Surface lime (SL)	35.77 a	3.91	19.46	3.81	1.82 a	1.90 b
SL + MAP	31.99 b	4.35	21.33	3.80	1.91 a	2.04 b
SL + MAP + S	33.46 ab	4.38	20.00	4.26	2.25 a	2.44 a
$P > F$	0.036	0.170	0.203	0.170	0.006	0.017
CV (%)	4.5	8.0	5.7	9.6	16.6	10.3
	- - - - - - - - - - Wheat 2018 - - - - - - - - - -					
No lime	40.60	5.17	21.73	2.61 b	0.99 c	1.86 b
Surface lime (SL)	40.32	4.81	19.47	2.87 b	1.69 b	1.95 b
SL + MAP	40.39	5.08	19.86	3.54 a	2.01 a	1.99 b
SL + MAP + S	42.63	5.02	19.87	3.65 a	2.15 a	2.67 a
$P > F$	0.187	0.286	0.157	0.008	<0.001	0.005
CV (%)	3.8	5.0	6.8	11.5	9.3	11.9
	- - - - - - - - - - Wheat 2019 - - - - - - - - - -					
No lime	44.43	4.26	30.10	3.50	1.68	3.86
Surface lime (SL)	43.24	4.23	27.34	3.31	1.94	3.92
SL + MAP	42.30	4.31	28.45	2.82	1.91	3.92
SL + MAP + S	45.12	4.07	28.45	2.71	1.87	4.09
$P > F$	0.502	0.840	0.543	0.061	0.124	0.863
CV (%)	6.2	9.2	9.1	13.1	8.0	10.4
	- - - - - - - - - - Wheat 2020 - - - - - - - - - -					
No lime	32.70	3.33 b	36.94	2.39 c	0.94 c	2.33
Surface lime (SL)	30.38	3.25 b	32.01	2.60 bc	1.49 b	2.25
SL + MAP	33.32	4.49 a	33.15	2.80 ab	1.68 ab	2.45
SL + MAP + S	31.87	4.14 a	32.89	2.98 a	1.79 a	2.69
$P > F$	0.177	0.001	0.159	0.027	<0.001	0.367
CV (%)	5.5	9.1	8.7	8.4	8.2	14.5
Adequate range[1]	20–34	2.1–3.3	15–30	2.5–10	1.5-4.0	1.5–3.0

CV: coefficient of variation. Values followed by the same letter in a column within each growing season are not significantly different at $P < 0.05$ (LSD test). [1]van Raij (2011).

The levels of N, P, K, and Ca in soybean leaf tissue were within or slightly above levels considered appropriate for the crop in all seasons studied (Table 1.7). Leaf Mg content, especially in treatments without lime, and S content, especially in treatments without application of elemental S, were slightly below appropriate levels in 2017-2018, 2018-2019, and 2019-2020 harvests (van RAIJ, 2011).

The nutrient content of soybean leaves grown in 2016-2017 was not significantly changed by the treatments (Table 1.7). In subsequent harvests, the applied treatments improved the nutrient content of soybeans.

For soybeans grown in 2017-2018, the SL and SL + MAP treatments provided higher leaf tissue N content than the no-lime treatment, and the SL + MAP + elemental S treatment provided even higher leaf N content (Table 1.7). Compared to the treatment without lime, leaf P content was higher in the SL + MAP treatment and even higher in the SL + MAP + elemental S treatment. The Ca content of leaves was higher in the treatments with SL and SL + MAP than in the treatment without lime. Regardless of fertilization with MAP and MAP + elemental S, surface lime provided higher Mg concentration in leaves compared to the treatment without lime. The S content in the leaves was higher in the treatment with SL + MAP + elemental S than in the treatment without lime.

In the 2018-2019 soybean crop, treatments with SL, SL + MAP, and SL + MAP + elemental S provided higher levels of N, Ca, and Mg in leaf tissue compared to treatments without lime (Table 1.7). The treatments with SL + MAP and SL + MAP + elemental S provided higher levels of P and S in leaves compared to the treatments without lime and with SL. K content in leaves was lower in the treatment with SL than in the treatment without lime, regardless of fertilization with MAP and MAP + elemental S.

In 2019-2020, N and Mg content in soybean leaf tissue was higher in treatments with SL, SL + MAP, and SL + MAP + elemental S than in treatments without lime (Table 1.7). Leaf P content was higher in the treatment with SL than in the treatment without lime and even higher in the treatment with SL + MAP + elemental S. The treatment with SL + MAP + elemental S also had higher Ca content than the treatment without lime and higher S content than the other treatments.

Table 1.7 - Nutrient concentrations in soybean leaves as affected by treatments with no lime addition and with surface lime (SL), SL + MAP, and SL + MAP + elemental S under a no-till system in southern Brazil.

Treatment	**Leaf nutrient concentrations of soybean (g kg^{-1})**					
	N	**P**	**K**	**Ca**	**Mg**	**S**
	---------------------------------- g kg^{-1} --------------------------------- ---					
	- - - - - - - - - - - - - - - - Soybean 2016–2017 - - - - - - - - - - - - - - - -					
No lime	64.40	8.01	27.34	9.29	3.51	2.46
Surface lime (SL)	63.14	8.11	26.20	9.53	3.93	2.82
SL + MAP	65.38	8.04	26.58	9.84	3.90	2.62
SL + MAP + S	59.92	7.86	25.07	8.99	3.73	2.60
$P > F$	0.218	0.606	0.200	0.656	0.328	0.111
CV (%)	5.6	3.4	5.2	10.2	8.9	7.1
	- - - - - - - - - - - - - - - - Soybean 2017–2018 - - - - - - - - - - - - - - - -					
No lime	40.11 c	5.50 c	28.23	5.09 b	2.16 b	1.75 b
Surface lime (SL)	45.29 b	5.74 bc	28.10	6.26 a	2.86 a	1.82 b
SL + MAP	44.87 b	6.15 b	27.85	5.90 a	2.96 a	1.85 b
SL + MAP + S	49.07 a	6.73 a	29.74	5.81 ab	2.93 a	2.06 a
$P > F$	<0.001	0.002	0.453	0.034	<0.001	0.007
CV (%)	4.1	5.3	6.1	8.0	5.5	5.0
	- - - - - - - - - - - - - - - - Soybean 2018–2019 - - - - - - - - - - - - - - - -					
No lime	42.98 b	4.56 b	23.05 a	6.22 b	2.58 b	1.66 b
Surface lime (SL)	48.86 a	4.41 b	20.15 b	7.53 a	3.25 a	1.67 b
SL + MAP	49.91 a	5.08 a	20.40 b	7.83 a	3.21 a	2.16 a
SL + MAP + S	51.87 a	5.29 a	20.15 b	7.67 a	3.10 a	1.98 a
$P > F$	0.001	<0.001	0.014	0.001	<0.001	0.008
CV (%)	4.3	4.2	5.4	5.4	5.4	9.8
	- - - - - - - - - - - - - - - - Soybean 2019–2020 - - - - - - - - - - - - - - - -					
No lime	43.22 b	5.46 c	31.38	5.81 b	2.52 b	1.27 b
Surface lime (SL)	49.53 a	5.82 b	32.14	7.14 ab	3.62 a	1.33 b
SL + MAP	50.88 a	5.93 ab	31.88	7.11 ab	3.55 a	1.34 b
SL + MAP + S	51.48 a	6.19 a	32.14	7.98 a	3.68 a	1.69 a
$P > F$	0.034	0.001	0.734	0.043	<0.001	0.024
CV (%)	7.3	2.9	3.4	12.6	6.8	11.9
	- - - - - - - - - - - - - - - - Soybean 2020–2021 - - - - - - - - - - - - - - - -					
No lime	42.67 b	5.36 c	25.95	6.31	3.15 b	2.79
Surface lime (SL)	49.70 a	5.86 bc	25.45	6.73	3.59 a	3.25
SL + MAP	51.74 a	6.36 ab	26.84	7.17	3.63 a	3.25
SL + MAP + S	52.36 a	6.78 a	26.96	7.17	3.56 a	3.72
$P > F$	0.003	0.018	0.566	0.149	0.025	0.123
CV (%)	5.8	8.5	6.5	8.0	5.7	14.6
Adequate range[1]	40–54	2.5–5.0	17–25	4–20	3–10	2.1–4.0

CV: coefficient of variation. Values followed by the same letter in a column within each growing season are not significantly different at $P < 0.05$ (LSD test). [1]van Raij (2011).

In the 2020-2021 soybean crop, the treatments with SL, SL + MAP, and SL + MAP + elemental S provided higher levels of N and Mg in leaf tissue compared with the treatment without lime, and leaf P content was higher in the treatments with SL and SL + MAP compared with the treatment without lime (Table 1.7).

Softening of soil acidity by surface lime (Figures 1.2, 1.3, and 1.4) improved N, Ca, and Mg supply to soybeans (Table 1.7). Fertilization with MAP + elemental S associated with surface lime favored the uptake of other nutrients such as N, P, and Ca, in addition to increasing S content in leaf tissue. The increase in leaf Mg content may have been one of the main factors in increasing soybean grain yield with surface liming (Figure 1.7), as leaf Mg content was below the level considered adequate for the crop in three of the five harvests evaluated, especially in the no-lime treatment (Table 1.7).

1.3.4 Crop grain yield

Wheat grain yields were significantly affected by treatments in the five seasons evaluated (Figure 1.6). Average yields were 3868, 1249, 2013, 2150, and 2477 kg ha^{-1} in the 2016, 2017, 2018, 2019, and 2020 harvests, respectively. Wheat yield in 2016 was 22% higher than the Brazilian average (CONAB, 2022) due to excellent weather conditions, especially adequate rainfall distribution during the crop development cycle (Table 1.2). Subsequent wheat crops lacked rainfall during the crop cycle, which affected productive potential and resulted in yields that were below the Brazilian average (CONAB, 2022).

Wheat grain yield in 2016 was significantly higher in the treatment with SL + MAP + elemental S, resulting in an increase in grain yield of about 39% (1256 kg ha^{-1}) compared to the control treatment (Figure 1.6a). In 2017, the treatments with SL and SL + MAP + elemental S provided 56% (509 kg ha^{-1}) higher wheat yield than the treatment without lime (Figure 1.6b). In the 2018 season, treatment with SL resulted in an increase in wheat grain yield of about 22% compared to treatment without lime (355 kg ha^{-1}), while treatment with SL + MAP + elemental S resulted in an increase in wheat grain yield of the order of 44% (714 kg ha^{-1}) and 18% (358 kg ha^{-1}) compared to treatments without lime and with SL, respectively (Figure 1.6c). For wheat grown in 2019, treatments with SL + MAP and SL + MAP + elemental S resulted in an increase in wheat grain yield of about 87% (1304 kg ha^{-1}) compared to the average of treatments without lime and with SL (Figure 1.7d). In 2020, wheat grain yield practically doubled with SL compared to the treatment without lime, but the treatments with SL + MAP and SL + MAP +

elemental S resulted in an even greater increase in wheat grain yield on the order of 160% (1774 kg ha^{-1}) and 30% (670 kg ha^{-1}) compared to the treatments without lime and SL, respectively (Figure 1.7e). The cumulative grain yield of wheat in the five harvests (2016, 2017, 2018, 2019, and 2020) was about 40% (3237 kg ha^{-1}) higher with SL compared to the treatment without lime SL, and the treatment with SL + MAP + elemental S provided an increase of about 74% (5935 kg ha^{-1}) and 24% (2698 kg ha^{-1}) compared to the treatments without lime and with SL, respectively (Figure 1.6f). Cumulative grain yield of wheat in the SL + MAP treatment was not significantly different from the SL and SL + MAP + elemental S treatments.

Considering that the average productivity of wheat grains in the treatment without liming was 1608 kg ha^{-1} in the five years of cultivation, only surface lime provided a gain of two harvests (3237 kg ha^{-1}) in five years (Figure 1.6). When surface liming was combined with MAP + elemental S fertilization, there was a gain of almost four wheat harvests (5935 kg ha^{-1}) in five years compared to the treatment without liming.

The use of MAP and elemental S together with surface lime was important in increasing wheat grain yield as early as the first harvest in 2016 (Figure 1.6a). Lime alone increased wheat grain yield starting in the second crop of 2017 (Figure 1.6b), and the application of MAP, without the combination with elemental S, increased wheat grain yield in the fourth (2019) and fifth (2020) crops (Figures 1.6d and 1.6e). MAP and fertilization with elemental S in combination with surface lime provided an increase in wheat grain yield compared to surface lime in the third (2018), fourth (2019), and fifth (2020) harvests (Figures 1.6c, 1.6d, and 1.6e).

The five soybean crops evaluated produced average grain yields of 3937, 3771, 3170, 3721, and 4027 kg ha^{-1} in 2016-2017, 2017-2018, 2018-2019, 2019-2020, and 2020-2021, respectively (Figure 1.7). In the 2018-2019 crop alone, soybean grain yield was 167 kg ha^{-1}, slightly lower than the national average. In the other harvests, soybean grain yields each year ranged from 8% (267 kg ha^{-1}) to 16% (545 kg ha^{-1}) above the national average (CONAB, 2022).

Soybean grain yields in the SL and SL + MAP treatments did not differ from each other in 2016-2017 and were about 9% (330 kg ha^{-1}) higher than in the no lime treatment (Figure 1.7a). Soybean yields of treatments with SL, SL + MAP, and SL + MAP + elemental S did not differ from each other in 2017-2018 (Figure 1.7b), 2018-2019 (Figure 1.7c), 2019-2020 (Figure 1.7d) and 2020-2021 (Figure 1.7e) harvests, but were about 61% (1582 kg ha^{-1}), 91% (1715 kg ha^{-1}), 36% (1045 kg ha^{-1}) and 17% (622 kg ha^{-1}) higher than in the treatment without lime. The cumulative yield of soybean in the five harvests (2016-2017, 2017-2018, 2018-2019, 2019-2020, and 2020-2021) was about 36% (5247 kg ha^{-1}) higher in the treatments with SL, SL + MAP, and SL + MAP + elemental S than in the treatment without lime (Figure 1.7f). The treatments with SL, SL + MAP, and SL + MAP + elemental S showed similar performance in cumulative soybean grain yield.

Considering that the average productivity of soybeans in the five consecutive harvests was 2939 kg ha^{-1} in the treatment without liming, the correction of soil acidity by surface liming, regardless of fertilization with MAP and elemental S, provided a gain of almost two harvests in the same period (5247 kg ha^{-1})

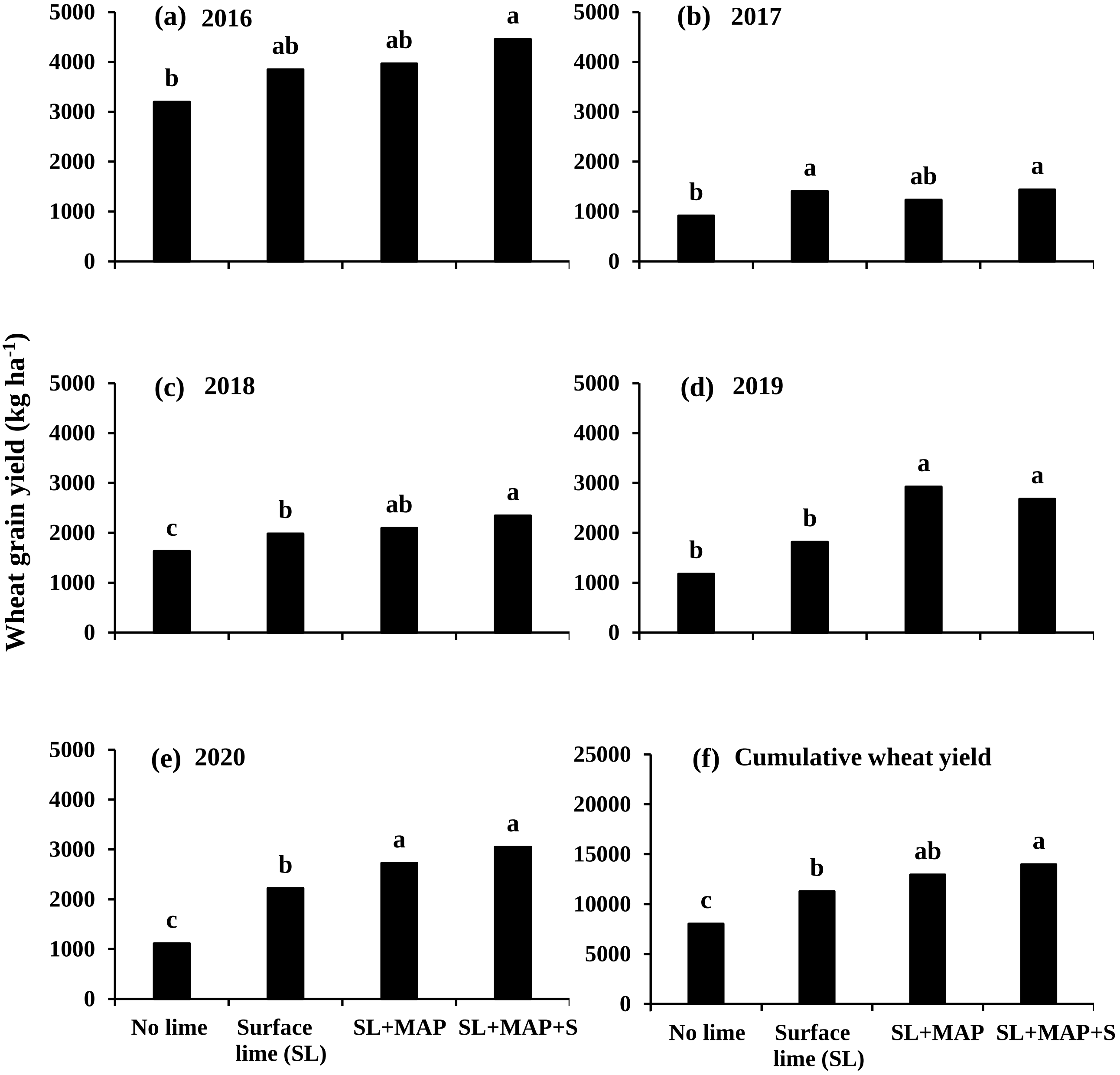

Figure 1.6 - Influence of treatments with no lime and with surface lime (SL), SL + MAP, and SL + MAP + elemental S on wheat grain yields in (a) 2016, (b) 2017, (c) 2018, (d) 2019, (e) 2020 and (f) in the five cumulative harvests. Values followed by the same letter in columns within each growing season are not significantly different at $P < 0.05$ (LSD test).

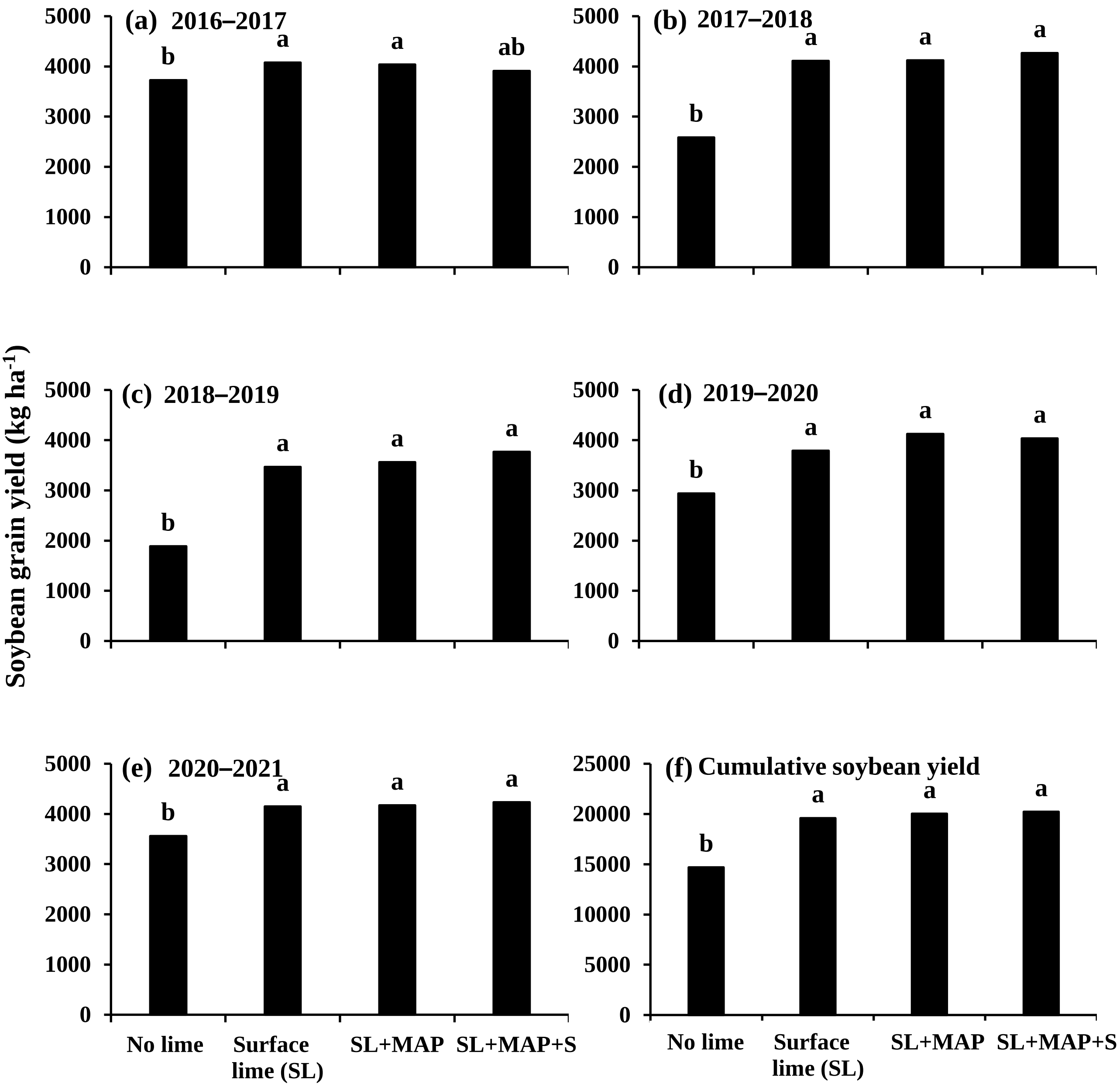

Figure 1.7 - Influence of treatments with no lime and with surface lime (SL), SL + MAP, and SL + MAP + elemental S on soybean grain yields in (a) 2016–2017, (b) 2017–2018, (c) 2018–2019, (d) 2019–2020, (e) 2020–2021 and (f) in the five cumulative harvests. Values followed by the same letter in columns within each growing season are not significantly different at $P < 0.05$ (LSD test).

1.3.5 Correlations of soil chemical properties with root growth and grain yield

Wheat grain yield was positively correlated with root length per area to a depth of 100 cm (Figure 1.8a). This shows that wheat grain yield increased by 8.43 kg ha^{-1} for each increment of 1 cm cm^{-2} root. In contrast, soybean grain yield did not show a significant correlation with root length per area (Figure 1.8b). These results are consistent with those of Caires et al. (2008), who observed that root length per area was positively correlated with wheat grain yield, but not with corn and soybean grain yield. These results could be related to the fact that wheat yield was more affected by the lack of rain during its development than soybean yield (Table 1.2).

Wheat root length per soil surface area to a depth of 100 cm was positively correlated with soil pH, exchangeable Ca^{2+} content, and base saturation, and negatively correlated with exchangeable Al^{3+} content and Al^{3+} saturation in all layers of the soil profile (Table 1.8). Exchangeable Mg^{2+} content also correlated positively with wheat root length per soil surface area in the 10-100 cm layers. In soybean crop, root length per soil surface area up to a depth of 100 cm correlated positively with soil pH, exchangeable Ca^{2+} content, and base saturation, and negatively with exchangeable Al^{3+} content and Al^{3+} saturation, only in the layers of 0-10 and 10-20 cm depth; Mg^{2+} content in the layer of 10-20 cm also showed a significant correlation with soybean root length. Wheat and soybean grain yields correlated positively with soil pH, exchangeable Ca^{2+} and Mg^{2+} content, and base saturation, and negatively with exchangeable Al^{3+} content and Al^{3+} saturation in all soil profile (Table 1.8).

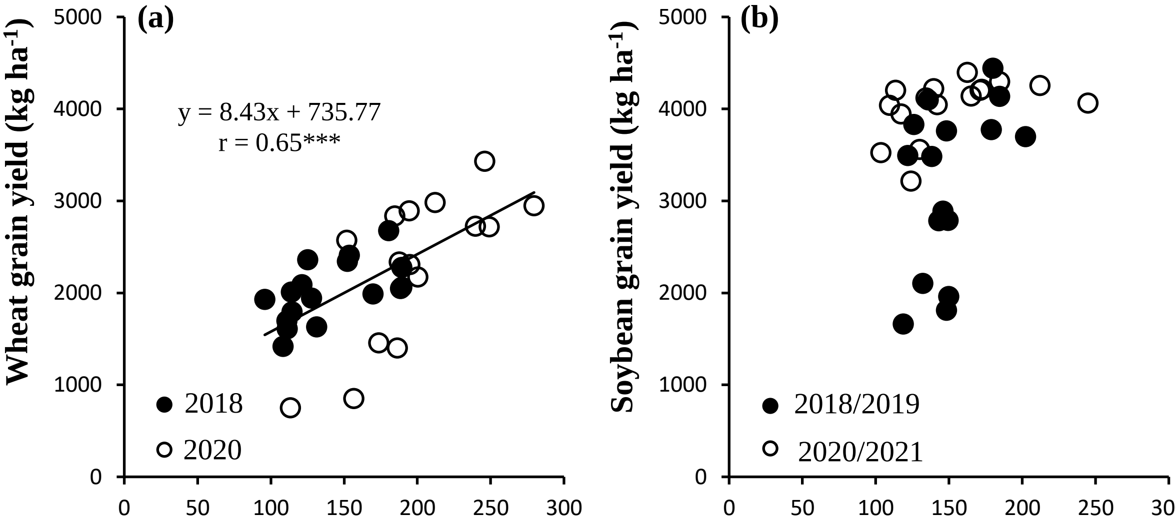

Figure 1.8 - Crop grain yield of (a) wheat and (b) soybean as affected by root length per area per unit soil surface aera to a depth of 100 cm. ***: $P < 0.001$.

Our study showed that surface lime reduced soil acidity to a depth of 100 cm and resulted in an increase in pH, exchangeable Ca^{2+} and Mg^{2+} content, and base saturation, and a decrease in exchangeable Al^{3+} content and Al^{3+} saturation. The effects of surface lime in correcting soil acidity were evident after one year of lime application, intensified after three years, and persisted up to five years after application. Consequently, surface lime increased root growth, improved plant nutrition, and increased grain yield. When MAP or MAP + elemental S was associated with surface lime, there was no advance in acidity correction front or increase in Ca^{2+} and Mg^{2+} availability in the soil profile compared to surface lime alone. Thus, if the use of MAP or MAP + elemental S improved plant nutrition or increased grain yield, it was because of its fertilizing effect and not as an accelerator of the reaction of the surface lime.

Table 1.8 - Correlation coefficients (*Pearson*) between some soil properties related to acidity and wheat and soybean root length per unit soil surface area to a depth of 100 cm and grain yield.

Soil chemical properties	**Depth (cm)**	**Root length per unit soil surface area**		**Grain yield**	
		Wheat	**Soybean**	**Wheat**	**Soybean**
	0–10				
pH 0.01 mol L^{-1} $CaCl_2$		0.42*	0.38*	0.71***	0.59***
Exchangeable Ca^{2+}		0.53**	0.42*	0.74***	0.66***
Exchangeable Mg^{2+}		0.32ns	0.24ns	0.59***	0.62***
Exchangeable Al^{3+}		-0.41*	-0.39*	-0.75***	-0.60***
Al^{3+} saturation		-0.43*	-0.39*	-0.73***	-0.65***
Base saturation		0.41*	0.37*	0.69***	0.60***
	10–20				
pH 0.01 mol L^{-1} $CaCl_2$		0.76***	0.43*	0.75***	0.68***
Exchangeable Ca^{2+}		0.68***	0.48**	0.81***	0.71***
Exchangeable Mg^{2+}		0.74***	0.38*	0.76***	0.78***
Exchangeable Al^{3+}		-0.49**	-0.39*	-0.73***	-0.59***
Al^{3+} saturation		-0.61***	-0.43*	-0.78***	-0.71***
Base saturation		0.73***	0.48**	0.82***	0.73***
	20–40				
pH 0.01 mol L^{-1} $CaCl_2$		0.68***	0.23ns	0.63***	0.65***
Exchangeable Ca^{2+}		0.55**	0.32ns	0.65***	0.73***
Exchangeable Mg^{2+}		0.72***	0.26ns	0.65***	0.81***
Exchangeable Al^{3+}		-0.39*	-0.21ns	-0.58***	-0.61***
Al^{3+} saturation		-0.52**	-0.22ns	-0.61***	-0.74***
Base saturation		0.64***	0.34ns	0.70***	0.74***
	40–60				
pH 0.01 mol L^{-1} $CaCl_2$		0.68***	0.06ns	0.51**	0.58***
Exchangeable Ca^{2+}		0.67***	0.25ns	0.58***	0.67***
Exchangeable Mg^{2+}		0.72***	0.03ns	0.47**	0.72***
Exchangeable Al^{3+}		-0.51**	-0.28ns	-0.65***	-0.65***
Al^{3+} saturation		-0.62***	-0.20ns	-0.58***	-0.74***
Base saturation		0.69***	0.18ns	0.58***	0.65***
	60–80				
pH 0.01 mol L^{-1} $CaCl_2$		0.65***	0.03ns	0.48**	0.55**
Exchangeable Ca^{2+}		0.54**	0.10ns	0.38*	0.64***
Exchangeable Mg^{2+}		0.73***	0.34ns	0.66***	0.73***
Exchangeable Al^{3+}		-0.43*	-0.20ns	-0.56***	-0.52**
Al^{3+} saturation		-0.60***	-0.22ns	-0.57***	-0.70***
Base saturation		0.66***	0.20ns	0.54**	0.73***
	80–100				
pH 0.01 mol L^{-1} $CaCl_2$		0.58***	0.01ns	0.45**	0.57***
Exchangeable Ca^{2+}		0.53**	0.19ns	0.42*	0.65***
Exchangeable Mg^{2+}		0.75***	0.14ns	0.56***	0.74***
Exchangeable Al^{3+}		-0.37*	-0.27ns	-0.53**	-0.50**
Al^{3+} saturation		-0.55**	-0.25ns	-0.53**	-0.67***
Base saturation		0.66***	0.16ns	0.53**	0.70***

ns: non-significant; *: $P < 0.05$; **: $P < 0.01$, and ***: $P < 0.001$.

1.4 CONCLUSIONS

Surface application of dolomitic lime in an acidic Latosol under no-till in a region with an average annual rainfall of around 1550 mm reduced soil acidity up to a depth of 100 cm. Correction of soil acidity by surface lime occurred to a greater extent in the 0-10 cm layer and a lesser extent in the 10-100 cm layer. The effects of surface lime were evident after one year, intensified after 3 years, and persisted for up to 5 years after application.

Fertilization with MAP and MAP + elemental S associated with surface lime did not accelerate the reaction of surface-applied lime in correcting the acidity of the soil profile and showed lesser or equal effects to isolated surface lime.

Improving fertility in the soil profile by surface lime favored root growth of wheat more than soybean, although it increased productivity of both crops. Root length per soil surface area up to a depth of 100 cm showed a close correlation with wheat grain yield but not with soybean grain yield. This effect may be related to the fact that the wheat crop was more affected by the lack of rain than the soybean crop during its development.

Surface lime resulted in an average increase in wheat grain yield of around 40% when applied alone and 74% when associated with MAP + elemental S. Soybean grain yield increased by an average of 36% with surface lime, regardless of the use of MAP and MAP + elemental S. The wheat crop responded more strongly to the addition of soil P and S than the soybean crop. The increase in leaf Mg content may have been one of the major factors in the increase in soybean grain yield with surface liming.

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CHAPTER 2: SURFACE LIME COMBINED WITH PHOSPHOGYPSUM OR SINGLE SUPERPHOSPHATE IN A WHEAT-SOYBEAN CROPPING SYSTEM UNDER NO-TILL

Abstract: In Brazil, soils are commonly highly weathered and have high acidity, low levels of calcium (Ca), magnesium (Mg), potassium (K), and phosphorus (P) in addition to toxic levels of aluminum (Al) and manganese (Mn). At the same time Brazil is the world's largest producer of soybean and the fifth largest producer of wheat in the Americas, making it a key country from which it is hoped to increase food production to ensure global food security. Since the major challenges of this century are to ensure global food security and avoid production losses caused by climate change leading to irregular distribution of rainfall, sustainable and efficient management strategies to improve fertility across the soil profile are needed to increase the stability of production systems. Thus, our study had the following objectives: (i) to evaluate the reduction in soil acidity and chemical improvements along the soil profile after surface application of lime in a no-till system, (ii) to check whether combining surface lime with phosphogypsum (PG) or single superphosphate (SSP) improves the effect of surface lime in alleviating acidity along the soil profile, (iii) to observe whether the application of SSP by broadcast or in the sowing furrow has the same effect as PG in the chemical improvements of the soil profile, and (iv) to examine the effects of combining surface lime with PG or SSP by broadcast or in the sowing furrow on leaf nutrient contents and grain yields of wheat and soybean crops. A randomized complete block design was used with five treatments and four replications. The treatments were: control (without lime), surface application of lime (SL), SL + application of SSP by broadcast (SL + SSP_B), SL + application of SSP in the sowing furrow (SL + SSP_F), and SL + PG. The study was conducted from 2016 to 2021. Within this period, a wheat (*Triticum aestivum* L.)-soybean [*Glycine max* (L.) Merrill] succession was grown for five cycles. Soil chemical properties to a depth of 1.00 m, leaf nutrient contents, and grain yields of wheat and soybean were evaluated. Surface application of lime increased short- and medium-term pH, Ca, Mg, and base saturation, and decreased Al content and Al saturation in the soil profile down to a depth of 1.00 m. Applications of SSP_B, SSP_F, and PG in combination with lime increased P content in the soil surface layer (0–0.10 m), and this increase was more pronounced with SSP_B. In the short term, after 1 year, the addition of PG together with surface lime increased the SO_4-S content in the subsurface layers (0.10–1.00 m), while after 3 and 5 years there was an increase in SO_4-S content for the three treatments of S (SSP_B, SSP_F, and PG), with a more pronounced effect obtained by SSP_B. Surface application of lime increased Ca-leaf and Mg-leaf contents and reduced K-leaf content of wheat regardless of the addition of SSP_B, SSP_F, and PG. The addition of SSP_B, SSP_F, and PG increased leaf contents of P and S of wheat. In soybean, surface application of lime increased leaf contents of N, Ca, and Mg regardless of the addition of SSP_B, SSP_F, and PG. The addition of SSP_B, SSP_F, and PG increased leaf contents of P and S of soybean. The cumulative grain yield of five wheat harvests was increased by 40% with the application of lime to the soil surface, by 54% with SL + SSP_F, and by 70% with SL + SSP_B and SL + PG. The cumulative grain yield of five soybean harvests increased by 36% with application of lime to the soil surface, regardless of the addition of SSP_B, SSP_F, and PG. Surface application of lime proved to be essential for obtaining high yields in a wheat-soybean cropping system under no-till. The combined use of surface lime with PG or SSP applied by broadcast in a wheat-soybean cropping system under no-till should be encouraged because of the achievement of important increases in wheat grain yield.

Key words: *Triticum aestivum* L., *Glycine max,* acidity of the soil, simple superphosphate, phosphogypsum.

2.1 INTRODUCTION

Currently, the major challenge of the century is to maintain global food security. It is predicted that rainfall deficits in several countries of the world will lead to a decline in crop production (FAO, 2022) and that the world population, already over 8 billion, is expected to reach 9.7 billion in 2050 (DESA, 2015; POPULATION MATTERS, 2022). In the face of this population growth and climate change leading to water deficits, there is an increasing demand for sustainable agricultural practices and food production that maintains global food security. In this scenario, Brazil is a key-country with an important role in global food production.

Brazil is the largest producer of soybean (*Glycine max* (L.) Merrill) in the world and the fifth largest producer of wheat (*Triticum aestivum* L.) in the Americas (FAOSTAT, 2022). Soybean is an excellent source of protein and vegetable oils used in animal and human food, in addition to serving as a feedstock for fuels. Wheat is a basic component of the human diet, and its flour is used extensively in the production of bread, pasta, and cookies. Wheat is one of the most important crops for maintaining food security and is the second most consumed cereal in the world after maize (OLIVEIRA and PINTO-MAGLIO, 2017; FAO, 2022).

Brazilian soils usually have high acidity and low natural fertility (FAGERIA, 2001; van RAIJ, 2011). Soils from tropical and subtropical regions are affected by weathering that leaches cationic nutrients such as calcium (Ca), magnesium (Mg), and potassium (K), and accumulates toxic elements for plants such as aluminum (Al) and manganese (Mn). In addition, these soils also have low availability of phosphorus (P) (LYNCH, 2011), as it is mainly adsorbed to oxides of iron (Fe) and Al (van RAIJ, 2011; FINK et al., 2016; WITHERS et al., 2018). These factors limit the agricultural production potential. Therefore, it is necessary to adopt sustainable and efficient agricultural practices to increase crop yields and ensure global food security.

Brazilian agriculture has sought to use practices to mitigate damage caused by drought stress. The most important practices that have been adopted are: (i) conservation agriculture based on no-till systems, currently used on about 33 million hectares in Brazil (FEBRAPDP, 2022); (ii) correction of soil acidity through the application of lime (CAIRES et al., 2005; 2011; CRUSCIOL et al., 2019); and (iii) use of soil conditioners such as phosphogypsum (PG) to improve subsoil fertility (CAIRES et al. 2001; CAIRES and GUIMARÃES, 2018; BOSSOLANI et al. 2018; CRUSCIOL et al., 2019).

No-till systems improve the soil chemical, physical, and biological quality by increasing the soil organic carbon (SOC) stock and the availability of nutrients such as nitrogen (N), P, and sulfur (S) (INAGAKI et al., 2016; WEIL; BRADY, 2017; COOPER et al. 2021). Liming makes Ca and Mg available in the soil, and the carbonate from lime reacts with water to form bicarbonate (HCO_3^-) and hydroxyl (OH^-) which neutralize H^+ and Al^{3+} (SPOSITO, 2008; JORIS et al., 2016; AULLER et al., 2019). Because lime has low water solubility, its reaction is limited to the contact area with soil particles. In no-till systems, liming is carried out on the soil surface without incorporation (CAIRES et al., 2006; JORIS et al., 2016). The reaction of lime applied to the soil surface is limited to the surface layer in the short term and long time and higher rates are required for the lime reaction to reach the subsurface layers (CAIRES et al. 2011). High acidity and low levels of Ca and Mg in subsurface soil layers can limit root growth in depth, reducing water and nutrient uptake, and making plants susceptible during periods of drought (RITCHIE, 1980; CAIRES et al., 2016).

To improve the root penetration into the subsoil and make plants less susceptible to water deficits under no-till, the use of PG in addition to surface liming has been recommended (CAIRES and GUIMARÃES, 2018; CRUSCIOL et al., 2019; BOSSOLANI et al., 2022). Because PG is much more soluble than lime, its application increases Ca and SO_4-S levels and reduces Al toxicity in subsurface soil layers (RITCHEY et al., 1982; BLUM et al., 2014; DUART et al. 2021), increasing root growth, N use efficiency, and crop yield (CAIRES et al., 2016; CRUSCIOL et al., 2016).

Simple superphosphate (SSP) was the first commercial mineral fertilizer and led to the development of the modern plant nutrient industry. It was once the most widely used fertilizer, but other phosphorus (P) fertilizers have largely displaced SSP because of its relatively low P content. The advantage of using SSP over other phosphate sources is that in addition to P (16% to 20% P_2O_5), it also contains Ca (16% to 21%) and S (11% to 12%) in its composition, making it an excellent source of these three nutrients (P, Ca, and S). In addition, studies have shown that the increase of SO_4-S and Ca in the soil profile when PG is applied has increased grain yield of crops such as wheat, soybean, maize, and rice (CAIRES et al., 2002; BLUM et al., 2014; CAIRES et al., 2021; DUART et al., 2021). Because SSP contains $CaSO_4$ in its composition, we hypothesized that continued use of SSP to supply the P requirements of the crops after surface liming in a no-till system could increase Ca and SO_4-S levels, and reduce Al saturation in subsoil layers, consequently improving root development, plant nutrition, and crop grain yields.

This study reports a 5-year field experiment that examined in a wheat-soybean cropping system under no-till: (i) the alleviation in soil acidity and the improvement in the soil profile by surface application of lime; (ii) whether the effect of surface liming in correcting acidity and improving the soil profile is enhanced by combining surface liming with the use of SSP to the broadcast or in the sowing furrow, or PG; (iii) whether SSP to the broadcast or in the sowing furrow has a similar effect to PG in improving soil profile; and (iv) plant nutrition and grain yield of wheat and soybean in response to surface liming combined with SSP application to the broadcast or in the sowing furrow, or PG.

2.2 MATERIAL AND METHODS

2.2.1 Site description and soil

The experiment was carried out in the "Capão da Onça" School Farm of the State University of Ponta Grossa, in the Central-South region of Parana (Southern latitude 25°05'35" and Western longitude 50°02'49") in soil classified as dystrophic Red Latosol of medium texture. According to Köppen-Geiger System (Peel et al., 2007), the climate at the site is categorized as a Cfb type (mesothermal, humid, subtropical), with mild summer and frequent frosts during the winter.

The experimental area was managed under a no-till cropping system with no history of lime application and S sources. Table 2.1 shows the results of chemical (Pavan et al., 1992) and particle-size distribution (Embrapa, 2011) analyses at different soil depths in May 2016 before the establishment of the experiment.

Table 2.1 - Results of chemical and particle-size distribution analyzes at different soil depths in May 2016 before the establishment of the experiment in Ponta Grossa, Southern Brazil.

Depth	**pH$^{(1)}$**	**Al**	**Ca**	**Mg**	**K**	**CTC$^{(2)}$**	**V$^{(3)}$**	**m$^{(4)}$**	**P$^{(5)}$**	**S**	**C**	**Clay**	**Silt**	**Sand**
m				------- mmol$_c$ dm^{-3} ---------			--- % ---		mg dm^{-3}		g dm^{-3}		- - - - g kg^{-1} - - - - -	
0–0.10	4.5	6	16	6	1.4	92,8	25	20	45.5	3.7	17	260	57	683
0.10–0.20	4.0	12	5	3	1.1	99,2	9	57	6.7	5.7	12	260	51	689
0.20–0.40	4.1	9	6	3	0.9	100,0	10	48	0.8	9.9	9	279	45	676
0.40–0.60	4.3	7	7	3	0.8	77,7	14	39	1.3	8.8	9	280	79	641
0.60–0.80	4.5	4	9	5	0.4	70,0	18	24	0.3	9.4	10	320	75	605

[1]pH in 0,01 mol L^{-1} $CaCl_2$; [2] Cation exchange capacity (Ca + Mg + K + H + Al); [3]V: base saturation; [4]m: Al saturation; [5]Phosphorus extracted by Mehlich-1.

2.2.2 Experimental design and treatments

A randomized complete block design was used, with five treatments and four replications. Plot size was 15 m × 6 m (90 m^2). The treatments were (Table 2.2): control (without lime), surface application of lime (SL), SL + application of SSP by broadcast (SL + SSP$_B$), SL + application of SSP in the sowing furrow (SL + SSP$_F$), and SL + PG. The experiment started in 2016 and was conducted during five cycles of a wheat-soybean cropping system. SSP had 3% N, 17% P_2O_5, and 11% S, and PG had 17% Ca and 14% S.

Table 2.2 – Treatments and doses of lime, MAP and elemental S for the establishment of the experiment. Ponta Grossa-PR, 2016-2021.

Treatments	Lime (t ha^{-1})	(kg P_2O_5 ha^{-1})[a]	(kg S ha^{-1})[a]
1. Control	0	0	0
2. Surface lime (SL)	5,4	0	0
3. Surface lime + SSP broadcast (SL + SSP_B)	5,4	100	65
4. Surface lime + SSP sowing furrow (SL + SSP_F)	5,4	100	65
5. Surface lime + phosphogypsum (SL + PG)	5,4	100	65

[a] The P_2O_5 and S was applied annually in each sowing wheat crop.

The control treatment received no application of lime, SSP, and PG. On June 3, 2016, dolomitic lime [327 g kg^{-1} of CaO, 206 g kg^{-1} of MgO, and 95% effective calcium carbonate equivalent (ECCE)] was surface-applied at the rate of 5.4 Mg ha^{-1} to increase the soil base saturation in the 0–20 cm layer to 70% (CAIRES et al., 2005) in treatments with SL.

For each cycle of wheat-soybean succession, a rate of 100 kg ha^{-1} of P_2O_5 was applied at wheat sowing. In the SL + SSP_F treatment, SSP was mechanically applied in the sowing furrow along with the wheat sowing using a no-till seeder with fertilizer placed beside and below the seed. In the SL + SSP_B treatment, the SSP was distributed manually by broadcast on the soil surface on the day of wheat sowing. In the treatment with SL + PG, PG was spread on the soil surface at a rate of 1395 kg ha^{-1} in a single application before the first wheat crop, in June 2016. In this treatment with PG, monoammonium phosphate (MAP) (11% N and 52% P_2O_5) was applied in the wheat sowing furrow at a rate of 100 ka ha^{-1} P_2O_5 to balance the amount of P_2O_5 provided by SSP application. The PG rate (PG, in kg ha^{-1}) was calculated based on the clay content (279 g kg^{-1}) of the 0.20–0.40 m layer using the following equation: $PG = 5 \times 279 = 1395$ kg ha^{-1}.

2.2.3 Crop sowing and establishment

The study was conducted from 2016 to 2021 with wheat in the autumn-winter season and with soybean in the spring-summer season. In order to improve straw production under no-till, cover crops were grown between soybean harvest and wheat sowing. Fodder radish (*Raphanus sativus* L.) was sown between the first and second cycle in n 2017, and black oat (*Avena strigosa* Schreb) was grown between the other cycles (2018, 2019, and 2020). More details on the cropping sequence during the experimental period are shown in Table 2.3. Wheat was sown at a rate of 250 kg ha^{-1} of seed and row spacing of 0.17 m. Based on the composition of the phosphate fertilizers, nitrogen (N) was applied annually at wheat sowing at a rate 18 kg N ha^{-1} via SSP and 21 kg N ha^{-1} via MAP. In top dressing to the wheat crop, N was applied as urea at a rate of 100 kg N ha^{-1} in 2016, 2017, 2018, and 2019, and 120 kg N ha^{-1} in 2020 (60 to 80 kg N ha^{-1} at the beginning of tillering and 40 kg ha^{-1} at the end of booting). Soybean was sown at a rate of 14 seeds m^{-1} (inoculated with *Bradyrhizobium japonicum*) and row spacing of 0.45 m, without P fertilization. In all wheat and soybean crops, potassium chloride (KCl – 60% K_2O) was surface-applied immediately after sowing at a rate at 84 kg K_2O ha^{-1}. Crop protection management was carried out according to the needs of wheat and soybean crops to achieve adequate plant health during the development cycle.

Table 2.3 - Cropping sequence from 2016 to 2021 in an experiment under a no-till system in Southern Brazil.

Year	**Crop**	**Cultivation**	**Sowing**	**Cultivar**
2016–2017	Wheat	Autumn-Winter	June	TBIO Toruk
	Soybean	Spring-Summer	December	Nidera 5909 IPRO
2017	Fodder radish	Autumn	April	-----
2017–2018	Wheat	Autumn-Winter	June	TBIO Iguaçu
	Soybean	Spring-Summer	November	Nidera 5445 IPRO
2018	Black oat	Autumn	April	Common
2018–2019	Wheat	Autumn-Winter	July	Quartzo
	Soybean	Spring-Summer	December	LG 60158 IPRO
2019	Black oat	Autumn	April	Common
2019–2020	Wheat	Autumn-Winter	June	TBIO Toruk
	Soybean	Spring-Summer	December	Nidera 5445 IPRO
2020	Black oat	Autumn	April	Common
2020–2021	Wheat	Autumn-Winter	June	TBIO Ponteiro
	Soybean	Spring-Summer	November	Nidera 5445 IPRO

2.2.4 Rainfall

Monthly rainfall data from the beginning of the experiment (June 2016) to the end of the present study (May 2021) are shown in Figure 2.1. Rainfall data occurred during the experiment were obtained from the BASF meteorological station located at the “Capão da Onça” School Farm, and the historical average rainfall data between the years 1954 and 2001 were obtained from the Agronomic Institute of the Parana State meteorological station (IAPAR, 2022).

Wheat was more affected than soybean by lower rainfall during the crop development cycle (Figure 2.1). Wheat grown in 2016 had excellent monthly rainfall throughout the development period, above the historical average, favoring crop development and setting the stage for a high grain yield. However, for wheat grown in subsequent years (2017, 2018, 2019, and 2020), post-sowing rainfall was below the historical average for the region, which affected plant development and grain yield.

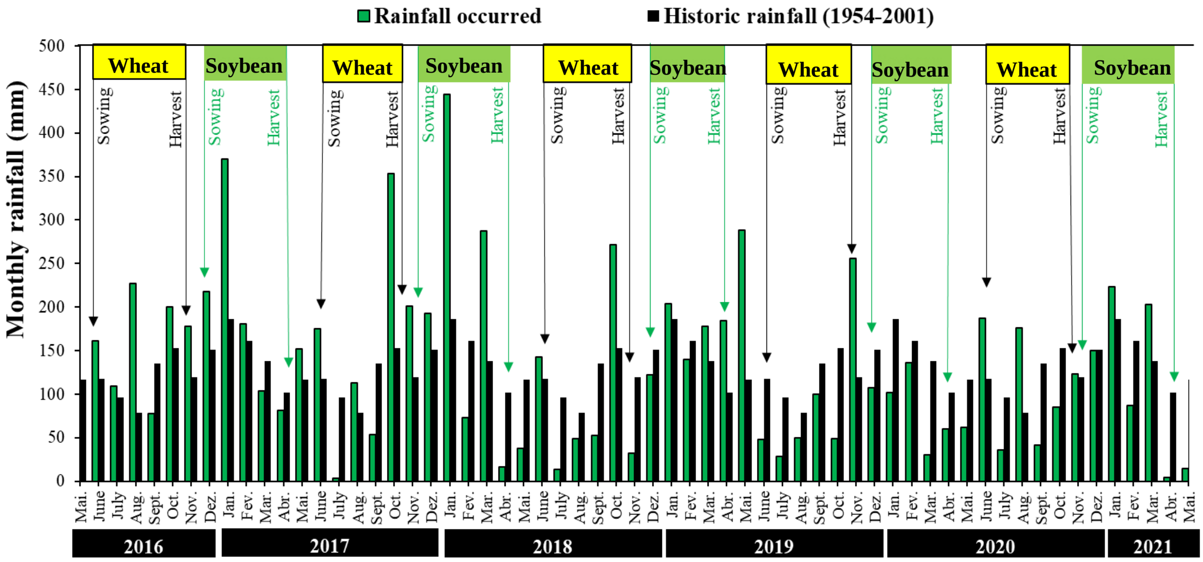

Figure 2.1 - Monthly and historical rainfall (2016-2021) from the beginning of the experiment (June 2016) until the conclusion of the experiment (May 2021). Source: Monthly rainfall data from the BASF meteorological station located at the "Capão da Onça" School Farm. Historical average rainfall data (1954 and 2001) obtained from the meteorological station of the Agronomic Institute of the Parana State (IAPAR, 2022).

2.2.5 Soil sampling and chemical analysis

Soil samples were taken after the soybean harvest in 2017, 2019, and 2021, at 1, 3, and 5 years after the beginning of the experiment. In order to obtain a composite sample, 12 soil cores were sampled at 0–0.10 and 0.10–0.20 m depths, and five soil cores were sampled at 0.20–0.40, 0.40–0.60, 0.60–0.80, and 0.80–1.00 m depths in each plot using a soil probe sampler. Prior to the chemical analysis, soils were air-dried and ground to pass through a 2-mm sieve. Soil pH ($CaCl_2$), exchangeable Al, Ca, Mg, and K contents, and extractable P (Mehlich-1) content were determined according to the standard methods used by the Agronomic Institute of the Parana State (Pavan et al., 1992). Soil SO_4-S content was extracted with a 0.01 mol L^{-1} calcium phosphate solution and determined by the turbidimetric method (CANTARELLA and PROCHNOW, 2001).

2.2.6 Leaf sampling and chemical analysis

In each crop, wheat and soybean leaf samples were collected from 30 plants per plot during the flowering period of the crops for foliar diagnosis. In wheat was collected the flag leaf, and in the soybean the third trifoliate was collected from the apex of the plants. The samples were washed with deionized water, dried in a forced-air oven at 60°C until a constant mass achieved, and were ground. Leaf tissue analysis was performed using a sulfuric acid digestion for N determination and a nitric-perchloric acid digestion for the determinations of P, K, Ca, Mg, and S, according to the methods described by Malavolta et al. (1997).

2.2.7 Crop grain yield

Grain harvests were carried out mechanically with a plot harvester in the central rows after the physiological maturity of wheat and soybean crops. In each plot, soybean grain was harvest from 27 m^2 (middle 4 rows by 15 m in length), and wheat grain was harvest from 24 m^2 (1.6 m × 15 m in length). Grain yield was expressed at 130 g kg^{-1} of moisture content. Cumulative wheat and soybean grain yield was obtained by adding five wheat harvests and five soybean harvests.

2.2.8 Statistical analysis

The data from the soil chemical analysis were analyzed as a split-plot design by analysis of variance using the treatments as main plots and the soil depths as subplots. Grain yields and leaf nutrient contents of wheat and soybean were subjected to analysis of variance using a randomized complete block design. Means of treatments were compared using the LSD test at 5%. Statistical analyzes were performed using the Sisvar software (FERREIRA, 2011). A principal component analysis (PCA) was used to reduce a set of original variables to a smaller number to determine which components were responsible for the variation. PCA was based on the correlation matrix between soil chemical properties (soil pH, Al, Ca, Mg, P, and SO_4-S) at different depths in 2017, 2019, and 2021, and grain yields of wheat (2016, 2017, and 2020) and soybean (2016–2017, 2018–2019, and 2020–2021) from the field trial data set. The data set of soil chemical properties and grain yields of wheat and soybean was obtained from the average of the three years of evaluation. PCA was performed using CANOCO software for Windows, version 4.56.

2.3 RESULTS

2.3.1 Soil chemical properties

A significant interaction effect between the treatments and the soil depth was observed for all soil chemical properties evaluated. Surface liming increased soil pH with greater intensity at the first 0.10 m depth, rergadlles whether or not SSP or PG was added with SL. However, the increase in soil pH persisted to 1.00 m depth, mainly in the SL and SL + SSP_B treatments (Figures 2.2a, 2.2b, and 2.2c). At 1 year after surface liming, soil pH increased up to the 0–0.20 m layer with the treatments used, while there was no significant effect of the treatments on soil pH at 0.20–0.40 m depth. Soil pH increased again from 0.40 to 1.00 m depth only with surface appplication of lime (Figure 2.2a). At 3 years after surface liming, all treatments increased soil pH to a depth of 1.00 m compared to the control treatment, and the treatments with the greatest effect were SL and SL + SSP_B (Figure 2.2b). As early as 5 years after surface liming, all treatments were effective in increasing soil pH to a 0.20 m depth. However, at depths from 0.20 m to 1.00 m, only the SL and SL + SSP_B treatments significantly increased soil pH compared to the control treatment (Figure 2.2c).

Accompanying changes in soil pH, surface liming provided a more pronounced increase in soil base saturation in the first 0.10 m and to a lesser extent up to 1.00 m in depth (Figures 2.2a, 2.2b, and2.2c). At 1 year after surface liming, all treatments significantly increased the soil base saturation to a 1.00 m depth compared to the control treatment; only the SL + PG treatment did not significantly change soil base saturation at 0.80–1.00 m depth compared to the other treatments (Figure 2.2a). The effect of the treatments in increasing base saturation throughout the soil profile (0 to 1.00 m) persisted up to 3 years (Figure 2.2b) and 5 years (Figure 2.2c) after surface application of lime, with more pronounced effect in the SL and SL + SSP_B treatments.

After 1 year of surface liming, exchangeable Ca content in the soil increased with the treatments used compared the the control at 0–0.10, 0.10–0.20, and 0.40–0.60 m depths (Figure 2.3a). At 3 years after surface liming, the treatments increased soil exchangeable Ca content to a depth of 1.00 m compared with the control treatment. Exchangeable Ca content did not differ among SL, SL + SSP_B, SL + SSP_F, and SL + PG treatments, although it was higher in these treatments compared to the control (Figure 2.3b). At 5 years after surface liming, the increase in exchangeable Ca content was more pronounced in the SL + SSP_B treatment at 0–0.10 m depth, and in the SL and SL + SSP_B treatments at depths from 0.20 m to 0.80 m; there was no significant effect of treatments on exchangeable Ca content at 0.80–1.00 m depth (Figure 2.3c).

Compared with the control treatment, all treatments increased exchangeable Mg content in the soil after 1 year of surface liming, with a more pronounced effect in treatments SL + SSP_F at a depth of 0–0.10 m depth and SL at a depth of 0.10–0.20 m (Figure 2.3a). At 3 years after surface liming (Figure 2.3b), compared to the control, the SL and SL + SSP_B treatments increased exchangeable Mg content to a depth of 1.00 m. At 5 years after liming (Figure 2.3c), the largest increases in exchangeable Mg content were obtained in treatments SL and SL + PG at 0–0.10 m depth; SL, SL + SSP_B, SL + SSP_F, and SL + PG from from 0.10 to 0.60 m; and SL and SL + SSP_B from 0.60 to 1.00 m.

Treatments with surface application of lime significantly reduced the exchangeable Al content in the soil (Figures 2.4a, 2.4b, and 2.4c). At 1 year after surface liming, compared to the control, there was a reduction in soil exchangeable Al content in treatments SL, SL + SSP_B, SL + SSP_F, and SL + PG to a depth of 0.40 m (Figure 2.4a). At 3 years after surface liming, the reduction in exchangeable Al content by the treatments was observed throughout the soil profile to a depth of 1.00 m (Figure 2.4b), and if this effect extended to 5 years after surface liming (Figure 2.4c). At 5 years of liming, the greatest reduction in exchangeable Al content in the subsoil layers (0.20 to 1.00 m) was obtained by treatments with SL or SL + SSP_B.

Compared to the control, soil Al saturation was reduced in the SL, SL + SSP_B, SL + SSP_F, and SL + PG treatments throughout the soil profile to a depth of 1.00 m at 1 year (Figure 2.4a), whose effect persisted for up to 3 years (Figure 2.4b) and 5 years (Figure 2.4c) after surface application of lime. At 3 and 5 years after surface liming, a reduction more pronounced in soil Al saturation was obtained by treatments with SL or SL + SSP_B.

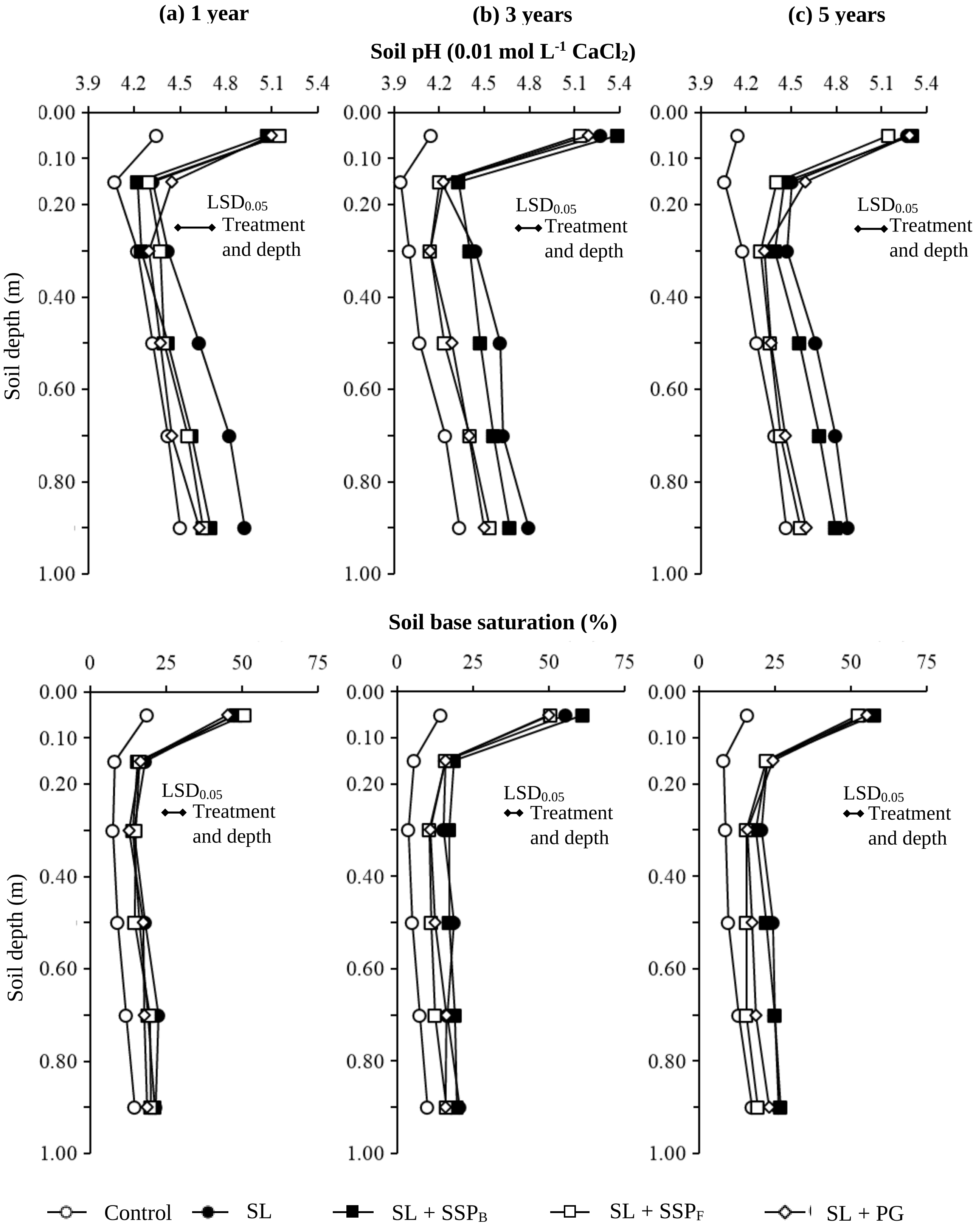

Figure 2.2 - Soil pH (0.01 mol L^{-1} $CaCl_2$) and base saturation to a depth of 1.00 m as affected by surface application of lime (SL), SL + SSP_B (broadcast), SL + SSP_F (furrow), and SL + PG. Lime was surface-applied in June 2016 and soils were sampled after 1 (a), 3 (b), and 5 (c) years of application. Horizontal bars represent the least significant difference (LSD) by the t-test (LSD) at *P* = 0.05.

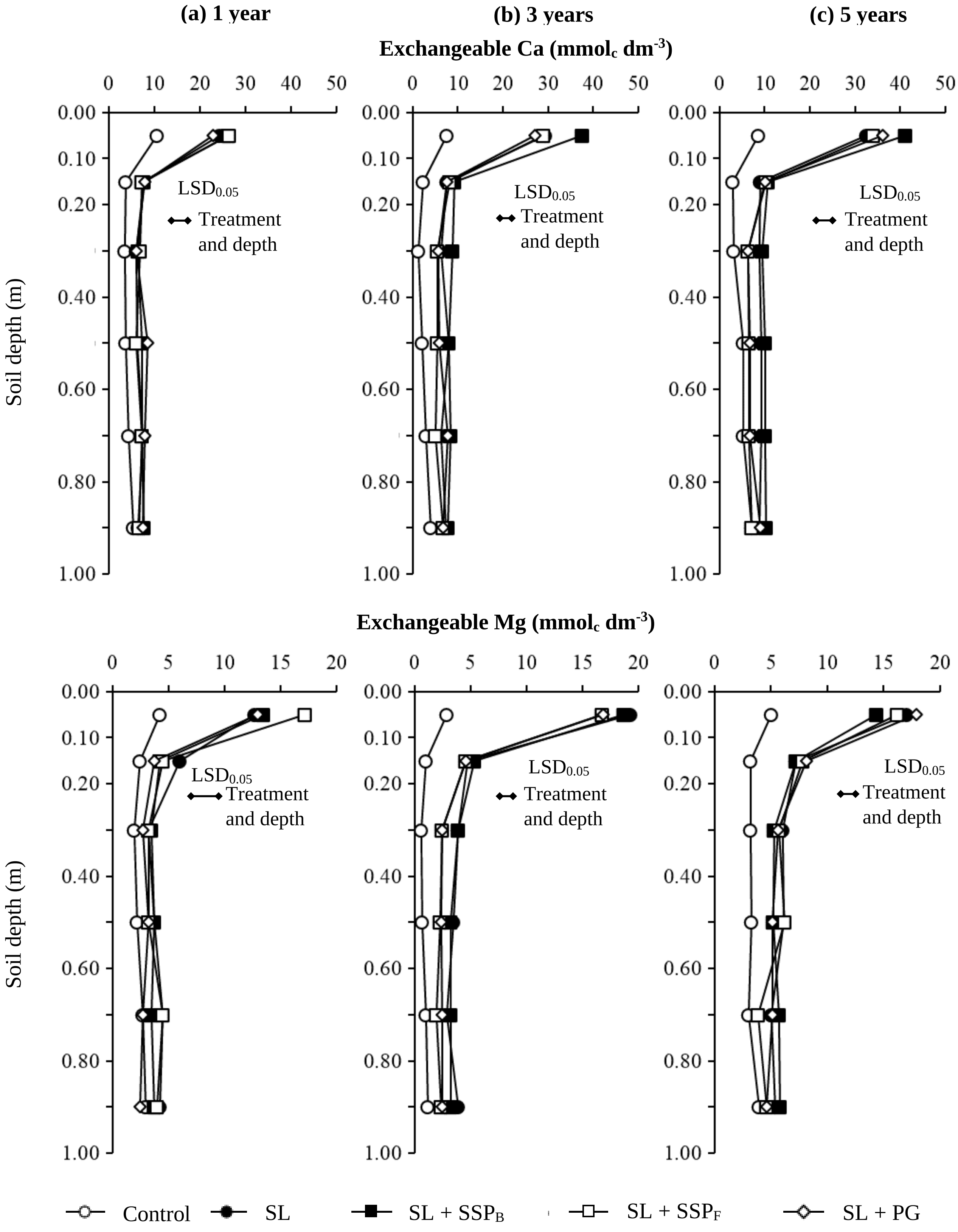

Figure 2.3 - Soil exchangeable Ca and Mg contents to a depth of 1.00 m as affected by surface application of lime (SL), SL + SSP$_B$ (broadcast), SL + SSP$_F$ (furrow), and SL + PG. Lime was surface-applied in June 2016 and soils were sampled after 1 (a), 3 (b), and 5 (c) years of application. Horizontal bars represent the least significant difference (LSD) by the t-test (LSD) at *P* = 0.05.

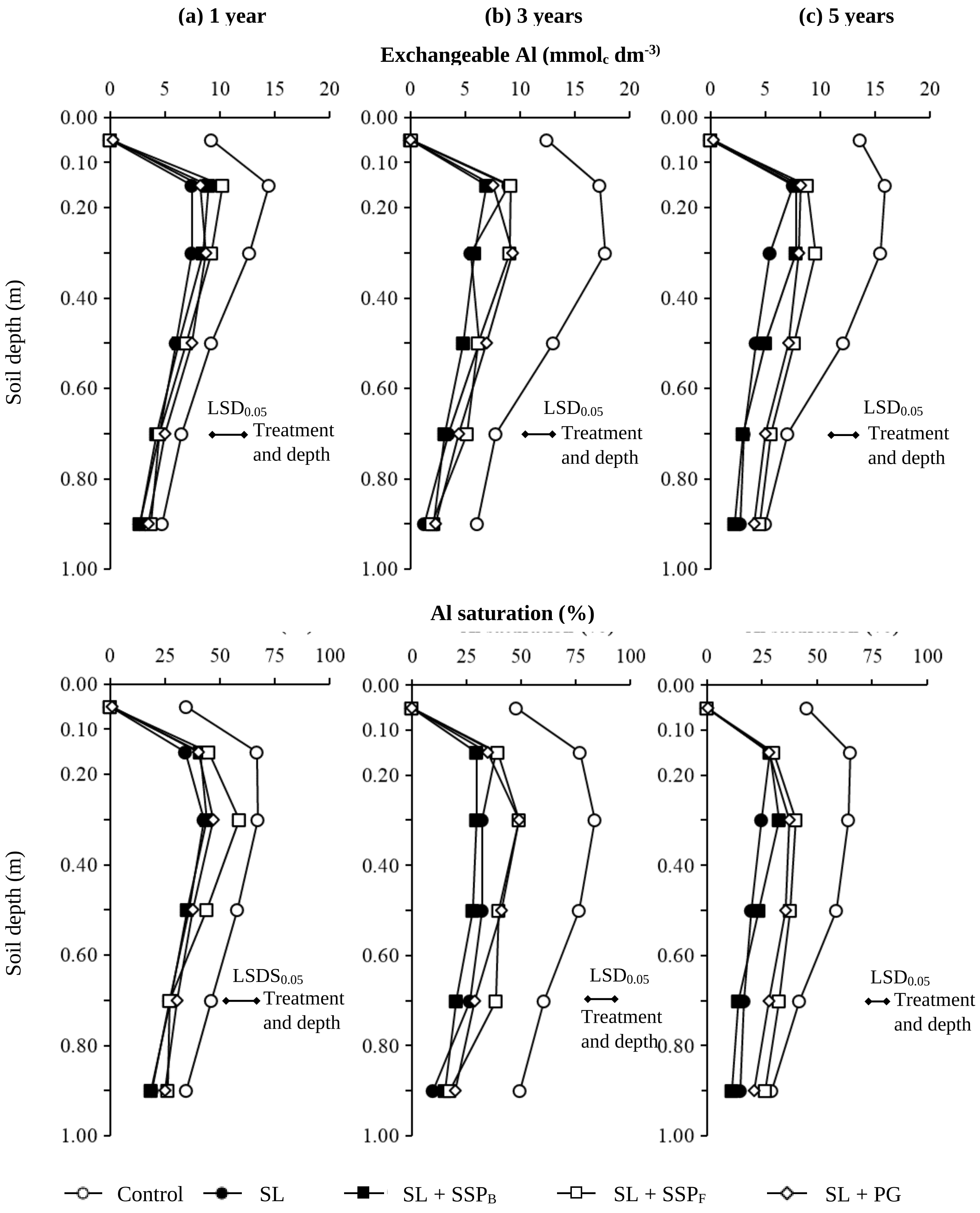

Figure 2.4 - Exchangeable Al content and Al saturation in the soil to a depth of 1.00 m as affected by surface application of lime (SL), SL + SSP$_B$ (broadcast), SL + SSP$_F$ (furrow), and SL + PG. Lime was surface-applied in June 2016 and soils were sampled after 1 (a), 3 (b), and 5 (c) years of application. Horizontal bars represent the least significant difference (LSD) by the t-test (LSD) at *P* = 0.05.

Extractable P (Mehlich 1) content was affected by treatments only in the soil surface layer (0–0.10 m) (Figures 2.5a, 2.5b, and 2.5c). At 1 year after surface liming, the P content at 0–0.10 m depth was higher in the SL + SSP_B and SL + SSP_F treatments compared to the SL + PG treatment, and the latter treatment provided higher P content compared to the control and SL (Figure 2.5a). At 3 years after surface liming, there was an increase in P content at 0–0.10 m depth in the SL + SSP_F and SL + PG treatments, and an even greater increase in the SL + SSP_B treatment compared to the SL and control treatments (Figure 2.5b). At 5 years after surface liming, the SL treatment showed a lower P content in the soil surface layer compared to the control treatment, while SL + SSP_F, SL + PG, and mainly SL + SSP_B treatments provided higher P content (Figure 2.5c).

Soil SO_4-S content was affected by treatments at depths from 0.10 m to 1.00 m (Figures 2.5a, 2.5b, and 2.5c). After 1 year of surface liming, the treatment with SL + PG increased the SO_4-S content from 0.10 m to 1.00 m, while less expressive increments in SO_4-S content were observed in the treatments with SL + SSP_B and SL + SSP_F (Figure 2.5a). At 3 years after surface liming, treatments with S source (SL + SSP_B, SL + SSP_F, and SL + PG) increased the SO_4-S content at depths from 0.20 m to 1.00 m. The greatest increases in S-SO_4 content were obtained with SL + PG at a depth of 0.20-0.40 m, with SL + PG and SL + SSP_B at a depth of 0.40-0.60 m, and with SL + SSP_B at depths from 0.60 m to 1.00 m (Figure 5b). At 5 years after surface liming, the SO_4-S content was increased in all soil layers from 0.10 m to 1.00 m, with emphasis on the SL + SSP_B treatment (Figure 2.5c).

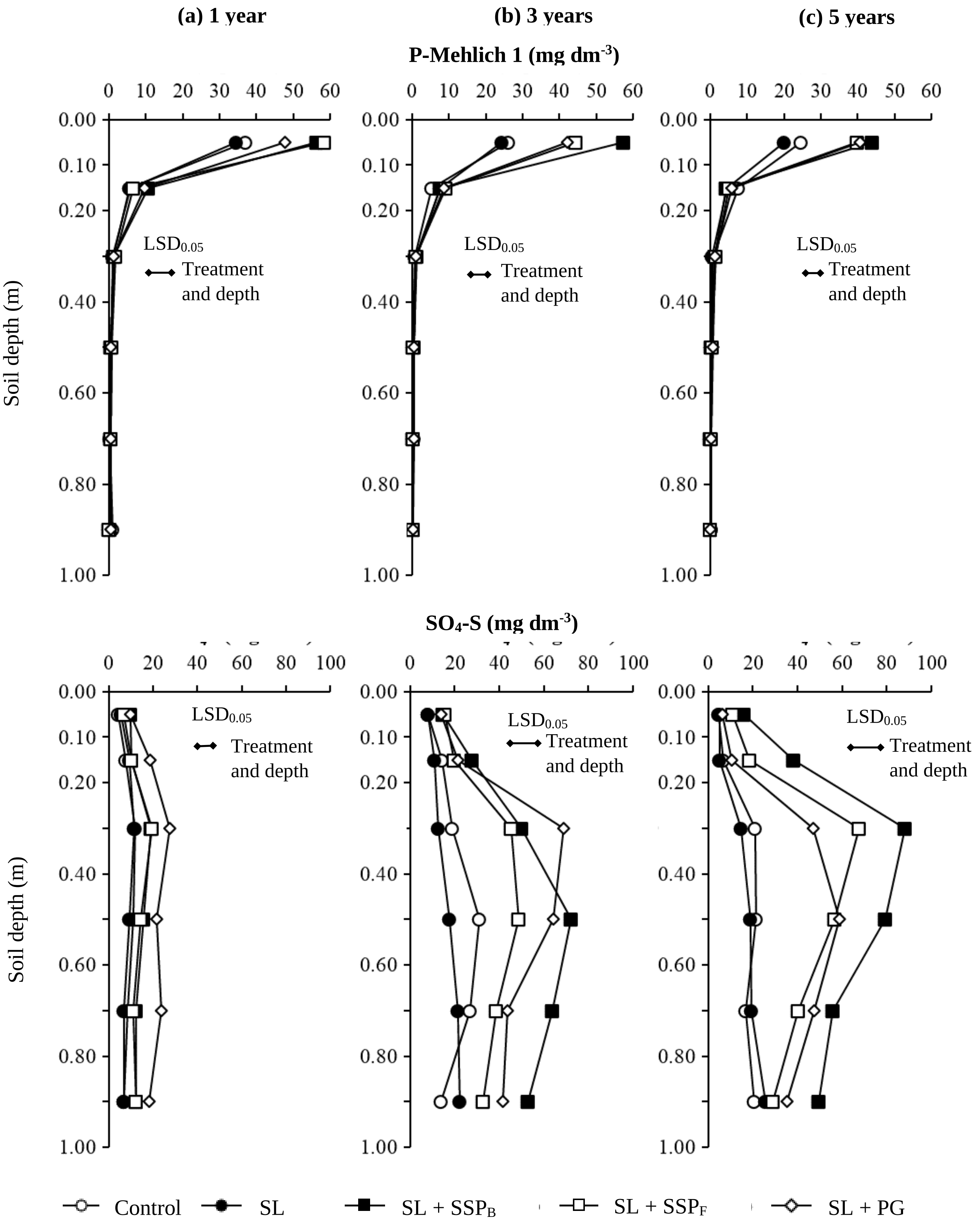

Figure 2.5 - Extractable P (Mehlich 1) and SO_4-S contents to a depth of 1.00 m as affected by surface application of lime (SL), SL + SSP_B (broadcast), SL + SSP_F (furrow), and SL + PG. Lime was surface-applied in June 2016 and soils were sampled after 1 (a), 3 (b), and 5 (c) years of application. Horizontal bars represent the least significant difference (LSD) by the t-test (LSD) at *P* = 0.05.

2.3.2 Wheat and soybean plant nutritional status

The treatments had a positive effect on the nutrient leaf contents of wheat (Table 2.4). Leaf N content was not affected by treatments in the five wheat cropping seasons. Leaf P content increased with the treatments SL + SSP_B, SL + SSP_F, and SL + PG in the 2017 and 2020 cropping seasons. Leaf K content decreased with the treatments SL + SSP_F and SL + PG in 2018 and also with the treatments SL, SL + SSP_F, and SL + PG in 2020. Leaf Ca content increased with the treatments SL, SL + SSP_B, and SL + PG in 2016 and also with the treatments SL + SSP_B, SL + SSP_F, and SL + PG in the 2018 and 2020 seasons. Leaf Mg content was increased in the five wheat cropping seasons with treatments SL, SL + SSP_B, SL + SSP_F, and SL + PG. Compared to the control and SL treatments, leaf S content increased in the SL + SSP_B and SL + PG treatments in 2016, 2017, 2018, and 2020. Compared to the control treatment, leaf S content increased in the SL, SL + SSP_B, SL + SSP_F, and SL + PG treatments in 2019.

The treatments significantly affected the nutrient leaf contents of soybean in four of the five cropping seasons (Table 2.5). Leaf N content increased with SL, SL + SSP_B, SL + SSP_F, and SL + PG compared to the control treatment in 2017–2018, 2018–2019, 2019–2020, and 2020–2021. Compared to the control treatment, SL + SSP_B, SL + SSP_F, and SL + PG increased P-leaf content in 2017–2018 and 2020–2021; in 2018–2019, P-leaf content increased with SL + PG and in 2019–2020, P-leaf content increased in all treatments compared to the control treatment, with a more pronounced increase in the treatment SL + SSP_B. Compared to the control treatment, K-leaf content was reduced with SL, SL + SSP_B, SL + SSP_F, and SL + PG in 2018–19, and increased with SL + SSP_B and SL + PG in 2019–2020. Leaf Ca content increased with SL, SL + SSP_B, SL + SSP_F, and SL + PG in 2017–2018, 2018–2019, and 2019–2020, and also with SL + SSP_B, SL + SSP_F, and SL + PG in 2020–2021 compared to the control treatment. Leaf Mg content increased with SL, SL + SSP_B, SL + SSP_F, and SL + PG in 2017–2018, 2018–2019, 2019–2020, and 2020–2021 compared to the control treatment. Leaf S content increased with SL + SSP_B, SL + SSP_F, and SL + PG compared to the control treatment in 2017–2018, 2018–2019, and 2019–2020.

Table 2.4 - Nutrient contents in wheat leaves as affected by surface application of lime (SL), SL + single superphosphate in the sowing furrow (SL + SSP$_F$), SL + single superphosphate applied by broadcast (SL + SSP$_B$), and SL + phosphogypsum (SL + PG) under a no-till cropping system in Southern Brazil.

Treatment	**Leaf nutrient content of wheat ($g\ kg^{-1}$)**					
	N	**P**	**K**	**Ca**	**Mg**	**S**
- - - - - - 2016 - - - - - -						
Control	37.94	4.21	12.19	3.58 c	1.19 c	2.63 b
SL	38.36	3.81	11.69	4.70 ab	1.72 a	2.87 b
SL + SSP$_B$	39.97	4.05	11.18	4.71 ab	1.66 ab	3.51 a
SL + SSP$_F$	41.72	4.10	11.81	4.06 bc	1.51 b	2.86 b
SL + PG	40.39	4.11	11.31	5.25 a	1.63 ab	3.72 a
P > F	0.673	0.545	0.316	0.001	<0.001	<0.001
CV (%)	10.1	8.1	6.1	10.1	8.1	7.7
- - - - - - 2017 - - - - - -						
Control	34.37	4.00 b	20.53	3.62	1.21 b	1.89 b
SL	35.77	3.91 b	19.46	3.81	1.82 a	1.90 b
SL + SSP$_B$	34.16	4.78 a	20.80	3.94	1.99 a	2.59 a
SL + SSP$_F$	33.18	4.51 a	20.26	3.39	1.70 a	2.18 ab
SL + PG	32.90	4.55 a	20.80	4.09	1.80 a	2.53 a
P > F	0.181	0.005	0.529	0.125	0.001	0.007
CV (%)	4.9	6.9	5.9	9.7	11.5	12.3
- - - - - - 2018 - - - - - -						
Control	40.60	5.17	21.73 ab	2.61 b	0.99 c	1.86 d
SL	40.32	4.81	19.47 bc	2.87 b	1.69 b	1.95 cd
SL + SSP$_B$	42.84	4.98	21.86 a	3.58 a	1.98 a	3.02 a
SL + SSP$_F$	42.56	4.86	18.80 c	3.67 a	1.97 a	2.24 bc
SL + PG	42.91	4.94	19.20 c	3.94 a	1.92 a	3.50 b
P > F	0.253	0.265	0.034	<0.001	<0.001	<0.001
CV (%)	4.9	4.5	7.5	9.7	6.6	8.2
- - - - - - 2019 - - - - - -						
Control	44.43	4.26	30.10	3.50	1.68 b	3.86
SL	43.24	4.23	27.34	3.31	1.94 a	3.92
SL + SSP$_B$	42.95	4.11	27.89	3.43	1.89 a	4.42
SL + SSP$_F$	46.01	4.14	27.89	2.93	1.88 a	4.14
SL + PG	44.81	4.35	28.45	3.07	1.89 a	4.02
P > F	0.540	0.887	0.391	0.213	0.077	0.123
CV (%)	6.2	8.7	7.1	11.5	6.6	7.2
- - - - - - 2020 - - - - - -						
Control	32.70	3.33 bc	36.94 a	2.39 c	0.94 c	2.33 c
SL	30.38	3.25 c	32.01 b	2.60 bc	1.49 b	2.25 c
SL + SSP$_B$	28.91	4.10 a	34.79 ab	3.13 a	1.68 a	3.24 a
SL + SSP$_F$	33.42	3.96 ab	33.27 b	2.82 ab	1.71 a	2.58 bc
SL + PG	31.29	4.54 a	32.39 b	2.90 ab	1.66 a	2.97 ab
P > F	0.176	0.004	0.044	0.012	<0.001	0.014
CV (%)	8.4	10.9	6.4	9.0	5.7	14.4
Adequate range[1]	20-34	2.1-3.3	15-30	2.5-10.0	1.5-4.0	1.5-3.0

CV: coefficient of variation. Values followed by the same letter in a column within each growing season are not significantly different at $P < 0.05$ (LSD test). [1]van Raij (2011).

Table 2.5 - Nutrient contents in soybean leaves as affected by surface application of lime (SL), SL + single superphosphate in the sowing furrow (SL + SSP$_F$), SL + single superphosphate applied by broadcast (SL + SSP$_B$), and SL + phosphogypsum (SL + PG) under a no-till cropping system in Southern Brazil.

Treatments	**Leaf nutrient concentration of soybean (g kg^{-1})**					
	N	**P**	**K**	**Ca**	**Mg**	**S**
2016–2017						
Control	64.40	8.01	27.34	9.29	3.51	2.46
SL	63.14	8.11	26.20	9.52	3.93	2.62
SL + SSP$_B$	67.34	8.26	26.58	9.30	3.78	2.59
SL + SSP$_F$	64.40	8.33	26.21	10.01	3.79	2.44
SL + PG	59.64	8.39	25.95	9.56	3.70	2.53
P > F	0.074	0.294	0.406	0.796	0.248	0.275
CV (%)	5.2	3.2	3.9	9.6	6.5	10.1
2017–2018						
Control	40.11 d	5.50 d	28.23	5.09 c	2.16 b	1.75 c
SL	45.29 c	5.74 cd	28.10	6.26 a	2.86 a	1.82 bc
SL + SSP$_B$	51.10 a	7.48 a	29.49	6.01 ab	2.86 a	2.08 a
SL + SSP$_F$	59.91 ab	6.67 ab	28.60	5.68 b	2.91 a	2.07 ab
SL + PG	48.44 b	6.54 bc	29.36	5.91 ab	2.82 a	2.13 a
P > F	<0.001	0.003	0.783	0.008	<0.001	0.021
CV (%)	3.4	9.1	6.76	6.4	5.3	8.3
2018–2019						
Control	42.98 b	4.56 b	23.05 a	6.22 d	2.58 c	1.66 b
SL	48.86 a	4.41 b	20.15 b	7.53 c	3.25 a	1.67 b
SL + SSP$_B$	50.68 a	4.77 b	20.52 b	8.51 a	2.94 b	2.34 a
SL + SSP$_F$	51.10 a	4.72 b	20.65 b	7.68 bc	3.04 ab	2.04 a
SL + PG	47.81 a	5.19 a	20.15 b	8.12 ab	3.06 ab	2.01 a
P > F	0.004	0.014	0.022	<0.001	0.005	0.004
CV (%)	5.1	5.7	5.6	4.9	6.5	11.2
2019–2020						
Control	43.22 b	5.46 c	31.38 c	5.81 b	2.52 b	1.28 c
SL	49.53 a	5.82 ab	32.14 bc	7.14 a	3.62 a	1.33 bc
SL + SSP$_B$	52.47 a	6.48 a	33.53 a	8.34 a	3.41 a	1.62 a
SL + SSP$_F$	52.06 a	5.90 b	32.64 abc	7.79 a	3.41 a	1.62 a
SL + PG	49.47 a	5.87 ab	33.15 ab	8.02 a	3.54 a	1.53 ab
P > F	0.008	0.004	0.031	0.005	<0.001	0.021
CV (%)	6.3	4.7	2.6	10.5	7.1	10.6
2020–2021						
Control	42.67 b	5.36 b	25.95	6.31 c	3.15 c	2.79
SL	49.70 a	5.86 ab	25.45	6.73 bc	3.59 a	3.25
SL + SSP$_B$	51.62 a	6.55 a	26.08	7.97 a	3.48 ab	3.36
SL + SSP$_F$	51.35 a	6.45 a	26.33	7.42 ab	3.38 b	3.18
SL + PG	50.59 a	6.41 a	26.58	7.16 b	3.49 ab	3.36
P > F	0.005	0.020	0.763	0.002	0.004	0.382
CV (%)	5.9	7.9	4.8	6.4	3.7	18.0
Adequate range[1]	40-50	2.5-5.0	17-25	4-20	3-10	2.1-4.0

CV: coefficient of variation. Values followed by the same letter in a column within each growing season are not significantly different at $P < 0.05$ (LSD test). [1]van Raij (2011).

2.3.3 Crop grain yield

Wheat grain yield assessed in the five harvests was significantly affected by treatments (Figure 2.6). In the 2016 season, wheat grain yield increased by approximately 28% with the SL, SL + SSP_B, SL + SSP_F, and SL + PG treatments compared to the control treatment (Figure 2.6a). In the 2017 season, treatments with SL, SL + SSP_B, and SL + PG increased wheat grain yield by around 61% compared to the control treatment (Figure 2.6b). In the 2018 season, the application of SL regardless of SSP_B, SSP_F, and PG increased wheat grain yield by around 30% compared to the control treatment (Figure 2.6c). Wheat grain yield in the 2019 season increased by around 54% with SL, 89% with SL + SSP_F, and 129% with SL + SSP_B and SL + PG compared to the control treatment (Figure 2.6d). In the 2020 season, compared to the control treatment, SL alone increased grain yield by around 99%, while SL + SSP_B, SL + SSP_F, and SL + PG have not differed each other and increased wheat grain yield by around 163% (Figure 2.6e). Compared to the control treatment, the cumulative grain yield of wheat, in five harvests (2016, 2017, 2018, 2019, and 2020) increased by about 40% (3.2 Mg ha^{-1}) with surface application of lime, 54% (4.4 t ha^{-1}) with surface liming combined with application of SSP in the sowing furrow, and 70% (5.6 t ha^{-1}) with surface liming combined with surface application of SSP or PG (Figure 2.6f).

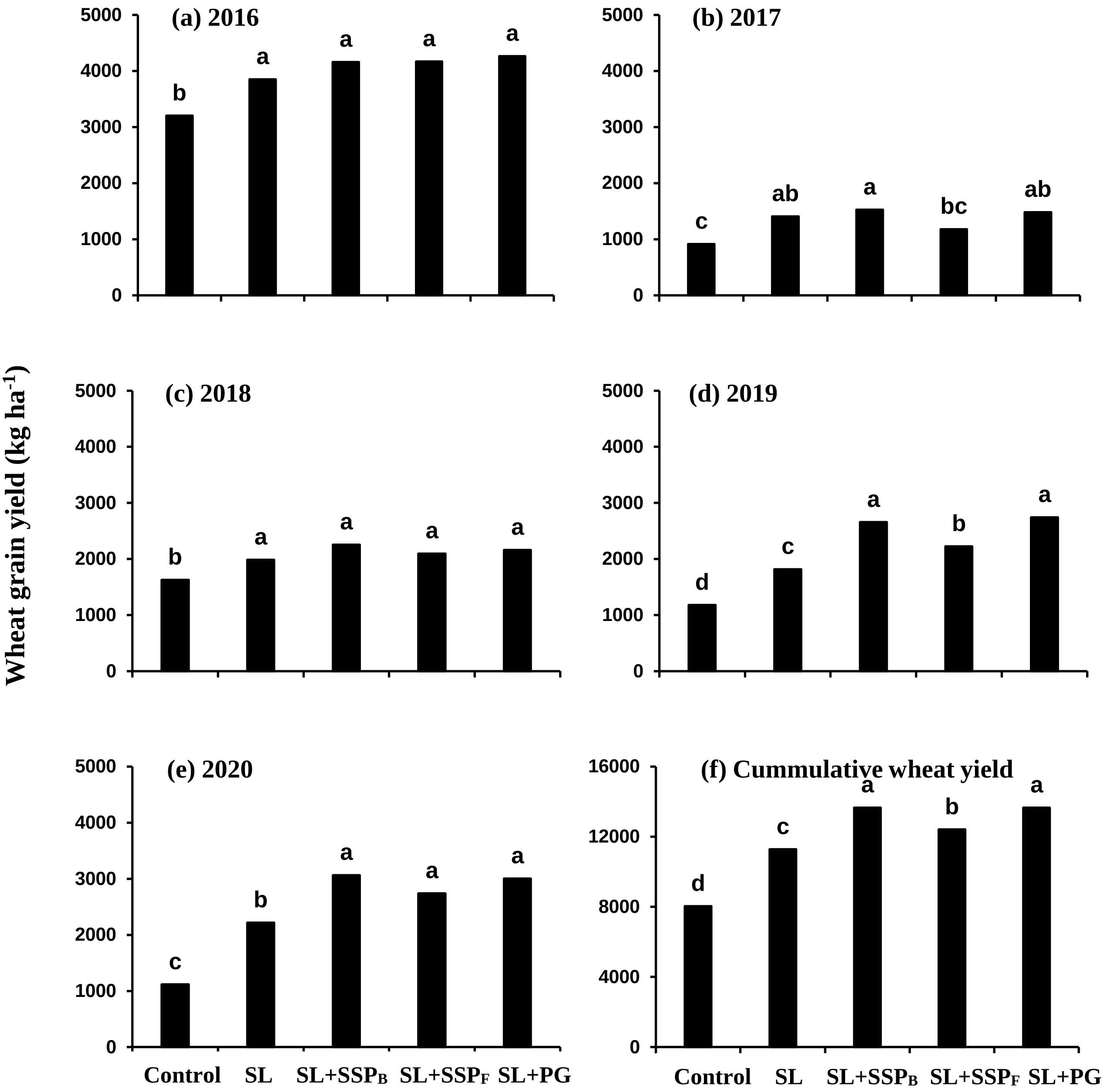

Figure 2.6 - Wheat grain yield in (a) 2016, (b) 2017, (c) 2018, (d) 2019, and (e) 2020, and (f) cumulative wheat yield as affected by surface application of lime (SL), SL + SSP$_B$ (broadcast), SL + SSP$_F$ (furrow), and SL + PG. Equal letters do not differ by LSD test at *p* = 0.05.

Soybean grain yield in all cropping seasons increased only with surface application of lime (Figure 2.7). Treatments with SL, SL + SSP$_B$, SL + SSP$_F$, and SL + PG did not differ from each other and increased soybean grain yield and cumulative soybean yield. Increases in soybean yield due to surface liming were in the order of 9% in 2016–2017 (Figure 2.7a), 64% in 2017–2018 (Figure 2.7b), 91% in 2018–2019 (Figure 2.7c), 35% in 2019–2020 (Figure 2.7d), and 17% in 2020–2021 (Figure 2.7e). The cumulative grain yield of soybean, in five harvests

(2016–2017, 2017–2018, 2018–2019, 2019–2020, and 2020–2021) increased by about 36% (5.3 Mg ha^{-1}) with surface application of lime, regardless of SSP and PG applications (7f).

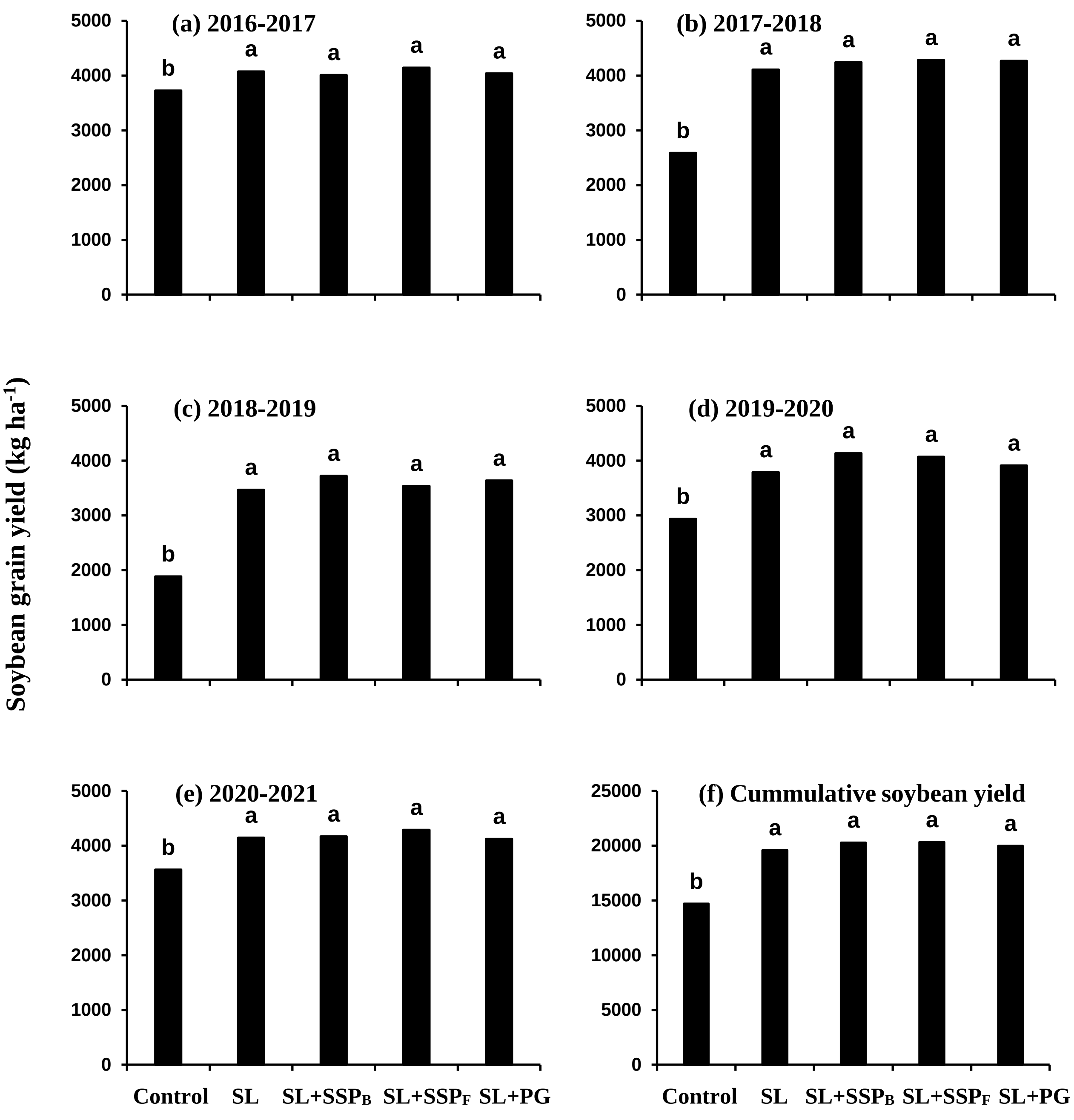

Figure 2.7 - Soybean grain yield in (a) 2016–2017, (b) 2017–218, (c) 2018–2019, (d) 2019–2020, and (e) 2020–2021, and (f) cumulative soybean yield as affected by surface application of lime (SL), SL + SSP_B (broadcast), SL + SSP_F (furrow), and SL + PG. Equal letters do not differ by LSD test at *p* = 0.05.

2.3.4 Principal component analysis

Principal component analysis performed with wheat and soybean grain yields and soil chemical properties (pH, Ca, Mg, Al, P, and SO_4-S) to a depth of 1.00 m explained 68.8% of the phenomenon in the first component and 21.2% in the second component, corresponding to 90.0% of the phenomenon (Figure 2.8). In the first principal component, there was a separation between treatments with SL (left) and without SL (right), and in the second principal component, there was a separation between treatments that received only SL (top) and when SSP_B, SSP_F, and PG were also added (bottom).

The vectors of Al in the soil profile (a, b, c, d, e, and f) point to the right where the control treatment is located, while the vectors with pH, Ca, Mg, P, and SO_4-S point to the left where the SL, SL + SSP_B, SL + SSP_F, and SL + PG treatments are located (Figure 2.8). It is clearly observed that soil pH and Ca and Mg contents have a greater influence of the SL treatment with the vectors to the left, in the opposite direction to the control treatment. Soil pH and Mg content at depth (c, d, e, and f), and Ca content increase in the direction of SL treatment (to the left and upward), showing that SL alone was more efficient in correcting soil acidity and increasing the Ca and Mg contents. The SO_4-S content in the soil profile (a, b, c, d, e, and f) and P content in the surface layers (a, b, and c) increased with SL + SSP_B, SL + SSP_F, and SL + PG, with their vectors pointing to the left and downward.

Wheat and soybean grain yields were strongly affected by the application of SL because its vectors were directed to the left (Figure 2.8), and wheat was positively affected by the addition of SSP_B, SSP_F, and PG because its vector were directed to the left and down. Wheat grain yield was positively affected by improving soil acidity (pH), increasing Ca, Mg, P, and SO_4-S contents, and decreasing Al content. Soybean grain yield showed a stronger positive correlation with pH, Ca, and Mg, and a negative correlation with Al content, but it was not affected by soil P and SO_4-S contents. Our results indicate that wheat was more responsive to P and S fertilization than soybean.

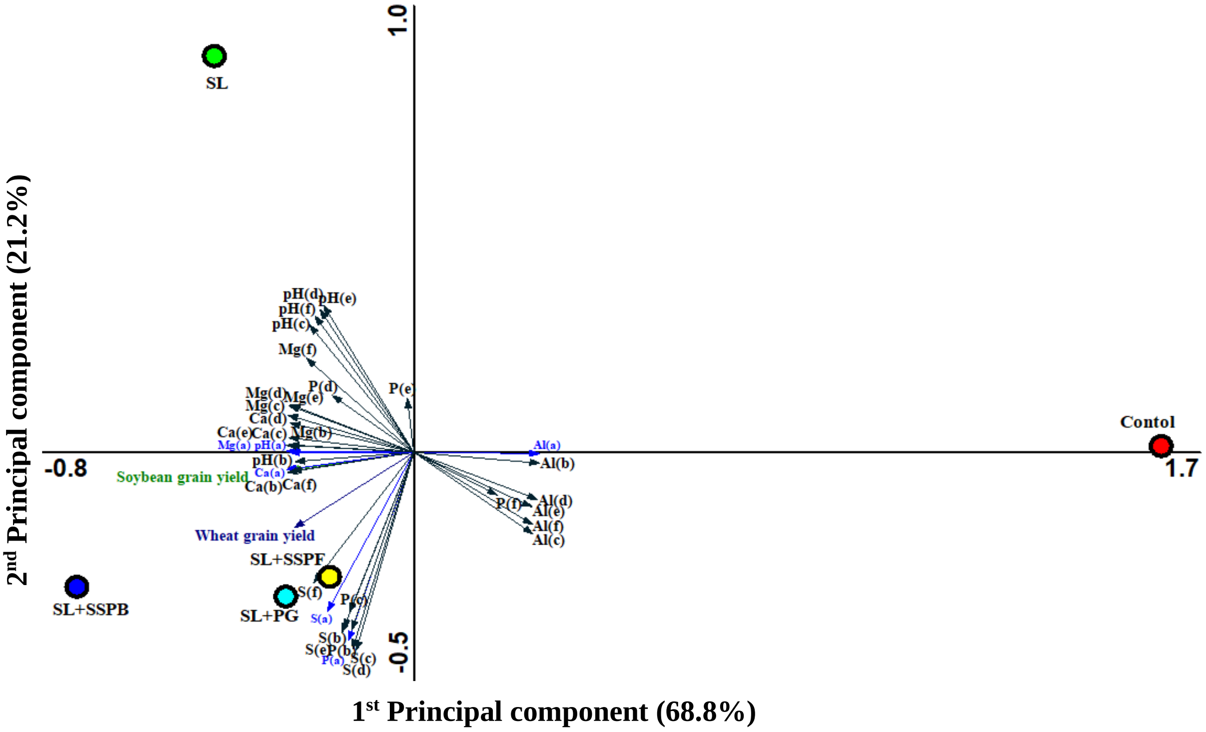

Figure 2.8 - Principal component analysis considering grain yields of wheat (2016, 2018, and 2020) and soybean (2016–2017, 2018–2019, and 2020–2021), and soil chemical properties (pH, Ca, Mg, Al, P, and SO_4-S) in 2017, 2019, and 2021. Letters following soil properties indicate the depths: a = 0–0.10 m, b = 0.10–0.20 m, c = 0.20–0.40 m, d = 0.40–0.60 m, e = 0.60–0.80 m, and f = 0.80–1.00 m.

2.4 DISCUSSION

2.4.1 Amendment effects on soil and plant nutrition

The surface application of lime improved soil acidity and chemical properties (pH in $CaCl_2$, Ca, Mg, Al, Al saturation, and base saturation) with greater intensity in the soil surface layer (0–0.10 m), although the same effect was observed to a lesser extent in subsoil layers (from 0.10 m to 1.00 m) (Figures 2.2, 2.3, and 2.4). These results are consistent with those found in the literature (CAIRES et al., 2006; 2011; SPOSITO, 2008; JORIS et al., 2016; AULLER et al., 2019). Lime, when dissolved in the soil, makes available and increases the exchangeable Ca and Mg contents in the soil, and also releases HCO_3^- and OH^- which neutralize H^+ and Al^{3+}. With the decrease in H^+ in the soil solution there is an increase in soil pH. With increasing the exchangeable Ca and Mg contents and decreasing the exchangeable Al content there is an increase in soil base saturation and a decrease in soil Al saturation.

In no-till systems, the reaction of the lime applied to the soil surface occurs with greater intensity in the topsoil (CAIRES et al., 2008; SORATTO and CRUSCIOL, 2008; CAIRES et al; 2011; 2015; CRUSCIOL et al., 2016). In addition, there is an accumulation of crop residues that increase the organic matter to the surface layer of the soil (BRIEDS et al., 2012; INAGAKI et al., 2016), which improves fertility and increases the amount of negative electrical charges in the soil, causing increased retention of cations (Ca and Mg).

No-till systems also improve aggregate formation and stability (SCHILLER et al., 2018), allowing finer lime particles to move inward and downward in the soil profile along with water infiltration, reducing acidity below the surface layer (AMARAL et al., 2004). Surface application of lime in no-till systems has been effective in correcting soil acidity below the point of application (CAIRES et al., 2008; 2011; 2015; SORATTO and CRUSCIOL, 2008; CRUSCIOL et al., 2019; VARGAS et al., 2019).

Five mechanisms of action of surface lime in correcting subsoil acidity are reported in the literature for no-till systems, which together helps explain the effect of surface lime in alleviating subsoil acidity as found in our study (OLIVEIRA and PAVAN, 1996; AMARAL et al., 2004; CAIRES et al., 2002; GASSEN and KOCHHANN, 1998; PETRERI and ANGHINONI, 2001): (i) vertical displacement of fine lime particles due to continuous porosity in the soil profile; (ii) presence of canaliculi formed by dead roots and mesofauna galleries; (iii) formation and migration of $Ca(HCO_3)_2$ and $Mg(HCO_3)_2$ in the soil profile; (iv) formation of organic compounds released by the decomposition of plant residues; and (v) formation and migration of cation pairs (Ca^{2+} and Mg^{2+}) with organic or inorganic anions (NO_3^- and SO_4^{2-}). In addition, our study was conducted in a latosol with 260 to 320 g kg^{-1} clay along the soil profile, and it rained a lot following the surface application of lime, with accumulated rainfall of 2057 mm, 5687 mm, and 8042 mm after 1 year, 3 years, and 5 years of lime application, respectively (Figure 2.1).

Although it is not possible to define the mechanism responsible for the improvement of acidity in the subsurface layers by applying lime to the soil surface, our study confirms that surface lime causes a reduction of soil acidity not only in the surface layers but also in the subsoil. The effect of surface lime on soil pH, exchangeable Ca and Mg contents, Al content, Al saturation, and base saturation (Figures 2.2, 2.3 and 2.4) was not improved with the addition of SSP by broadcast or in the sowing furrow and PG. Lime applied to the surface alone (SL) was better or equal to the SL + SSP_B, SL + SSP_F, and SL + PG treatments.

The lack of effect of adding SSP and PG on improving subsoil acidity was possibly due to the low rate applied. PG was added at a rate of 1395 kg ha^{-1}, which was calculated based on the clay content (279 g kg^{-1}) at 0.20–0.40 m depth. According to the new recommendation method based on the increase of Ca saturation in the effective cation exchange capacity at 0.20–0.40 m depth (CAIRES and GUIMARÃES, 2018), the rate of PG would be 3400 kg ha^{-1}. In the

SL + PG treatment, 238 kg ha^{-1} Ca and 196 kg ha^{-1} S were supplied in a single application via PG. In the SL + SSP$_F$ and SL + SSP$_B$ treatments, 124 kg ha^{-1} Ca and 65 kg ha^{-1} S were supplied annually via SSP application, for a total of 620 kg ha^{-1} Ca and 325 kg ha^{-1} S over the five growing seasons of wheat-soybean succession. Using the new method by Caires and Guimarães (2018), the PG rate (3400 kg ha^{-1}) would provide 578 kg ha^{-1} Ca and 476 kg ha^{-1} S. A single application of lime to the soil surface added 1262 kg ha^{-1} Ca and 671 kg ha^{-1} Mg. In addition, the application of Ca in a single rate via PG and in annual rates via SSP was not cumulative.

The treatments with SL + SSP$_B$, SL + SSP$_F$, and SL + PG increased soil P content (Figure 2.5) as each treatment added 100 kg ha^{-1} P_2O_5 annually via SSP or MAP (SL + PG). Because P is an immobile nutrient in the soil (MALAVOLTA et al., 2006; NOVAIS et al., 2007), the effects of the treatments on P content were limited only to the soil surface layer (0–0.10 m).

Soil SO_4-S levels were increased in the soil profile in the treatments where S sources were added (SL + SSP$_B$, SL + SSP$_F$, and SL + PG) (Figure 2.5). Several studies in the literature have shown similar results with an increase in SO_4-S in the soil profile after the application of S (BLUM et al., 2014; CRUSCIOL et al., 2019; CAIRES et al., 2002; 2016; 2021; DUART et al., 2021; BOSSOLANI et al., 2018; 2022). At 1 year after lime application, the treatment with SL + PG increased the SO_4-S content in the soil profile compared to the treatments with SL + SSP$_B$ and SL + SSP$_F$ due to a greater amount of S applied (196 kg ha^{-1} S with PG and 65 kg ha^{-1} S with SSP annually). The increase in soil SO_4-S with the SL + SSP$_B$ and SL + SSP$_F$ treatments followed the increase with the SL + PG treatment, with emphasis on the SL + SSP$_B$ treatment which was generally more efficient in increasing SO_4-S in the soil than the treatment SL + SSP$_F$ after 3 years and better than the treatments SL + SSP$_F$ and SL + PG after 5 years of lime application. The increase in SO_4-S over time in the SL + SSP$_B$ and SL + SSP$_F$ treatments was mainly due to the 65 kg ha^{-1} S annual application.

Overall, the SL + SSP$_B$ treatment outperformed the SL + SSP$_F$ treatment in correcting chemical properties related to soil acidity and SO_4-S content due to the fact that nutrients moving in the soil by mass flow (Ca and SO_4) present a better response when applied by broadcast to the soil surface (MALAVOLTA et al., 2006).

Surface application of dolomitic lime resulted in higher Mg-leaf content in five wheat and four soybean cropping seasons, higher Ca-leaf content in one wheat and three soybean cropping seasons, and higher N-leaf content in four soybean cropping seasons (Tables 2.4 and 2.5). When SSP or PG was added along with surface liming, there was an increase in leaf contents of P, Ca, and Mg of wheat and N, P, and Ca of soybean.

An increase in leaf contents of Ca and Mg of wheat and soybean due to application of dolomitic lime to the soil surface was also observed in other studies (CAIRES et al., 2002; CRUSCIOL et al., 2019; BOSSOLANI et al., 2022) and was mainly due to the increase in exchangeable of Ca and Mg levels in the soil profile (Figure 2.3). Surface liming combined with SSP and PG further enhanced the leaf contents of N, P, Ca, and Mg of wheat and soybean, possibly by making more P and SO_4-S available in the soil (Figure 2.5), thus improving nutrient uptake and the development of wheat and soybean crops.

2.4.2 Grain yield of wheat and soybean and correlations

Surface application of lime under a no-till cropping system efficiently increased wheat (Figure 2.6) and soybean (Figure 2.7) grain yields in the first year after application with consistent increases over the five cycles of wheat-soybean succession. The cumulative wheat and soybean grain yields increased by 40% and 36%, respectively due to surface liming. Since the average wheat and soybean yields in the control treatment were 1.6 and 2.9 Mg ha^{-1}, respectively, the surface application of lime resulted in a gain of two wheat harvests (3.2 Mg ha^{-1}) and nearly two soybean harvests (5.3 Mg ha^{-1}) in five cycles of a wheat-soybean succession. Our results are consistent with those found in the literature on increasing grain yields by applying lime to the soil surface under no-till cropping systems (CAIRES et al., 2015; CRUSCIOL et al., 2019; FIRMANO et al., 2021; HAMMERSCHMITT et al., 2021; BOSSOLANI et al., 2022). Higher grain yields of wheat and soybean with surface lime reflect improved fertility and lower acidity in the soil profile (Figures 2.2, 2.3, and 2.4) and higher Ca and Mg uptake by the plants (Tables 2.4 and 2.5).

Applications of SSP_B, SSP_F, and PG in combination with surface lime increased wheat grain yield in three of the five cropping seasons evaluated (Figure 2.6) and did not affect soybean grain yield (Figure 2.7). During the five cycles of a wheat-soybean crop succession, there was an increase in wheat grain yield of 2.7 harvests (4.4 Mg ha^{-1}) in the SL + SSP_F treatment and 3.5 harvests (5.6 Mg ha^{-1}) in the SL + SSP_B and SL + PG treatments (Figure 2.6). Soybean is considered a more rustic crop than wheat, so wheat is more likely to show a positive response to fertilization.

Overall, wheat yield was slightly lower in the SL + SSP_F treatment than in the SL + SSP_B and SL + PG treatments (Figure 2.6) probably because nutrients that move by mass flow show better performance when applied by broadcast than when applied in the sowing furrow (MALAVOLTA et al., 2006).

Based on principal components analysis (Figure 2.8), we can clearly conclude that wheat and soybean grain yields were positively correlated with soil pH, and exchangeable Ca and Mg contents, and negatively correlated with exchangeable Al content in the soil profile. However, only wheat grain yield was positively correlated with P and SO_4-S contents in the soil.

Our study confirms the importance of surface lime under no-till to reduce acidity in the soil profile with significant gains in wheat and soybean grain yields. Although the applications of SSP by broadcast or in-furrow and PG have not contributed with surface liming in improving acidity in the soil profile, their additions were important in making more P and SO_4-S available in the soil and increasing wheat yield.

2.5 CONCLUSIONS

Surface-applied lime under a no-till cropping system in Southern Brazil was effective in alleviating soil acidity from the soil surface to a 1.00 m depth. The addition of SSP broadcast or in the sowing furrow as well as PG in combination with surface liming did not cause a more pronounced improvement effect on the acidity of the soil profile.

Applications of SSP by broadcast or in the sowing furrow and PG combined with surface liming increased P content in the soil surface layer (0–0.10 m), with a more pronounced increase in soil P content when SSP was broadcast to the soil surface.

In the short term, after 1 year after lime application, the addition of PG combined with surface liming increased the SO_4-S content in the soil in the layers from 0.10 m to 1.00 m, while after 3 and 5 years of lime application there was an increase in SO_4-S content both with the use of SSP, broadcast or in the sowing furrow, and PG, with the effect being more pronounced with application of SSP by broadcast.

Lime application to the soil surface, regardless of the addition of SSP and PG, increased the leaf contents of Ca and Mg, and reduced the K-leaf content of wheat. The additions of SSP, both broadcast and in the sowing furrow, and PG increased the leaf contents of P and S of wheat. In soybean, the surface application of lime increased the leaf contents of N, Ca, and Mg, while the additions of SSP, both broadcast and in the sowing furrow, and PG increased the leaf contents of P and S.

In a wheat-soybean cropping system under no-till for five years, the cumulative grain yield of wheat increased by about 40% with surface application of lime, 54% with surface lime combined with application of SSP in the sowing furrow, and 70% with surface lime combined with surface application of SSP or PG. The cumulative grain yield of soybean increased by about 36% with surface application of lime, regardless of SSP and PG applications. Wheat was more responsive to P and S fertilization than soybean.

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CHAPTER 3: SOURCES AND APPLICATION MODES OF PHOSPHORUS IN A NO-TILL WHEAT–SOYBEAN CROPPING SYSTEM

Abstract: Grain production in Brazil takes place in acid soils with low fertility. In Brazil, phosphorus (P) is the nutrient least required by plants, but it is the most limiting for plant growth and the most used in fertilization. Fertilizer management has been carried out in the most operational and efficient way possible, with application of phosphate fertilizer in the autumn-winter crop to supply the demand of the autumn-winter and spring-summer crops. The mode of application of phosphate fertilizer has raised doubts about its efficiency in several regions of Brazil. Broadcast application of phosphate fertilizer without incorporation, while increasing operational efficiency of sowing. The lack of information with continued long-term repeatability on the application mode of P makes this work essential in providing practical information. The most commonly used P sources in agriculture are the fully acidulated as single superphosphate (SSP), triple superphosphate (TSP), monoammonium phosphate (MAP), and diammonium phosphate (DAP). This study reports a field experiment that examined the effects of P sources and modes of application on topsoil P levels, plant P nutrition, and grain yield of wheat and soybean during five cycles of a wheat–soybean cropping system under no-till. The study was carried out in five crop succession cycles with wheat-soybean in an experiment installed at Fazenda Escola Capão da Onça of the State University of Ponta Grossa, in the Center-South region of Parana. Starting in 2016, with five cycles of a wheat-soybean cropping system, a study was installed on a randomized complete block design, with four replications in a split-plot arrangement. The treatments consisted of annual applications of MAP and SSP at the rate of 100 kg ha^{-1} P_2O_5 in the wheat crop, in addition to a control treatment without P, to subplots within plots with P application in the furrow and by broadcast. The P soil concentration throughout the 5 years, levels of P leaf nutrition, and grain yield of wheat and soybean were analyzed. The soil P status are reduced in no-till with wheat-soybean succession crops without P application after 5 years. The annual application of 100 kg P_2O_5 ha^{-1} in the wheat crop as fully acidulated phosphate regardless of application mode, whether broadcast or in the sowing furrow, was sufficient for maintain an adequate level of P in the soil, supply P demand for the secession of wheat-soybean crops with high leaf P content, and obtain high grain yield. The application of phosphate fertilizers in the sowing furrow or broadcast in wheat crop using MAP or SSP as sources is a strategy that should be encouraged in highly weathered soils under no-till to minimize P fixation to soil particles, improve P- leaf content, and simultaneously increase wheat and soybean grain yields.

Key words: *Glycine max* (L.) Merrill, *Triticum aestivum* L., P efficiency management, P sources, Sustainable agriculture.

3.1 INTRODUCTION

Brazil has great importance in the world scenario in food production, being the world's largest producer of soybean [*Glycine max* (L.) Merrill] (FAO, 2021). With a production of 124 million tons of grains in the 2021/2022 harvest (CONAB, 2022), soybean is grown in Brazil in the spring-summer season. In the autumn-winter crop rotation, wheat (*Triticum aestivum* L.) is widely grown in southern Brazil, whose country is the fourth largest producer in America (FAO, 2021). With an increase of 23% in wheat production in 2021 compared to 2020, a production of 9.2 million tons of wheat could have been harvested in 2022 in Brazil (CONAB, 2022).

Grain production in Brazil takes place in acid soils with low fertility (FAGERIA, 2001; van RAIJ, 2011). In Brazil, phosphorus (P) is the nutrient least required by plants, but it is the most limiting for plant growth and the most used in fertilization (NOVAIS et al., 2007; van RAIJ, 2011).

Proper soil management through lime and fertilization is of great importance for the grain production process. The most used practice to correct the harmful effects of soil acidity in agriculture is the application of lime [calcium carbonate ($CaCO_3$) and magnesium carbonate ($MgCO_3$)] (CAIRES et al., 2000; 2002; 2005; CRUSCIOL et al., 2019). No-till systems have emerged as one of the most effective strategies to improve the sustainability of agriculture in tropical and subtropical regions. In Brazil, the cultivated area with no-till systems exceeded 33 million hectares (FEBRAPDP, 2021). No-till provides a potential physical mechanism for the protection of soil organic carbon (SOC), contributing to minimizing soil and nutrient losses through erosion, and increasing the long-term natural soil fertility (LAL, 1995; HOBBS et al., 2008; CAIRES et al., 2011; GONZALEZ-SANCHEZ et al. 2019; COOPER et al. 2021).

Due to the huge global demand of fertilizers for agriculture, which represents around 28% of the production cost in soybean and wheat crops (CONAB, 2016; CONAB, 2018), efforts have been made to progressively improve the fertilizer use efficiency (NOVAIS et al., 2007, CAIRES et al., 2017). Brazil has emphasized to be inefficient in the current P use, for applying amounts in excess of crop demand and increasing P level in the soil (WITHERS et al., 2018).

With the potential to reduce the use of inorganic P inputs to a level close to maintenance to improve the P use efficiency, it is recommended the use of combined management of no-till, cover crop, correction of soil acidity, and adoption of the 4R principles of nutrient management (Right rate, Right source, Right time, and Right place) (IPNI, 2012; SOUZA et al., 2016). Fertilizer management has been carried out in the most operational and efficient way possible, with application of phosphate fertilizer in the autumn-winter crop to supply the demand of the autumn-winter and spring-summer crops (CAIRES et al., 2017).

The mode of application of phosphate fertilizer has raised doubts about its efficiency in several regions of Brazil. Broadcast application of phosphate fertilizer without incorporation, while increasing operational efficiency of sowing (FINK et al., 2016; OLIBONE and ROSOLEM, 2010), can lead to a less efficient P uptake than the application of the seeding furrow (SCHMIDT et al., 1997). The lack of information with continued long-term repeatability on the application mode of P makes this work essential in providing practical information. The most commonly used P sources in agriculture are the fully acidulated as single superphosphate (SSP), triple superphosphate (TSP), monoammonium phosphate (MAP), and diammonium phosphate (DAP).

This study reports a field experiment that examined the effects of P sources and modes of application on topsoil P levels, plant P nutrition, and grain yield of wheat and soybean during five cycles of a wheat–soybean cropping system under no-till. We hypothesized that the efficiency of P fertilization does not change with the application mode, whether by broadcasting or in sowing furrow, using fully acidulated fertilizers (MAP and SSP) in a no-till Oxisol with high P content.

3.2 MATERIAL AND METHODS

3.2.1 Characterization of the area

The study was carried out in five crop succession cycles with wheat-soybean in an experiment installed at Fazenda Escola Capão da Onça of the State University of Ponta Grossa, in the Center-South region of Parana (south latitude 25°05'35" and longitude west 50°02'49"). The local climate is categorized as Cfb type (mesothermal, humid, subtropical), with cool summers and frequent frosts during winter, with no defined dry season (PEEL et al., 2007). The annual precipitation is around 1550 mm, and the average maximum and minimum temperatures are 22 and 13°C, respectively.

The soil in the experimental area is classified as dystrophic Red Latosol of medium texture, cultivated under a no-till system. Table 3.1 shows the results of chemical (PAVAN et., 1992) and particle-size distribution (EMBRAPA, 2011) analyses at different soil depths (0–10 and 10–20 cm) in May 2016 before the establishment of the experiment.

Table 3.1 - Results of chemical and particle-size distribution analyses at different soil depths (0–10 and 10–20 cm) in May 2016 before the establishment of the experiment in Ponta Grossa, Southern Brazil.

Depth	**pH (1)**	**Al**	**Ca**	**Mg**	**K**	**CTC(2)**	**V(3)**	**m(4)**	**P (5)**	**S**	**C**	**Clay**	**Silt**	**Sand**
cm		------- mmol$_c$ dm^{-3} ---------					--- % ---		- mg dm^{-3}-		g dm^{-3}	- - - - g kg^{-1} - - - - -		
0–10	4.5	6	16	6	1.4	92,8	25	20	45.5	3.7	17	260	57	683
10–20	4.0	12	5	3	1.1	99,2	9	57	6.7	5.7	12	260	51	689

[1] pH in 0,01 mol L^{-1} $CaCl_2$; [2] Cation exchange capacity (Ca + Mg + K + H + Al); [3] V: base saturation; [4] m: Al saturation; [5] Phosphorus extracted by Mehlich-1.

On June 3, 2016, dolomitic lime [327 g kg^{-1} of CaO, 206 g kg^{-1} of MgO, and 95% effective calcium carbonate equivalent (ECCE)] was surface-applied at the rate of 5.4 Mg ha^{-1} to increase the soil base saturation in the 0–20 cm layer to 70% (CAIRES et al., 2005).

3.2.2 Experimental design

Starting in 2016, with five cycles of a wheat-soybean cropping system, a study was installed on a randomized complete block design, with four replications in a split-plot arrangement. Plot size was 45 by 6 m and subplot size were 15 by 6 m (90 m^2). The treatments consisted of annual applications of P sources (PS), MAP and SSP at the rate of 100 kg ha^{-1} P_2O_5 in the wheat crop, in addition to a control treatment without P, and in subplots application modes (AM) within plots with P application in the furrow and by broadcast. The fertilizers used had the following compositions: MAP (11% N and 52% P_2O_5) and SSP (3% N, 17% P_2O_5, and 11% S). Phosphate fertilizers in the sowing furrow were applied in a mechanized way together with the sowing of wheat using a no-till seeder, placing the fertilizers beside and below the seeds. When phosphate fertilizers were applied by broadcast, the application was carried out manually in the total area on the surface at the time of wheat sowing. To balance the amount of S added with the SSP application, the MAP treatment received 65 kg S ha^{-1} as elemental S annually broadcast on the soil surface.

3.2.3 Crop management

The study was carried out from 2016 to 2021 with wheat (*Triticum aestivum* L.) in the autumn-winter season and soybean [*Glycine max* (L.) Merrill] in the spring-summer season. More details about crops and fertilization throughout the experiment period are shown in Table 3.2. Wheat was sown at a rate of 250 kg ha^{-1} of seeds and row spacing of 0.17 m. Based on the composition of the phosphate fertilizers, nitrogen (N) was applied annually at wheat sowing at a rate of 21 kg N ha^{-1} via MAP and 18 kg N ha^{-1} via SSP. In top dressing to the wheat crop, N was applied as urea at a rate of 100 kg N ha^{-1} in 2016, 2017, 2018, and 2019, and 120 kg N ha^{-1} in 2020 (60 to 80 kg N ha^{-1} at the beginning of tillering and 40 kg ha^{-1} at the end of booting). Soybean was sown at a rate of 14 seeds m^{-1} (inoculated with *Bradyrhizobium japonicum*) and row spacing of 0.45 m, without P fertilization. In all wheat and soybean crops, potassium chloride (KCl – 60% K_2O) was surface-applied immediately after sowing at a rate at 84 kg K_2O ha^{-1}. The phytosanitary management was carried out according to the needs of wheat and soybean crops to obtain adequate plant health during the development cycle.

Table 3.2 - Cropping sequence and amounts (kg ha^{-1}) of nitrogen (N), phosphorus (P), potassium (K) and sulfur (S) applied from 2016 to 2020 in an experiment under a continuous no-till system in Southern Brazil

Year	**Crop**	**Cultivation**	**Sowing**	**Cultivar**	**N^1**	**P_2O_5^{2}**	**K_2O^{3}**	**S^4**
2016	Wheat	Autumn-Winter	June	TBIO Toruk	100	100	84	65
	Soybean	Spring-Summer	December	Nidera 5909 IPRO	0	0	84	0
2017	Wheat	Autumn-Winter	June	TBIO Iguaçu	100	100	84	65
	Soybean	Spring-Summer	November	Nidera 5445 IPRO	0	0	84	0
2018	Wheat	Autumn-Winter	July	Quartzo	100	100	84	65
	Soybean	Spring-Summer	December	LG 60158 IPRO	0	0	84	0
2019	Wheat	Autumn-Winter	June	TBIO Toruk	100	100	84	65
	Soybean	Spring-Summer	December	Nidera 5445 IPRO	0	0	84	0
2020	Wheat	Autumn-Winter	June	TBIO Ponteiro	120	100	84	65
	Soybean	Spring-Summer	November	Nidera 5445 IPRO	0	0	84	0

[1]Ureia in top-dressing; [2]MAP and SSP application in the furrow and by broadcast; [3]Potassioum chloride; [4]SSP and elemental S.

3.2.4 Rainfall

The monthly rainfall data from the beginning of the experiment (June 2016) to the conclusion of the present study (May 2021) are in Figure 3.1. The wheat crop was more influenced by drought stress during the development cycle than the soybean crop. Rainfall above the region's historical average in 2016 favored wheat grain yield. In the following years (2017, 2018, 2019, and 2020), rainfall was below the historical average for the region after wheat sowing, which compromised plant development and grain yield. It rained well during soybean development in most crop cycles.

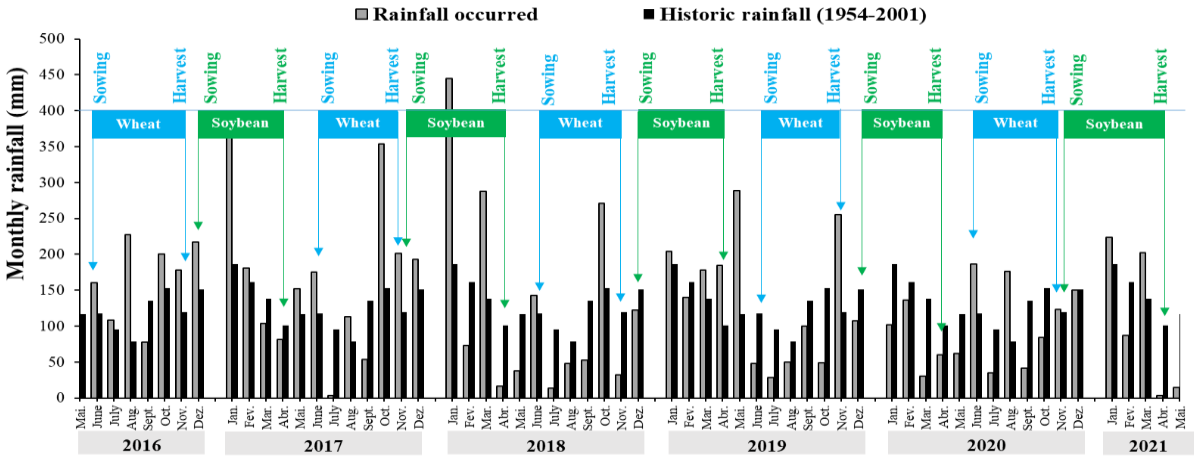

Figure 3.1 - Monthly and historical rainfall of the region from the beginning (June 2016) until the conclusion of the experiment (May 2021). Source: Monthly rainfall data obtained from BASF's meteorological station, located on the Capão da Onça farm. Historical average rainfall data (1954 and 2001), obtained from the meteorological station of the Agronomic Institute of Paraná (IAPAR, 2022).

3.2.5 Soil sampling and chemical analysis

Soil samples were taken after the soybean harvest in 2017, 2019, and 2021, at 1, 3, and 5 years after the beginning of the experiment. Using a soil probe sampler, 10 soil cores were collected per subplot to constitute a composite sample at 0–10 and 10–20 cm depths. Then, the soils were air-dried and ground to pass through a 2 mm sieve. Extractable P was extracted by a Mehlich-1 solution (0.05 mol L^{-1} H_2SO_4 + 0.05 mol L^{-1} HCl), according to standard methods used by the Agronomic Institute of Parana State (PAVAN et al., 1992). Phosphorus was determined by UV-visible spectrophotometry.

3.2.6 Leaf sampling and chemical analysis

Wheat and soybean leaf samples were collected from 30 plants per subplot during the flowering period of the crops for foliar diagnosis. In wheat crop was collected the flag leaf, and in the soybean crop the third trifoliate was collected from the apex of the plants. The samples were washed with deionized water, dried in a forced-air oven at 60°C until a constant mass achieved, and were ground. The leaf tissue analysis was performed using nitric-perchloric acid digestion, and P concentration was determined by the metavanadate colorimetry method (MALAVOLTA et al., 1997).

3.2.7 Crop grain yield

Grain harvests were carried out mechanically in the central rows after the physiological maturity of wheat and soybean crops. In each subplot, soybean grain was harvest from 27 m^2 (middle 4 rows by 15 m in length), and wheat grain was harvest from 24 m^2 (1.6 m × 15 m in length). Grain yield was expressed at 130 g kg^{-1} of moisture content.

3.2.8 Statistical analysis

The results were submitted to an analysis of variance (ANOVA) according to the model of randomized complete block design in a split-plot arrangement. When there was no significant interaction between application modes (AM) and P sources (PS), data were analyzed by means of observations. When a significant interaction between AM and PS was found, the treatment effects were unfolded. Treatment means were compared using the LSD test ($p<0.05$). Statistical analyses were performed with the help of Sisvar statistical programs (FERREIRA, 2011).

3.3 RESULTS

3.3.1 Soil P change

The analysis of variance showed a significant interaction ($p<0.05$) between application modes (AM) and P sources (PS) for the P content in the soil surface layer (0–10 cm) in the three soil sampling times (1, 3, and 5 years of the beginning of the experiment). After the first cycle of wheat-soybean succession (first soil sampling, 2017), when the P source was applied in the sowing furrow, SSP increased soil P content at 0–10 cm depth compared to MAP, which in turn was superior to the control treatment (Figure 3.2). When the P source was applicated by broadcast, there was no significant difference in soil P content at 0–10 cm depth between the MAP and SSP applications, although they were superior compared to control. Only broadcast application of MAP increased the P content in the soil at a depth of 0–10 cm depth compared to application in the sowing furrow. At the 10–20 cm depth, the application of SSP provided higher P content compared to the control treatment, and the application of P in the broadcast provided higher P content compared to the sowing furrow.

After the third cycle of wheat-soybean succession (second soil sampling, 2019), the application of P by broadcast increased soil P content at the 0–10 cm depth compared to the application of P in the sowing furrow for the two P sources used (MAP and SSP) (Figure 3.2). The application of SSP in the sowing furrow increased the P soil content compared to the treatments with MAP and control. However, with broadcast application of P, both MAP and SSP increased soil P content at 0–10 cm depth compared to the control treatment, but there was no difference between them. At the 10–20 cm depth, soil P content was not influenced by P sources and modes of application.

After the five cycle of wheat-soybean succession (third soil sampling, 2021), the application of P by broadcast increased soil P content at 0–10 cm depth compared to the application in the sowing furrow just with MAP (Figure 3.2). When P fertilization was applied in the sowing furrow, there was no difference in the soil P content at 0-10 cm depth with the MAP and SSP applications, although both increased the P content in the soil compared to the control treatment. When P fertilization was applied by broadcast, the treatment with MAP increased the P soil content compared to the SSP treatment which in turn was higher than the control treatment. At the 10–20 cm depth, soil P content was not influenced by P sources and modes of application.

The P source applied annually to supply the P demand for the wheat-soybean succession-maintained P levels in the soil over time (Figure 3.3). In the first soil sampling (2017), one year after the beginning of the experiment, a reduction in soil P levels at 0–10 and 10–20 cm depths were observed in the control treatment (without P) compared to treatments with MAP and SSP. After three years (second soil sampling, 2019), MAP showed a lower soil P content than SSP at 0–10 cm depth, but the soil P content was still close to the initial one, while the control treatment showed even lower P content; at 10–20 m depth there was no difference in soil P content. At five years after the beginning of the experiment (2021), the control treatment showed a lower P level compared to treatments with MAP and SSP at 0–10 cm depth; at 10–20 cm depth, the control treatment showed lower soil P content than the MAP treatment.

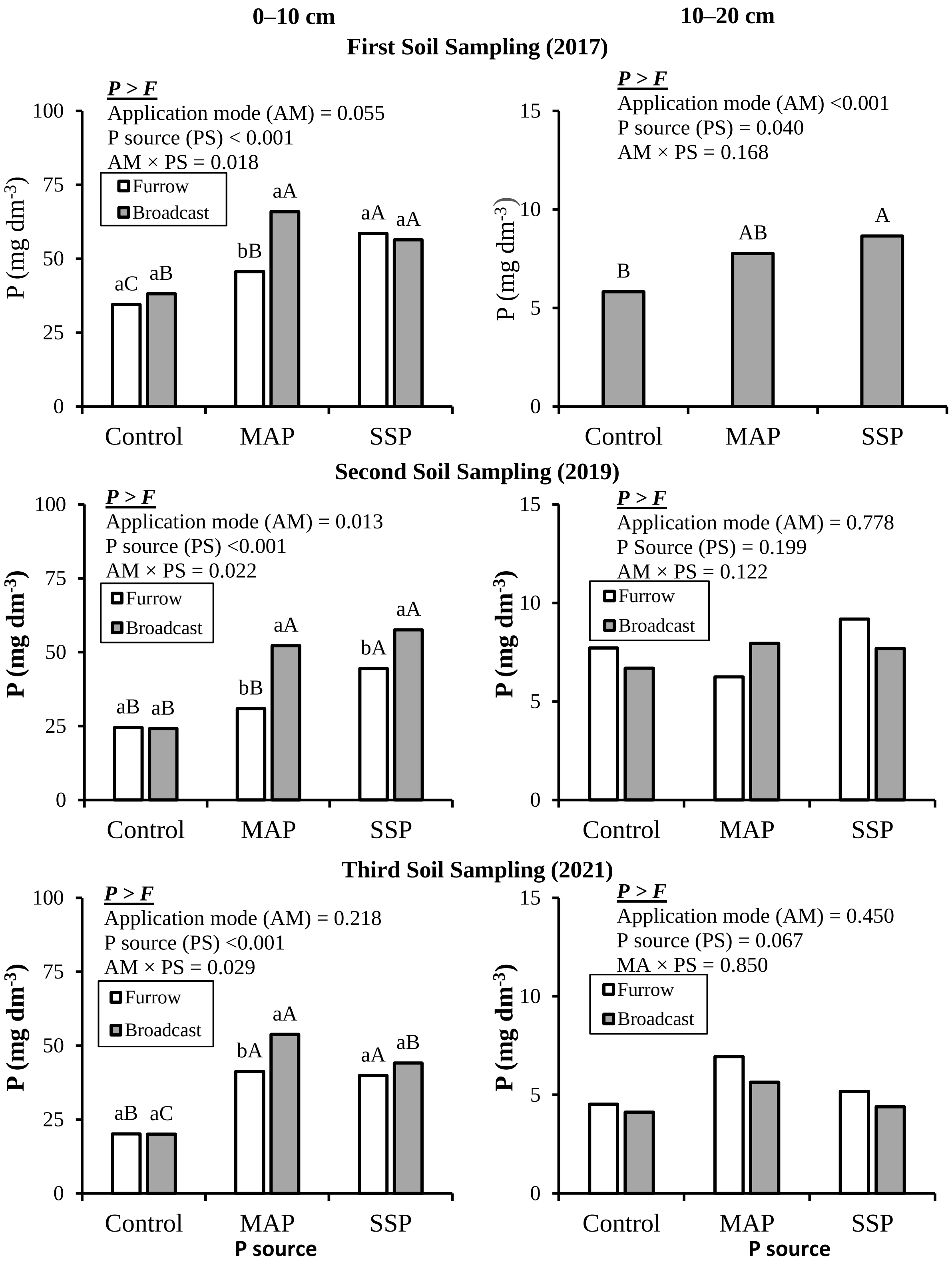

Figure 3.2 - P (Mehlich-1) levels in the soil at the 0–10 and 10–20 cm depths after the soybean harvest in 2017 (first soil sampling), 2019 (second soil sampling), and 2021 (third soil sampling) as affected by application mode (AM) and P sources (PS). Equal letters lowercase for application mode and uppercase for P sources do not differ from each other by the LSD test. Ponta Grossa-PR, Southern Brazil.

In the soil surface layer (0–10 cm), there was a decrease in soil P content with over time (Figure 3.3). In the control treatment, the reduction in soil P level was in the order at 20%, 46%, and 56%, respectively at 1, 3, and 5 years after the beginning of the experiment. When phosphate fertilizers were applied, soil P content increased in the order of 24% after 1 year, and stabilized the levels close to the initial soil P content in 2016 after 3 and 5 years. At 10–20 cm depth, the reduction in soil P content was in the order of 13% in the control treatment at 1 year after the beginning of the experiment, and there was a greater reduction in soil P content at 5 years, which was around 36% in the control treatment, 28% with SSP, and 6% with MAP.

Even with the reductions observed in soil P content, the P levels remained at values considered high for the Parana State (> 18 mg kg^{-1}) including control treatment (PAULETTI and MOTTA, 2017). Thus, the level of P in the soil was not a limiting factor for the productive potential of wheat and soybean crops.

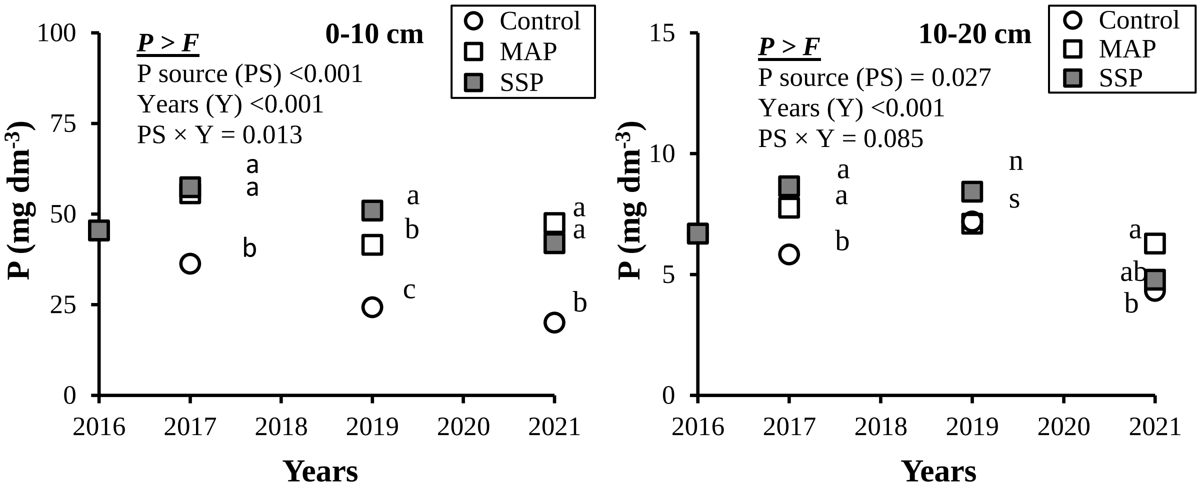

Figure 3.3 - P levels (Mehlich-1) in the soil at the 0–10 and 10–20 cm depths considering the P sources (Control, MAP, and SSP) throughout the growing years. Equal letters within each year do not differ from each other by the LSD test. Ponta Grossa-PR, Southern Brazil.

3.3.2 P nutrition of wheat and soybean plants

Leaf P contents of wheat (Table 3.3) and soybean (Table 3.5) remained at levels considered adequate or above (van Raij, 2011) in all growing seasons. The modes of P application did not influence the leaf P content of wheat and soybean in the five cycles of wheat-soybean succession.

Phosphate fertilization with both MAP and SSP increased leaf P content of wheat in 2017 and 2020. (Table 3.3). In 2020, a significant interaction (p<0.05) between application mode (AM) and P source (PS) was found for the leaf P content of wheat. The unfolding of this interaction revealed that P application in the sowing furrow increased the P leaf content of wheat compared to the application by broadcast only when using MAP (Table 3.4). When the application was broadcast, the fertilizations with MAP and SSP increased the leaf P content of wheat in an equivalent way compared to the control treatment. However, when P fertilization was in the sowing furrow, the increase in leaf P content of wheat was in the following order: MAP > SSP > control.

Table 3.3 - Leaf P content of wheat as affected by application mode (MA) and P sources (PS). Ponta Grossa-PR, Southern Brazil.

Treatment	**Leaf P content of wheat (g kg^{-1})**				
	2016	**2017**	**2018**	**2019**	**2020**
Application mode (AM)					
Broadcast	4.06	4.54	4.92	4.17	3.74
Furrow	4.01	4.26	4.92	4.22	3.90
CV (%)[1]	5.9	5.9	4.7	3.9	9.2
P source (PS)					
Control	3.84	3.93 b	4.85	4.20	3.26 b
MAP	4.19	4.62 a	5.00	4.26	4.16 a
SSP	4.08	4.65 a	4.92	4.13	4.03 a
CV (%)	6.6	7.4	4.6	10.1	6.9
Adequate range[2]	2.1-3.3	2.1-3.3	2.1-3.3	2.1-3.3	2.1-3.3
			P > F		
AM	0.693	0.076	0.942	0.447	0.334
PS	0.066	0.001	0.436	0.832	<0.001
AM × PS	0.847	0.331	0.426	0.982	0.025

[1]CV (%) = coefficient of variation. [2]van Raij (2011). Equal letters do not differ by the LSD test at *p*<0.05.

Table 3.4 - Unfolding in the interaction of leaf P content of wheat in 2020 as affected by application mode (AM) and P sources (PS) in a wheat-soybean cropping system under no-till. Ponta Grossa-PR, Southern Brazil.

Treatment	**P source (PS)**			***P > F***
	Control	**MAP**	**SSP**	
Application mode (AM)		kg ha^{-1}		
Broadcast	3.27 aB	3.84 bA	4.10 aA	0.002
Furrow	3.25 aC	4.49 aA	3.96 aB	<0.001
P > F	0.938	0.005	0.477	

Equal lowercase letters in the column and uppercase in the row do not differ from each other by the LSD test at *p*<0.05.

There was an increase in leaf P content of soybean with SSP in the 2017-2018 and 2019-2020 seasons, with MAP in the 2018-2019 season, and with both SSP and MAP in the 2020-2021 season compared to the control treatment (Table 3.8).

Table 3.5 - Leaf P content of soybean as affected by application mode (MA) and P sources (PS). Ponta Grossa-PR, Southern Brazil.

Treatment	**Leaf P content of soybean (g kg^{-1})**				
	2016-2017	**2017-2018**	**2018-2019**	**2019-2020**	**2020-2021**
Application mode (AM)					
Broadcast	8.09	6.73	4.82	6.17	6.39
Furrow	8.16	6.19	4.73	5.89	6.22
CV (%)[1]	4.3	7.6	5.1	8.6	3.9
P source (PS)					
Control	8.03	5.90 b	4.55 b	5.76 b	5.91 b
MAP	8.05	6.39 b	5.03 a	6.12 ab	6.51 a
SSP	8.29	7.08 a	4.74 ab	6.19 a	6.50 a
CV (%)	5.5	9.0	5.9	5.7	3.2
Adequate range[2]	2.5-5.5	2.5-5.5	2.5-5.5	2.5-5.5	2.5-5.5
			P > F		
MA	0.643	0.075	0.473	0.275	0.193
PS	0.458	0.006	0.016	0.041	<0.001
AM × PS	0.929	0.700	0.444	0.159	0.532

[1]CV (%) = coefficient of variation. [2]van Raij (2011). Equal letters do not differ by the LSD test at $p<0.05$.

3.3.3 Wheat grain yield

Wheat grain yield was higher in the first harvest (2016) compared to subsequent harvests (Table 3.6). This can be explained by the fact that in the first wheat season the monthly rainfall was above the historical average and well distributed, while in the following seasons, drought stress occurred at some important moment in the wheat development cycle (Figure 3.1), compromising grain yield. Sources and application modes of P did not significantly influence wheat grain yield in the first three growing seasons (2016, 2017, and 2018). The average grain yields obtained in these harvests were 4163, 1329, and 2111 kg ha^{-1}, respectively. A significant interaction ($p<0.05$) between AM and PS was found for the wheat grain yield in 2019 (Table 3.7). The unfolding of this interaction revealed that wheat yield in 2019 was higher with P application in the sowing furrow compared with broadcast application when MAP was used for fertilization (Table 3.7). The SSP application modes did not influence the wheat grain yield. When phosphate fertilization was carried out by broadcast, both MAP and SSP did not cause gains in wheat grain yield. An increase in the order of 60% in wheat grain yield was observed with the application of MAP in the sowing furrow. Regardless of the mode of application, wheat grain yield in 2020 followed the following order: SSP > MAP > control.

Table 3.6 - Wheat grain yield as affected by application mode (MA) and P sources (PS) in a wheat-soybean cropping system under no-till. Ponta Grossa-PR, Southern Brazil.

Treatment	**Wheat grain yield**				
	2016	**2017**	**2018**	**2019**	**2020**
			kg ha^{-1}		
Application mode (AM)					
Broadcast	4331.8	1384.0	2163.3	2387.3	2649.3
Furrow	3993.7	1273.3	2059.3	2321.8	2561.1
CV (%)[1]	21.4	13.1	11.2	15.9	7.4
P source (PS)					
Control	3685.5	1376.4	2019.9	2076.6 b	2253.8 c
MAP	4639.6	1257.4	2138.1	2546.6 a	2660.4 b
SSP	4163.2	1352.2	2175.9	2440.4 ab	2901.4 a
CV (%)	20.6	18.7	8.0	16.8	7.2
			P > F		
AM	0.422	0.216	0.361	0.696	0.345
PS	0.126	0.397	0.202	0.082	<0.001
AM × PS	0.159	0.283	0.854	0.013	0.088

[1] CV (%) = coefficient of variation. Equal letters do not differ by the LSD test $p<0.05$.

Table 3.7 - Unfolding of the interaction of wheat grain yield in 2019 as affected by application mode (AM) and P sources (PS) in a wheat-soybean cropping system under no-till. Ponta Grossa-PR, Southern Brazil.

Treatment	**P sources (PS)**			***P > F***
	Control	**MAP**	**SSP**	
Application mode (AM)		kg ha^{-1}		
Broadcast	2335.4 aA	2170.0 bA	2656.6 aA	0.245
Furrow	1817.8 aB	2923.3 aA	2224.3 aB	0.006
P > F	0.089	0.020	0.149	

Equal lowercase letters in the column and uppercase in the row do not differ from each other by the LSD test at $p<0.05$.

The cumulative wheat grain yield over the five harvests (2016, 2017, 2018, 2019, and 2020) was not significantly influenced by application modes of P, reaching an average cumulative wheat grain yield of 12562 kg ha^{-1} (Figure 3.4A). Phosphate fertilization with both MAP and SSP increased cumulative wheat grain yield compared to the control treatment by around 15% (1725 kg ha^{-1}) (Figure 3.4B).

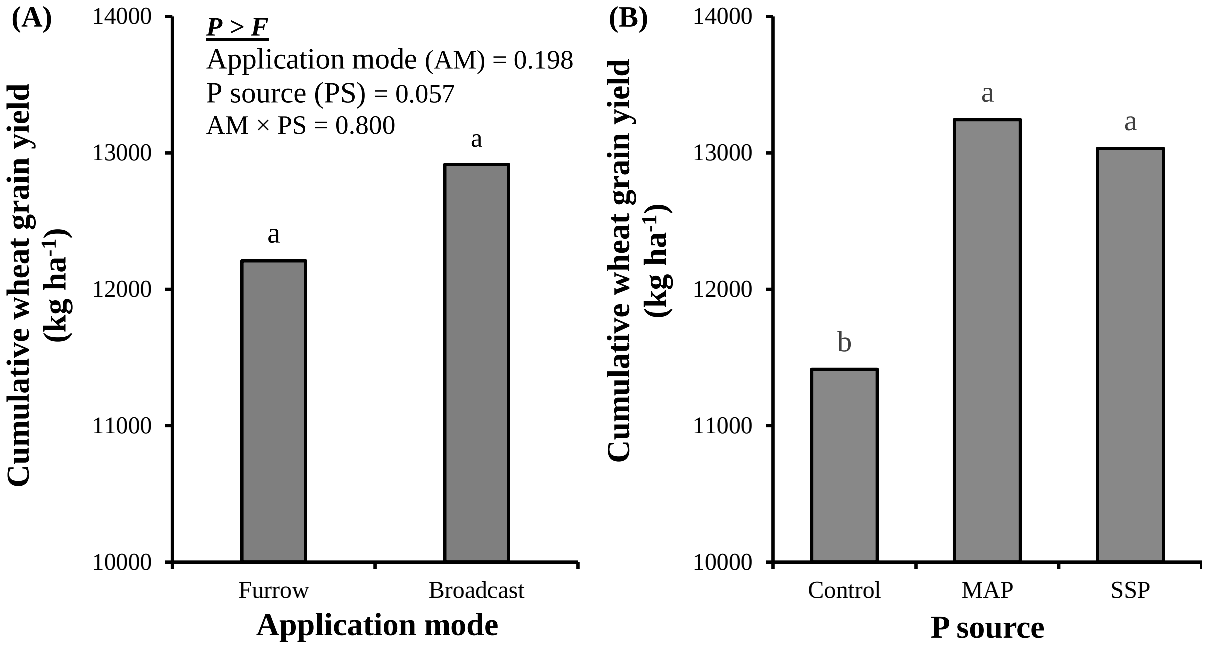

Figure 3.4 - Cumulative wheat grain yield of the 2016, 2017, 2018, 2019, and 2020 harvests as affected by application mode (A) and P sources (B). Equal letters do not differ by the LSD test at $p<0.05$. Ponta Grossa-PR, Southern Brazil.

3.3.4 Soybean grain yield

No significant interaction of AM and PS on the soybean grain yield of five harvests (2016-2017, 2017-2018, 2018-2019, 2019-2020, and 2020-2021) was observed (Table 3.8). The modes of P application did not cause significant changes in the soybean grain yield of the five harvests. The average soybean yields obtained were 4044, 4133, 3545, 4001 and 4179 kg ha^{-1}, respectively in 2016-2017, 2017-2018, 2018-2019, 2019-2020, and 2020-2021. Phosphate fertilizers influenced soybean grain yield in the 2017-2018 (P = 0.029) and 2019-2020 (P = 0.065) growing seasons. In the 2017-2018 season, SSP fertilization increased soybean grain yield by around 5% compared to the MAP and control treatments. In the 2019-2020 season, both SSP and MAP increased soybean grain yield by around 7% compared to the control treatment.

Table 3.8 - Soybean grain yield as affected by application mode (MA) and P sources (PS) in a wheat-soybean cropping system under no-till. Ponta Grossa-PR, Southern Brazil.

Treatment	**Soybean grain yield**				
	2016-2017	**2017-2018**	**2018-2019**	**2019-2020**	**2020-2021**
			kg ha^{-1}		
Application mode (AM)					
Broadcast	4002.2	4093.5	3568.2	4008.3	4156.3
Furrow	4085.1	4172.3	3522.3	3994.7	4201.8
CV (%)[1]	6.9	5.7	14.0	2.4	6.4
P source (PS)					
Control	4022.7	4056.3 b	3422.2	3812.7 b	4109.0
MAP	4031.9	4078.6 b	3583.7	4088.4 a	4200.0
SSP	4076.4	4263.8 a	3629.9	4103.5 a	4228.2
CV (%)	3.1	3.5	8.1	6.2	3.0
			P > F		
MA	0.521	0.473	0.835	0.754	0.705
PS	0.667	0.029	0.353	0.065	0.190
AM × PS	0.573	0.888	0.638	0.831	0.367

[1]CV (%) = coefficient of variation. Equal letters do not differ by the LSD test at $p<0.05$.

The cumulative soybean grain over the five harvests was not significantly influenced by the application modes of P or by the interaction of application modes × P sources (Figure 3.5). The average cumulative soybean grain yield obtained in the five harvests was 19902 kg ha^{-1} (Figure 3.5A). Phosphate fertilization with both MAP and SSP caused an average increase of around 4% in the cumulative soybean yield (Figure 3.5B).

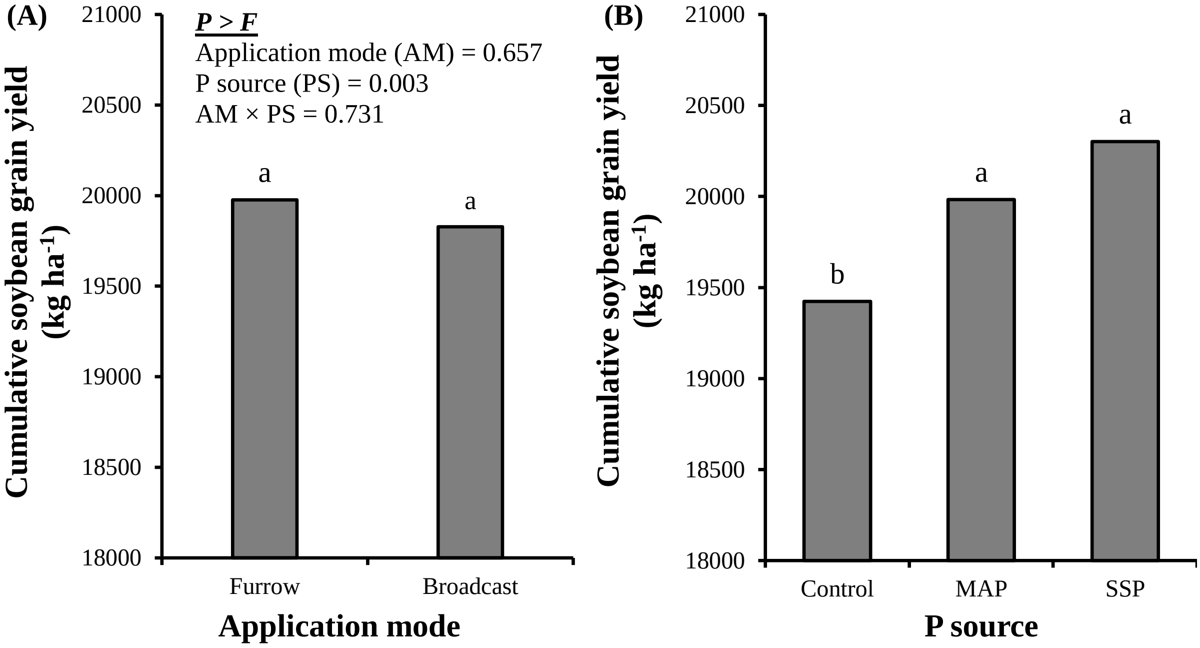

Figure 3.5 - Cumulative soybean grain yield of the 2016-2017, 2017-2018, 2018-2019, 2019-2020, and 2020-2021 harvests as affected by application mode (A) and P source (B). Equal letters do not differ by the LSD test at $p<0.05$. Ponta Grossa-PR, Southern Brazil.

3.3.5 Correlation test between relative cumulative grain yield and soil P content

Soil P content in the surface layer (0–10 cm depth) was positively ($p<0.01$) correlated with the relative cumulative grain yields of wheat (r = 0.56) (Figure 3.6A) and soybean (r = 0.58) (Figure 3.6C). Soil P content at the 10–20 cm depth did not correlate with the relative cumulative grain yields of wheat (Figure 3.6B) and soybean (Figure 3.6D).

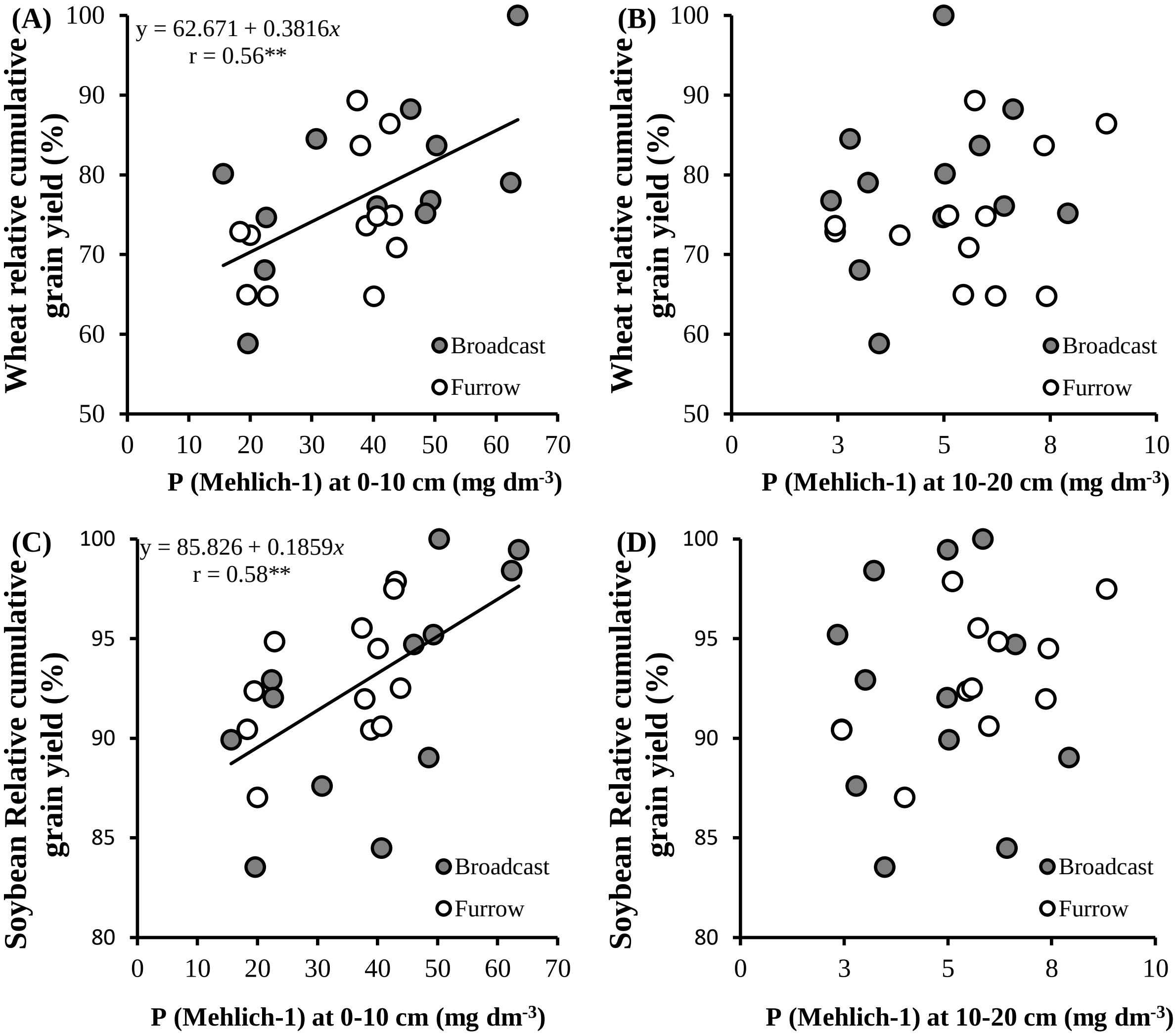

Figure 3.6 - *Pearson's* simple correlation test of relative cumulative grain yields of wheat and soybean vs. soil P content at depths of 0-10 and 10-20 cm. Soil sampled in 2021 at 5 years of begging of experiment. ** $p<0.01$. Ponta Grossa-PR, Southern Brazil.

3.4 DISCUSSION

3.4.1 Soil-P status changes

The low soil P content may limit the productive potential of crops (CORDELL and NESET, 2014). Levels between 9 and 12 mg dm^{-3} of P-Mehlich-1 are considered average levels in soils with clay content between 250 and 400 g kg^{-1} under no-till systems in the Parana State

(PAULETTI and MOTTA, 2017). The soil P level at the beginning of the experiment was considered very high (>18 mg dm^{-3}) with contents of 45.5 and 6.7 mg dm^{-3} at the 0–10 and 10–0.20 cm depths, respectively (Table 3.1), or 26.1 mg dm^{-3} of P in the 0–20 cm layer. After 5 years from the beginning of the experiment, a reduction in soil P content up to 56% and 36% at depths of 0–10 and 10–20 cm, respectively, was found in the control plots without P fertilization (Figure 3.3). Even with reductions in P content in the soil, P levels still remained high for soil in the Parana State, including the control treatment. Thus, the P content in the soil was not a limiting factor for wheat and soybean production (PAULETTI and MOTTA, 2017).

The reduction of available P in the soil commonly occurs in highly weathered soils from tropical and subtropical regions, which have high levels of iron (Fe) and aluminum (Al) oxides. A rapid immobilization of inorganic P is due to the high adsorption/fixation of P with Fe and Al oxides (VITOUSEK et al., 2010; van RAIJ, 2011; FINK et al., 2016). Due to this reaction, Brazil has been considered inefficient in the use of phosphate fertilizers by applying larger amounts than those demanded by crops to compensate for the P adsorbed on clays and left over for plant nutrition (RODRIGUES et al., 2016; WITHERS et al., 2018). In addition, we cannot rule out the removal of P from the grain's export which helped to reduce the soil P content.

In our study, the annual application of phosphate fertilizer as MAP or SSP at the rate of 100 kg P_2O_5 ha^{-1} in the autumn-winter crop (wheat) was sufficient for (i) compensate for the loss of P by the adsorption/fixation on clays maintaining a high soil P level after 5 years (25.1 mg dm^{-3}), similar to the initial soil P content (26.1 mg dm^{-3}) at 0-0.20 m depth (Figures 3.2 and 3.3); (ii) supplying P demand for the secession of wheat-soybean crops with high P content in the leaf tissue (Tables 3.3 and 3.5); and (iii) maintaining high grain yields (Figures 3.4 and 3.5).

Although phosphorus fertilizers maintained adequate P levels in the soil, they were influenced by the mode of application. The broadcast application provided higher levels of P in the soil compared to the application in the sowing furrow with MAP in the 0-10 cm depth after 1, 3, and 5 years from the start of the experiment, and with SSP in a depth of 0-10 cm after 3 years and 10-20 cm after 1 year from the start of the experiment (Figure 3.2).

Due to the non-response of the mode of P application, whether broadcast or in the sowing furrow, on grain yield (Tables 3.6 and 3.8) and leaf P content (Tables 3.3 and 3.5) of a wheat-soybean succession, we believe that the lower P content in the soil applied in the sowing furrow was due to the soil sampling system adopted. Soil sampling is a limiting factor associated with the precise determination of soil P availability under fertilizer conditions restricted to the sowing furrow (PAULETTI and MOTTA, 2017). Systematic sampling is an attempt to minimize the effects of horizontal variability that occurs under no-tillage conditions, and systematization associated with furrow positions and between furrows are recommended to minimize such variations (KITCHEN et al., 1990). Our study was based in such systematization sampling carried out on the soybean lines; however, the P fertilization treatments were carried out on the wheat sowing furrow, and it was not possible to visualize its lines at the time of soil collection after soybean harvest. Thus, as the treatments were applied in the wheat crop, broadcast application was not affected by systematic soil sampling, as there was no horizontal difference in the distribution of P in the soil, while application in the sowing furrow could have been affected by the systematic sampling carried out after the soybean harvest. Soil sampling after soybean harvest with phosphate application in wheat seeding could result in misinterpreted soil P contents. Similar problems in the interpretation of P content in the soil due to the systematic sampling of the soil carried out after the soybean harvest with P fertilization in the sowing furrow in the autumn-winter crop (black oat) were also reported by Caires et al. (2017).

3.4.2 Effects of P fertilization on leaf P content and grain yield

In the first wheat growing season (2016) grain yield was high and in the following growing seasons the grain yields were lower (Table 3.6). This was due to the fact that in the first wheat crop the monthly rainfall was above the historical average and well distributed in the season. In the following seasons, there was drought stress at some important moment in the crop development cycle, compromising wheat grain yield (Figure 3.1). In the soybean development cycles, there were no long periods of scarcity of rain did not affect the crop productive potential, reaching high yields (Table 3.8).

Leaf P contents of wheat and soybean (Tables 3.3 and 3.5) remained at levels considered adequate or above in all growing seasons, including control treatment without P addition (van RAIJ, 2011). The application modes of P influenced only one wheat crop in 2020. In this growing season, fertilization in the sowing furrow provided a higher P content with the use of MAP. A similar result was obtained in grain yield (Tables 3.6 and 3.8), since the application of MAP increased wheat grain yield in 2019 when P was applied in the sowing furrow. The response of wheat and soybean crops regarding leaf P content and grain yield was not influenced by the SSP application mode.

The non-response of P application modes, whether by broadcast or in the sowing furrow, on P nutrition and grain yield of a wheat-soybean cropping system under no-till is possibly related to the fact that the soil contains very high P content (Table 3.1). In these soil conditions with high fertility, plants may become less dependent on phosphate fertilizer applied in the sowing furrow (SCHMIDT et al., 1997). However, increases in wheat (Table 3.6 and Figure 3.4) and soybean (Table 3.8 and Figure 3.5) grain yields were observed as a function of phosphorus fertilization, either with MAP or SSP, increasing cumulative grain yield of wheat and soybean by 15% and 4%, respectively. In addition, a positive correlation between the P content in the soil surface layer (0–10 cm) and the cumulative grain yield of wheat and soybean was observed (Figure 3.6). Then, we can conclude that the maintenance of high grain yields of a wheat-soybean cropping system under a no-till Oxisol with high P content depends on the annual application of phosphate fertilizers as MAP or SSP to supply the demand of crops and to maintain high soil P level regardless of application mode, whether broadcast or in the sowing furrow.

3.5 CONCLUSION

The soil P status are reduced in no-till with wheat-soybean succession crops without P application after 5 years. The annual application of 100 kg P_2O_5 ha^{-1} in the wheat crop as fully acidulated phosphate regardless of application mode, whether broadcast or in the sowing furrow, was sufficient for maintain an adequate level of P in the soil, supply P demand for the succession of wheat-soybean crops with high leaf P content and obtain high grain yield.

The application of phosphate fertilizers in the sowing furrow or broadcast in wheat crop using MAP or SSP as sources is a strategy that should be encouraged in highly weathered soils under no-till to minimize P fixation to soil particles, improve leaf P content, and simultaneously increase wheat and soybean grain yields.

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CHAPTER 4: COMPARING VARIOUS SULFUR SOURCES FOR A WHEAT–SOYBEAN CROPPING SYSTEM UNDER NO-TILL

Abstract: Sulfur (S) is a nutrient required for proper crop growth and production. With the intensification of production systems, the continued use of concentrated fertilizers without S, and the reduction in the SO_2 emission into the atmosphere by industries, S deficiency by crops is increasingly widespread. Sources of S as phosphogypsum (PG) and single superphosphate (SSP) are efficient in providing S as sulfate (SO_4^{2-}), which is the form absorbed by plants. Elemental S (ES) is another form that has been used in agriculture to supply S to plants. Due to the need for oxidation of elemental S to SO_4^{2-} by microorganisms, elemental S has the characteristic of slower release of S to plants. Since Brazil is a major soybean producer and wheat is widely grown in succession to soybean in the southern region of Brazil, understanding the dynamics of these sources in the release of S into the soil as well as in the nutrition and grain yield of a succession wheat-soybean is a recurring need for a more assertive S recommendation. Our study aimed to compare various S sources for a wheat–soybean cropping system under no-till on an Oxisol in southern Brazil. SO_4-S availability in the soil profile, leaf S nutrition, and grain yield of wheat and soybean were evaluated. The experiment started in 2016 at the "Capão da Onça" Farm School of the State University of Ponta Grossa, Brazil and was conducted for three years with a wheat–soybean cropping system. A randomized complete block design was used with four replicates. The treatments were: control (without S), SSP, ES, and PG. The amount of S supplied by the sources was 195 kg S ha^{-1} in a single application as PG and in three annual applications of 65 kg S ha^{-1} as elemental S and SSP. The balance the amount of P applied with SSP and isolate the effect of S, monoammonium phosphate (MAP) was applied for each wheat-soybean succession at a rate of 100 kg P_2O_5 ha^{-1} in the control, ES, and PG treatments. The SO_4-S content in the soil profile efficiently increased with the SSP, ES, and PG applications. The S-leaf content of wheat increased with ES and PG applications, and the S-leaf content of soybean increased with PG application. Grain yield and agronomic efficiency index of wheat and soybean crops under a no-till system were not significantly influenced by S supply via SSP, ES, and PG. A level of 13 mg dm^{-3} of SO_4-S in the soil was sufficient to supply the S demand of a wheat-soybean cropping system under no-till, with no correlation between wheat and soybean grain yield and the increase in SO_4-S content in the soil.

Key words: *Triticum aestivum* L., *Glycine max*, Elementary sulfur, superphosphate simple, phosphogypsum.

4.1 INTRODUCTION

Brazil is the world's largest producer of soybean (*Glycine max* (L.) Merrill) and the fourth largest producer of wheat (*Triticum aestivum* L.) in America, with has of great importance in the world scenario in food production (FAO, 2021). Wheat during autumn-winter period in succession with soybean in the spring-summer season are widely grown in southern Brazil.

Due to the continued application of the most demanding plant nutrients such as nitrogen (N), phosphorus (P), and potassium (K) through concentrated fertilizer sources (e.g. urea, monoammonium phosphate [MAP], diammonium phosphate [DAP], triple superphosphate [STP], and potassium chloride [KCl]), without residual of sulfur (S), and a reduction in SO_2 emissions from the industry to the atmosphere (LEHMANN et al., 2008), soil S deficiencies have become a bigger problem for agricultural production in many countries and the application of S sources to maintain adequate levels of this nutrient and, consequently, the high crop productive potential has become an increasingly widespread management in agriculture.

The use of S fertilizers in agriculture has been highlighted for providing nutritional improvement and increased grain yield of wheat (ZHAO et al., 1999; BOURANIS et al., 2019; VICENSI et al. 2016), maize (CARCIOCHI et al., 2019; BOSSOLANI et al., 2020), rice (CRUSCIOL et al., 2016; DUART et al., 2021), and soybean (LOPES et al., 2017; FRANCISCO et al., 2022). Since the S is a nutrient necessary for plant growth and crop production, S deficiency is a limiting factor for yield and quality in production systems (ZHAO et al., 1999; BOURANIS et al., 2020). The limitation occurs because S is a constituent of the proteinaceous amino acids such as methionine and cysteine, glutathione, vitamins (biotin and thiamine), phytochelatins, chlorophyll, coenzyme A, and S-adenosyl-methionine (TAIZ et al., 2017; NARAYAN et al., 2022). S also positively influences biological N_2 fixation, increasing the number and size of nodules (ANDERSON & SPENCER, 1949), which can increase N concentration in legumes due to increased N_2 fixation by symbiotic bacteria, which allows plants to have adequate growth and synthesize more proteins (JORDEN, 1967).

In soil, S is found naturally in organic and inorganic forms. The S bound to the organic components of the soil constitutes the largest reserve of this nutrient, representing more than 90% of the total (TABATABAI & BREMNER, 1972; WAINWRIGHT, 1984; SOLOMON et al., 2009), which justifies the high correlation between total organic C, N, and S content existing in the soil. The inorganic fraction of S predominates as sulfate ion (SO_4^{2-}), which is the form absorbed by plants and/or adsorbed to soil colloids (WAINWRIGHT, 1984).

Applications of S-source fertilizers are important to make inorganic S available in the soil for the plant. In addition to common sources such as single superphosphate (SSP) and phosphogypsum ($CaSO_4.2H_2O$) (PG), another source of S-fertilizer that has been used in agriculture is elemental S (ES) (FRANCISCO et al. al., 2022). Thus, consistent field studies with a wheat-soybean cropping system on an Oxisol under no-till comparing the main sources of S available on the market should be carried out and disseminated to clarify the effectiveness of the application of S on crop nutrition and yield.

PG is a by-product of the phosphoric acid industry that contains calcium sulfate, small concentrations of P, and fluorine (F) and is an excellent input to increase S level in the soil. In addition to containing S in the form of SO_4^{2-}, PG has been used as an alternative to improve the root environment in the soil profile under no-till systems, mainly increasing calcium (Ca^{2+}) and SO_4^{2-} contents and reducing aluminum (Al^{3+}) toxicity for plants (CAIRES & GUIMARÃES, 2018; CRUCIOL et al., 2019). PG application in a long-term has also been shown to increase C content (labile and stable fractions), improve soil physical-chemical attributes, increase biological activity, and C stock (INAGAKI et al., 2016; BOSSOLANI et al., 2021). In addition, the presence of SO_4^{2-} in depth can reduce subsoil acidity and promote greater development of roots of crop species, increasing the tolerance of plants to water stress during periods of drought, allowing higher yields to be achieved (CAIRES et al., 2011; BOSSOLANI et al., 2018).

SSP is a source of P that also contains $CaSO_4.½H_2O$ in its composition. SSP has high solubility in water, making it readily available to crops when compared to ES (HEYDARNEZHAD et al., 2012). Different PG and SSP, ES can be considered a slow-release source of S, because S needs to be oxidized to SO_4^{2-} by microorganisms to be absorbed by plants (HOROWITZ & MEURER, 2006; TAIZ et al., 2017). When applied to the wheat crop aiming to supply the S demand for the wheat-soybean succession, ES could have a more synchronized release with the needs of the crops, avoiding a possible deficiency of SO_4^{2-} for the first crop (wheat) and the next crop (soybean) due to the high movement of SO_4^{2-} in the soil profile, leaving its residual effect for a longer time in the topsoil.

This study compared various S sources for a wheat–soybean cropping system under no-till on an Oxisol in southern Brazil. SO_4-S availability in the soil profile, leaf S nutrition, and grain yield of wheat and soybean were evaluated. We hypothesized that PG, SSP, and ES are efficient sources of S supply for a wheat–soybean cropping system under no-till.

4.2 MATERIAL AND METHODS

4.2.1 Site description

The experiment started in 2016 on a dystrophic Red Latosol of medium texture, located at the "Capão da Onça" Farm School of the State University of Ponta Grossa in the Center-South region of Parana, Brazil (south latitude 25°05'35" and west longitude 50°02'49") and was conducted for three years in a wheat-soybean succession system under no-till. The experimental area had no history of application of S sources. The local climate is categorized as Cfb type (mesothermal, humid, subtropical), with cool summers and frequent frosts during winter, with no defined dry season (PEEL et al., 2007). The annual precipitation is around 1550 mm, and the average maximum and minimum temperatures are 22 and 13°C, respectively. Table 4.1 shows the results of chemical (PAVAN et., 1992) and particle-size distribution (EMBRAPA, 2011) analyses at different soil depths (0–0.10, 0.10–0.20, and 0.20–0.40 m) in May 2016 before the establishment of the experiment.

Table 4.1 - Results of chemical and particle-size distribution analyzes at different soil depths in May 2016 before the establishment of the experiment in Ponta Grossa, Southern Brazil.

Depth	**pH** $^{(1)}$	**Al**	**Ca**	**Mg**	**K**	**CTC** $^{(2)}$	**V** $^{(3)}$	**m** $^{(4)}$	**P** $^{(5)}$	**S**	**C**	**Clay**	**Silt**	**Sand**
m		------- mmol$_c$ dm^{-3} ---------					--- % ---		- mg dm^{-3}-		g dm^{-3}	- - - - g kg^{-1} - - - - -		
0–0.10	4.5	6	16	6	1.4	92,8	25	20	45.5	6.7	17	260	57	683
0.10–0.20	4.0	12	5	3	1.1	99,2	9	57	6.7	8.7	12	260	51	689
0.20–0.40	4.1	9	6	3	0.9	100,0	10	48	0.8	9.9	9	279	45	676

[1]pH in 0,01 mol L^{-1} CaCl$_2$; [2] Cation exchange capacity (Ca + Mg + K + H + Al); [3]V: base saturation; [4]m: Al saturation; [5]Phosphorus extracted by Mehlich-1.

On June 3, 2016, dolomitic lime was surface-applied at the rate of 5.4 Mg ha^{-1} to increase the soil base saturation in the 0–0.20 m layer to 70% (CAIRES et al., 2005). Dolomitic lime had 32.7 % CaO, 20.6 % MgO, and 95% effective calcium carbonate equivalent (ECCE).

4.2.2 Experimental design

A randomized complete block design, with four replications was used. Plot size was 15 by 6 m (90 m^2). The treatments were: control (without S), SSP, ES, and PG (Table 4.2). The fertilizers used have the following compositions: SSP (3% N, 17% P_2O_5, and 11% S), ES (90% S), and PG (17% Ca and 14% S).

Table 4.2 – Treatments of the S sources for the establishment of the experiment. Ponta Grossa-PR, 2016-2021.

Treatments	(kg P_2O_5 ha^{-1})[a]	(kg S ha^{-1})[a]
1. Control	100	0
2. SSP	100	65
3. ES	100	65
4. PG	100	65

[a] The P_2O_5 and S was applied annually in each sowing wheat crop.

The control treatment did not receive application of S. In treatments with SSP and ES, fertilizers were applied at a rate of 65 kg S ha^{-1} at the time of wheat sowing in 2016, 2017 and 2018. The amount of S applied with SSP and ES was intended to supply S for the wheat-soybean succession. SSP was applied in the wheat sowing furrow with a no-till seeder, and the ES was applied by broadcast to the soil surface on the same day. The total amount of S applied in the three cycles of wheat-soybean succession was 195 kg S ha^{-1}. PG was spread over the soil surface in a single application at a rate of 1395 kg ha^{-1} at the beginning of the experiment, in June 2016. The amount of S supplied by PG was also 195 kg ha^{-1}, corresponding to three applications of 65 kg S ha^{-1} provided by the treatments with SSP and ES.

Aiming to supply P for the wheat-soybean succession, the treatment with SSP added 100 kg ha^{-1} P_2O_5. To balance the amount of P applied in the SSP treatment and isolate the effect of S, 100 kg ha^{-1} P_2O_5 were applied via MAP (11% N and 52% P_2O_5) in the control, ES, and PG treatments. The application of MAP was carried out in the wheat sowing furrow with a no-till seeder.

4.2.3 Crop management

The study was conducted from 2016 to 2019 with wheat in the autumn-winter season and with soybean in the spring-summer season. In order to improve straw production under no-till, cover crops were grown between soybean harvest and wheat sowing. Fodder radish (*Raphanus sativus* L.) and black oat (*Avena strigosa* Schreb) were sown between the first and second cycle, and between the second and the third cycle of wheat-soybean succession, respectively. More details on the cultivation sequence throughout the experiment period are in Table 4.2. Wheat was sown at a rate of 250 kg ha^{-1} of seed and row spacing of 0.17 m. Soybean was sown at a seeding rate of 14 seeds m^{-l} (inoculated with *Bradyrhizobium japonicum*) and row spacing of 0.45 m, without fertilization.

Based on the composition of the phosphate fertilizers used in the treatments, N was applied annually at wheat sowing at a rate of 18 kg N ha^{-1} via SSP and 21 kg N ha^{-1} via MAP (control, ES, and PG). In top dressing to the wheat crop, N was applied as urea at a rate of 100 kg N ha^{-1} in 2016, 2017, and 2018 (60 kg N ha^{-1} at the beginning of tillering and 40 kg ha^{-1} at the end of booting). In all wheat and soybean crops, potassium chloride (KCl – 60% K_2O) was surface-applied immediately after sowing at a rate at 84 kg K_2O ha^{-1}. The phytosanitary management was carried out according to the needs of wheat and soybean crops to obtain adequate plant health during the development cycle.

Table 4.3 - Cropping sequence from 2016 to 2020 in an experiment under a no-till system in southern Brazil.

Year	**Crop**	**Cultivation**	**Sowing**	**Cultivar**
2016–2017	Wheat	Autumn-Winter	June	TBIO Toruk
	Soybean	Spring-Summer	December	Nidera 5909 IPRO
2017	Fodder radish	Autumn	April	-----
2017–2018	Wheat	Autumn-Winter	June	TBIO Iguaçu
	Soybean	Spring-Summer	November	Nidera 5445 IPRO
2018	Black oat	Autumn	April	Common
2018–2019	Wheat	Autumn-Winter	July	Quartzo
	Soybean	Spring-Summer	December	LG 60158 IPRO

4.2.4 Rainfall

Monthly rainfall data from the beginning (June 2016) to the conclusion of the experiment (April 2019) are shown in Figure 4.1. The wheat crop was more influenced than the soybean crop by the lack of rainfall during the growing seasons. Wheat grown in 2016 had good monthly rainfall throughout the development period, with rainfall above the historical average, benefiting plant development and providing conditions for obtaining high grain yields. The wheat grown in the following years of 2017 and 2018 presented rainfall below the historical average for the region after sowing, which impaired plant development and grain yield.

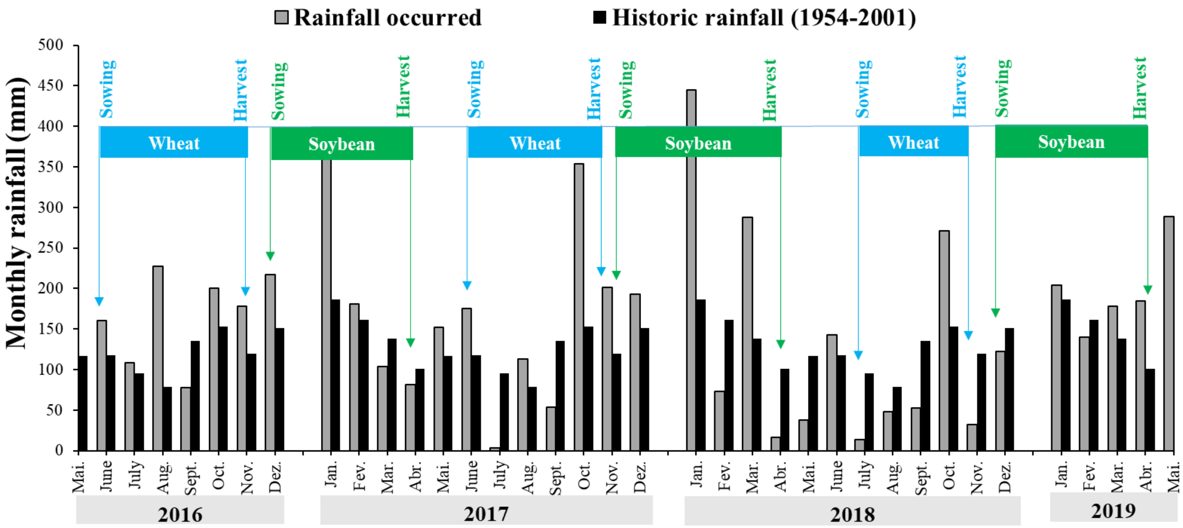

Figure 4.1 - Monthly and historical rainfall from the beginning (June 2016) to the conclusion of the experiment (April 2019). Source: Monthly rainfall data obtained from BASF's meteorological station, located on the “Capão da Onça” Farm School. Historical average rainfall data (1954 and 2001) obtained from the meteorological station of the Agronomic Institute of Parana (IAPAR, 2022).

4.2.5 Soil sampling and S chemical analysis

Soil sampling was carried out after the harvest of the third soybean crop in 2019, 36 months after the beginning of the experiment, when all treatments with S sources completed the rate of 195 kg S ha^{-1}. Soil samples were taken at 0–0.10, 0.10–0.20, 0.20–0.40, 0.40–0.60, 0.60–0.80, and 0.80–1.00 m depths. To obtain a composite sample, 10 soil cores were sampled at 0–0.10 and 0.10–0.20 m depths, and five soil core samples were sampled at 0.20–0.40, 0.40–0.60, 0.60–0.80, and 0.80–1.00 m depths in each plot using a soil probe. Before the chemical analysis, soils were air-dried and ground to pass through a 2-mm sieve. The SO_4-S content at different soil depths was extracted with a 0.01 mol L^{-1} calcium phosphate solution and it was later determined by the turbidimetric method (CANTARELLA & PROCHNOW, 2001).

4.2.6 Leaf sampling and S chemical analysis

Leaf samples of wheat and soybean included 30 plants per plot, collected during the flowering period of the crops. In wheat crop was collected the flag leaf, and in the soybean crop the third trifoliate was collected from the apex of the plants. The samples were washed with deionized water, dried in a forced-air oven at 60°C until a constant mass achieved, and were ground. The leaf tissue analysis was performed using nitric-perchloric acid digestion, and foliar S concentration was determined by turbidimetry as barium sulfate, according to the procedures described by Malavolta et al. (1997).

4.2.7 Crop grain yield

Wheat and soybean grain yields were obtained through the harvests carried out mechanically in the central rows after the physiological maturity of crops. In each plot, soybean was harvest from 27 m^2 (middle 4 rows by 15 m of length), and wheat was harvest from 24 m^2 (1.6 m x 15 m of length). Grain yield was expressed at 130 g kg^{-1} of moisture content. Cumulative wheat and soybean grain yield was obtained by adding three wheat harvests and three soybean harvests.

4.2.8 Statistical analysis

The data obtained were submitted for analysis of variance according to the randomized complete block model. Data from soil S content were analyzed as a split-plot design by analysis of variance using S sources treatments as main plots and depths as subplots. Means were compared using the LSD test at $p = 0.05$. *Pearson's* simple correlation analysis was performed between wheat and soybean grain yields and SO_4-S contents in the soil. Statistical analyzes were performed using the Sisvar software (FERREIRA, 2011).

4.3 RESULTS AND DISCUSSION

4.3.1 Soil S content

Soil S content was significantly influenced by the interaction of S sources and depth for soil sampled 36 months after the beginning of the experiment, when all treatments with S sources completed the rate of 195 kg S ha^{-1} (Figure 4.2). The S sources used did not significantly influence the SO_4-S content in the soil surface layer (0–0.10 m) and increased the SO_4-S content in the subsoil layers, from 0.10 to 1.00 m deep. The increase in the soil SO_4-S content in the control treatment compared to their level at the beginning of the study (from 8 to 13 mg dm^{-3} of SO_4-S in the 0-0.20 m depth) was probably due to the surface application of lime at the implementation of the experiment in order to increase the soil base saturation in the 0-0.20 m layer to 70%. In the experiment, soil pH increased from 4.5 to 5.2 in the surface layer of 0–0.10 m after 3 years of surface lime. With the increase in soil pH, there is an increase in negative electrical charges on the surface of soil colloids and a decrease in the adsorption of SO_4^{2-} (COUTO et al., 1979; CASAGRANDE et al., 2003). In addition, the management system under no-till together with soil acidity correction practices and fertilization improve soil fertility (INAGAKI et al., 2016). In our study, fodder radish and black oat, which were grown between the wheat-soybean succession cycles, added about 2.5 and 3.3 Mg ha^{-1} of shoot dry mass, respectively, contributing to a greater input of crop residue biomass on the soil surface. This higher input of crop residues may have favored the plant development (BRIEDIS et al., 2012; CAIRES et al., 2006) and the availability of SO_4-S in the soil, since the largest fraction of S in the soil comes from mineralization of organic compounds (VICENSI et al. 2019).

The application of ES provided a higher SO_4-S content than the control treatment at the 0.10-0.20 m depth (Figure 4.2), showing to be a source of S with slower and more gradual release than SSP and PG, with good sulfate movement in the soil profile up to a depth of 1.00 m. Therefore, as the release of SO_4-S in the soil is slower with ES application due to the oxidation of S^0 to SO_4^{2-} by microorganisms (HOROWITZ & MEURER, 2006), there was no movement of all sulfate from the surface to the subsoil, showing a more gradual increase in SO_4-S contents throughout the soil profile.

The applications of SSP and PG showed higher levels of SO_4-S in the soil than the control treatment from the layer of 0.20-0.40 m to a depth of 1.00 m (Figure 4.2). At 0.20-0.40 m and 0.40-0.60 m depths, the increases in SO_4-S content were even greater with the use of PG. The effects of SSP and PG in no increasing SO_4-S levels subsurface soil layers are due to their high solubility, in addition the high mobility of SO_4^{2-} in the soil profile (CAIRES et al., 2011; BOSSOLANI et al., 2022). Possibly, the movement of SO_4^{2-} from the surface layers to the subsoil resulting from the applied S sources was aided by rainfall peaks that occurred mainly in some months of the year, such as January, March, and October (Figure 4.1).

The improved performance of the ES compared to the SSP is possibly attributed to the application methods used. The SSP was applied in the sowing furrow, whereas the ES was applied through broadcasting. It has been observed that nutrients, such as SO_4-S, which are transported through mass flow, exhibit greater efficiency when applied via broadcasting rather than in the sowing furrow (MALAVOLTA, et al., 2006).

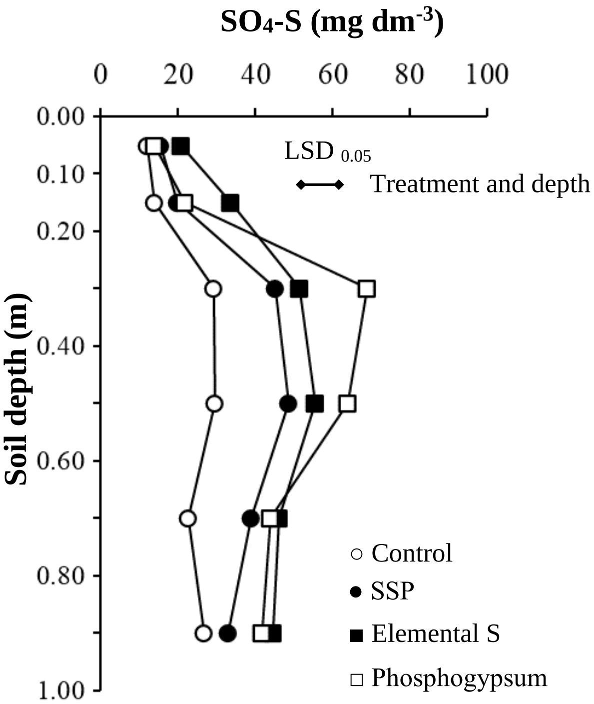

Figure 4.2 - Changes in SO_4-S contents at different soil depths as affected by application of S fertilizer sources in a wheat-soybean cropping system under no-till in southern Brazil. SSP was applied in the wheat sowing furrow at an annual rate of 65 kg S ha^{-1} for 3 years. Elemental S (ES) was applied by broadcast to the soil surface on the day of wheat sowing at an annual rate of 65 kg S ha^{-1} for 3 years. PG was spread over the soil surface in a single application at a rate of 195 kg S ha^{-1} before the first wheat crop. Soil was sampled after the third cycle of wheat-soybean succession. Horizontal bar represents the least significant difference by the LSD test at $p = 0.05$.

4.3.2 Leaf-S content of wheat and soybean

The leaf-S content of wheat remained at levels considered adequate in all treatments, including the control (Table 4.4). Compared to the control treatment, ES and PG increased the leaf-S content, while the application of SSP did not significantly change the leaf-S content in the three wheat growing seasons (2016, 2017, and 2018).

Table 4.4 - Leaf-S content of wheat as affected by application of S fertilizer sources in a wheat-soybean cropping system under no-till in southern Brazil.

Treatment	**Leaf-S content of wheat (g kg^{-1})**		
	2016	**2017**	**2018**
Control	2.51 c	2.03 c	1.99 c
SSP	2.86 bc	2.18 bc	2.24 bc
Elemental S (ES)	3.17 ab	2.44 ab	2.67 a
Phosphogypsum (PG)	3.72 a	2.52 a	2.50 ab
CV (%) [a]	11.4	9.0	10.5
P* > *F	0.005	0.030	0.017
Adequate range [b]	1.5–3.0	1.5–3.0	1.5–3.0

[a] CV, coefficient of variation. [b]van Raij (2011). Equal letters do not differ by the LSD test at $p = 0.05$. SSP was applied in the wheat sowing furrow at an annual rate of 65 kg S ha^{-1} for 3 years. Elemental S (ES) was applied by broadcast to the soil surface on the day of wheat sowing at an annual rate of 65 kg S ha^{-1} for 3 years. PG was spread over the soil surface in a single application at a rate of 195 kg S ha^{-1} before the first wheat crop.

For soybean grown in the 2016–2017 season, leaf-S content was not influenced by treatments and remained within levels considered adequate for the crop (Table 4.5). In the case of soybean grown in the 2017–2018 season, the control, SSP and PG treatments showed leaf-S content below the crop sufficiency level. The soybean grown in 2018–2019 presented leaf-S content was very close to the crop minimum sufficiency level and the treatments with S sources did not influence the leaf-S content.

Table 4.5 - Leaf-S content of soybean as affected by application of S fertilizer sources in a wheat-soybean cropping system under no-till in southern Brazil.

Treatment	**Leaf-S content of soybean (g kg^{-1})**		
	2016–2017	**2017–2018**	**2018–2019**
Control	2.62	1.85	2.16
SSP	2.44	2.07	2.04
Elemental S (ES)	2.60	2.06	1.98
Phosphogypsum (PG)	2.53	2.13	2.01
CV (%) [a]	7.8	7.5	9.6
P* > *F	0.573	0.115	0.600
Adequate range [b]	2.1-4.0	2.1-4.0	2.1-4.0

[a] CV, coefficient of variation. [b]van Raij (2011). Equal letters do not differ by the LSD test at $p = 0.05$. SSP was applied in the wheat sowing furrow at an annual rate of 65 kg S ha^{-1} for 3 years. Elemental S (ES) was applied by broadcast to the soil surface on the day of wheat sowing at an annual rate of 65 kg S ha^{-1} for 3 years. PG was spread over the soil surface in a single application at a rate of 195 kg S ha^{-1} before the first wheat crop.

The increases in leaf-S contents of wheat (Table 4.4) with the S sources were due to the addition of SO_4-S content in the soil profile (Figure 4.2). ES and PG increased the leaf-S content of wheat. These sources were the ones that provided the highest SO_4-S contents throughout the soil profile. The increased leaf-S level with PG application has been frequently reported in other studies (VICENSI et al., 2016; CAIRES et al., 2021; BOSSOLANI et al., 2022). The supply of Ca and S by PG application improves chemical conditions in the soil profile for root growth (RITCHEY et al. 1980; CAIRES et al. 2016; CAIRES et al., 2021; BOSSOLANI et al., 2022), consequently enhancing crop development. Overall, it was expected that PG and SSP would behave similarly regarding the availability of S to crops. On the other hand, ES had a relatively similar behavior to PG in the availability of SO_4-S in the soil profile and in the uptake of S by wheat and soybean plants. It is possible that these results were influenced by the mode of application of S through the fertilizer sources, since ES and PG were applied by broadcast and SSP was applied in the sowing furrow (MALAVOLTA et al., 2006).

4.3.3 Wheat and soybean grain yield

Wheat grain yields were not significantly influenced by SSP, ES, and PG applications (Table 4.6). The average yield of wheat was 4214, 1334, and 2174 kg ha^{-1} in 2016, 2017, and 2018, respectively. The cumulative yield of wheat in the three harvests was also not influenced by the applications of S fertilizer sources, although compared to the control treatment, the cumulative yield of wheat increased by 2%, 8%, and 13% with SSP, PG, and ES, respectively.

Table 4.6 - Wheat grain yield as affected by application of S fertilizer sources in a wheat-soybean cropping system under no-till in southern Brazil.

Treatment	**Wheat grain yield (kg ha^{-1})**			
	2016	**2017**	**2018**	**Cumulative**
Control	3965	1234	2096	7295
SSP	4167	1180	2097	7444
Elemental S (ES)	4458	1442	2343	8243
Phosphogypsum (PG)	4265	1482	2160	7906
CV (%) [a]	16.8	17.9	8.8	12.7
P > F	0.801	0.263	0.279	0.531

[a] CV, coefficient of variation. SSP was applied in the wheat sowing furrow at an annual rate of 65 kg S ha^{-1} for 3 years. Elemental S (ES) was applied by broadcast to the soil surface on the day of wheat sowing at an annual rate of 65 kg S ha^{-1} for 3 years. PG was spread over the soil surface in a single application at a rate of 195 kg S ha^{-1} before the first wheat crop.

Treatments with application of SSP, ES, and PG did not cause significant changes in soybean grain yields in the different growing seasons (Table 4.7). The average yield of soybean was 4032, 4236, and 3625 kg ha^{-1} in 2016–2017, 2017–2018, and 2018–2019, respectively. The cumulative yield of soybean was also not influenced by the applications of S fertilizer sources.

Table 4.7 - Soybean grain yield as affected by application of S fertilizer sources in a wheat-soybean cropping system under no-till in southern Brazil.

Treatment	**Soybean grain yield (kg ha^{-1})**			
	2016–2017	**2017–2018**	**2018–2019**	**Cumulative**
Control	4035	4122	3562	11718
SSP	4143	4284	3537	11964
Elemental S	3912	4268	3766	11945
Phosphogypsum	4038	4271	3635	11944
CV (%) [a]	3.7	4.3	4.2	2.3
P > F	0.261	0.575	0.215	0.549

[a] CV, coefficient of variation. SSP was applied in the wheat sowing furrow at an annual rate of 65 kg S ha^{-1} for 3 years. Elemental S (ES) was applied by broadcast to the soil surface on the day of wheat sowing at an annual rate of 65 kg S ha^{-1} for 3 years. PG was spread over the soil surface in a single application at a rate of 195 kg S ha^{-1} before the first wheat crop.

There was no water restriction during the development period of soybean crop (Figure 4.1) and grain yields were relatively high (Table 4.7) in the three growing seasons. Rainfall was very well distributed during wheat development in 2016 (Figure 4.1), which resulted in a high grain yield (Table 4.6). However, in the 2017 and 2018 growing seasons, there was little rain just after wheat sowing, causing a reduction in grain yield of the order of 70% and 50% compared to wheat grown in 2016, respectively. Despite the S sources showing a tendency to increase wheat grain yield from 2% to 13%, the increase in SO_4-S supply in the soil profile did not cause a significant increase in grain yield under drought stress (Table 4.6).

In the literature, it is more common to find a positive response to sources of S in wheat (CAIRES et al. 2002, 2011a; PAULETTI et al. 2014; VICENSI et al. 2016; DALLA NORA et al. 2017) than in soybean (PAULETTI et al. 2014; ZANDONA et al. 2015; COSTA & CRUSTIOL 2016; FRANSCICO et al., 2022). In addition, a positive response in soybean yield is usually associated with water stress during crop development and/or critical levels of SO_4-S in the soil (CAIRES et al., 2021; COSTA & CRUCIOL 2016). Even increasing the SO_4-S content in the soil profile (Figure 4.2) and the leaf-S content (Tables 4.3) with some sources of S, crop grain yields were not changed. Our results indicate that the SO_4-S content in the soil was sufficient to supply the demand for S by wheat and soybean crops. The critical level of SO_4-S in the topsoil in Brazil is commonly reported as 5 to 10 mg dm^{-3} (van RAIJ et al. 1997; PAULETTI & MOTTA 2017; PIAS et al. 2019). In a soil with 9 mg dm^{-3} of SO_4-S at 0–0.20 m depth, Francisco et al. (2022) observed an increase in S uptake and grain yield of soybean with the application of SSP, PG, and ammonium sulfate. However, when ES was applied alone, no difference was observed compared to the control treatment without S. The authors justify the lack of ES response due to the lack of oxidation of S to SO_4^{2-} by microorganisms. This effect was not confirmed in our study, since there an increase in the availability of SO_4-S by ES throughout the soil profile (Figure 4.2). In a recent study with a wheat–soybean rotation cropping system under conservation agriculture practices, Caires et al. (2021) established a critical level of SO_4-S of 14 mg dm^{-3} at 0–0.20 m depth. This level is very close to that found in the control treatment in our study (13 mg dm^{-3} of SO_4-S), justifying the lack of response in wheat and soybean grain yields due to the application of S sources under no-till.

4.3.4 Soil S *vs* cumulative grain yield of wheat and soybean

The cumulative grain yields of wheat (Figure 4.3A) and soybean (Figure 4.3B) were not significantly correlated by *Pearson*'s test with the SO_4-S content in the soil at 0–0.20 m depth. These results confirm that the SO_4-S content in the soil in our study (13 mg dm^{-3}) was sufficient to meet the demand for S by wheat and soybean crops under no-till. In plots with SO_4-S content at 0–0.20 m depth close to or above the critical level established by Caires et al. (2021), significant responses of wheat and soybean grain yields could not be observed with the application of fertilizer sources containing S.

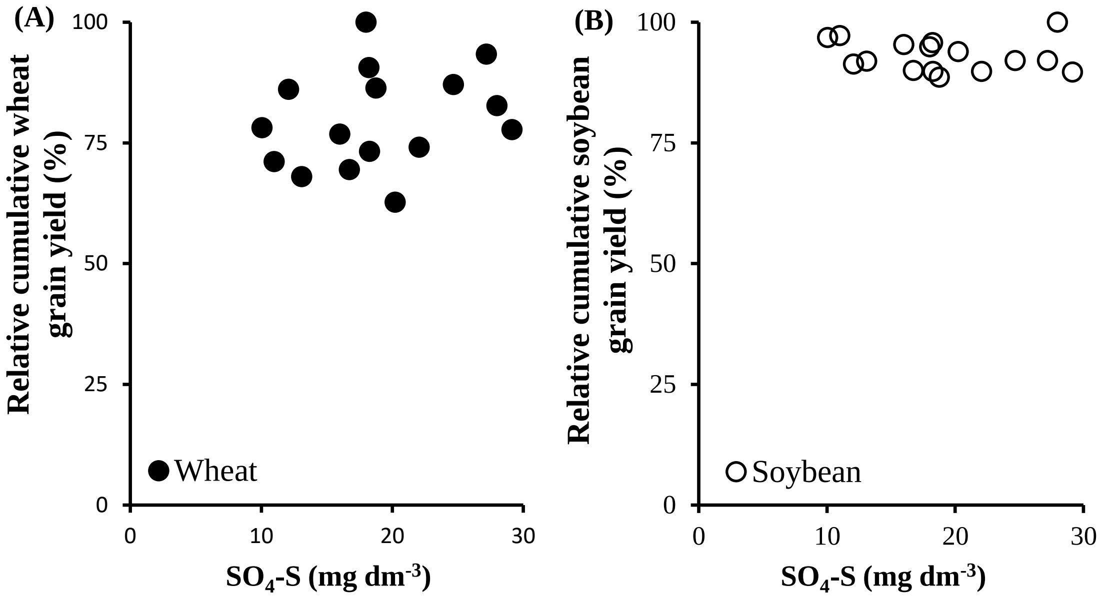

Figure 4.3 - Correlation simple *Pearson* test between the relative cumulative grain yield of wheat (A) and soybean (B) and SO_4-S content in the soil at 0–0.20 m depth. Soil was sampled after the soybean harvest in 2019. Ponta Grossa-PR, southern Brazil.

4.4 CONCLUSION

Applying PG and ES in the broadcast and SSP in the sowing furrow efficiently increases the SO_4-S contents in the soil profile.

The leaf-S content of wheat increased with ES and PG applications and leaf-S content of soybean was no affected.

Wheat and soybean grain yields in a no-till system were not influenced by SSP, ES, and PG applications, although fertilizer sources containing S showed a tendency to increase the cumulative grain yield of wheat from 2% to 13%.

A level of 13 mg dm^{-3} of SO_4-S in the soil at 0–0.20 m depth was sufficient to supply the demand for S by a wheat-soybean cropping system under no-till, since there was no correlation between grain yields of wheat and soybean and the increase in SO_4-S content in the soil.

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5 GENERAL CONCLUSIONS

The four chapters discuss the effects of surface lime and fertilization on soil acidity, nutrient content, and crop yield in a no-till cropping system in Southern Brazil. Surface lime effectively corrected soil acidity up to a depth of 1 m, with greater effects at the soil surface layer (0–0.10 m). Fertilization with MAP, MAP + elemental S, SSP by broadcast or in the sowing furrow as well as PG did not improve the effect of surface-applied lime in alleviating acidity in the soil profile. Wheat and soybean responded differently to surface lime and fertilization, with wheat being more responsive to P and S fertilization. The application of phosphate fertilizers in the sowing furrow or broadcast in the wheat crop was sufficient for maintaining an adequate level of P in the soil and obtaining high grain yield in a wheat-soybean cropping system. Applying PG and elemental S by broadcast and SSP in the sowing furrow increased the SO_4-S content in the soil profile, and a level of 13 mg dm^{-3} of SO_4-S in the soil at 0–0.20 m depth was sufficient to supply the demand for S by a wheat-soybean cropping system under no-till.