STATE UNIVERSITY OF PONTA GROSSA
SECTOR OF AGRICULTURAL SCIENCES AND TECHNOLOGY
GRADUATE PROGRAM IN AGRONOMY

JÉSSICA ALVES NOGAROLI

ACIDITY CONTROL OF A TYPIC DISTRUDEPT, UNDER NO-TILLAGE, AFTER SURFACE APPLICATION OF MICRONIZED LIMING MATERIALS: YIELD AND SOIL REACTION

PONTA GROSSA - PR

2019

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Thesis presented to the State University of Ponta Grossa to obtain the title of doctorate degree in Agronomy - Area of concentration: Agriculture. Research line: Soil use and management.

Advisor: Prof. Dr. Adriel Ferreira da Fonseca

PONTA GROSSA - PR

2019

Nogaroli, Jéssica Alves
N775 Acidity control of a Typic Distrudept, under no-tillage, after surface application of micronized liming materials: yield and soil reaction/ Jésica Alves Nogaroli. Ponta Grossa, 2019.
87 f.; il.

Thesis (Doctor in Agronomy – Concentration – Agriculture; Research line: Soil use and management), State University of Ponta Grossa.
Advisor: Prof. Dr. Adriel Ferreira da Fonseca

1. Soil reaction.2. Soil with variable charge. 3. Soil base saturation. 4. Nutrient available. 5. Crops yield. I. Fonseca, Adriel Ferreira da. II. State University of Ponta Grossa- Doctor in Agronomy. III. T.
CDD : 631.4

Ficha catalográfica elaborada por Maria Luzia F. Bertholino dos Santos– CRB9/986

UNIVERSIDADE ESTADUAL DE PONTA GROSSA
SETOR DE CIÊNCIAS AGRÁRIAS E DE TECNOLOGIA
PROGRAMA DE PÓS-GRADUAÇÃO EM AGRONOMIA

CERTIFICADO DE APROVAÇÃO

Título da Tese: **"Acidity control of a typic distrudept, under no-tillage, after surface application of micronized liming materials: yield and soil reaction".**

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Data da Realização: 14 de Fevereiro de 2019

To God.
To my mother Ana Luiza, my father José Edegar and my brothers José Edegar Filho and Jeanine.
To my brother-in-law Guilherme and my nephew João Vicente.
To my love, João Felipe.
I DEDICATE

ACKNOWLEDGEMENT

The author expresses her thanks to the following people and institutions, without which it would not have been possible to carry out the present work:

The State University of Ponta Grossa (UEPG), in which I had the opportunity to do the undergraduate and graduate course in Agronomy and the research facilities.

To Prof. Dr. Adriel Ferreira da Fonseca, for the encouragement, confidence, guidance, valuable criticism and friendship.

To the researchers Dr. Gabriel Barth and Dr Luiz Antonio Correa Lucchesi, for the support, suggestions and assistance in the qualification exam.

To Omya of Brazil, Igor Vieira, Domenico Zocco and Danielle Jeanneau for the support.

To the Professors of the Postgraduate Program in Agronomy, for the scientific contribution to carry out this work and professional training.

To CAPES Foundation (Coordination for the Improvement of Higher Education Personnel) for the granting of the scholarship and financial resources.

To Maranello Group for the concession of the agricultural area in Palmeira – PR.

To the Laboratory of Plant Nutrition and Laboratory of Soil Fertility of UEPG, and its employees and technicians: Verônica Dias Carneiro, Danilo Bachinski and Elias Luiz Meira for the help in the laboratorial analyzes.

To the UEPG Multiuser Laboratory for facilities and help.

To colleagues and friends Guilherme Moll, Keli Guera, Flávia Biassio, Silvano Harkatin, Moisés Marcondes de OLIVEIRA, Gabriel Gregório Soares, Jasmine Jurich Pilati, Bruna Simone Siqueira, Pâmela Scortegagna, Emerson Homenchuk, Juliano Garda, Sandoval

Carpenelli, Eduardo Güntzel, Fabrício Siqueira Hennipman, Luana Duda, Simone Miara, Julienne de Geus Moro, Elton Rech, André Vinícios Vam Beek, Adriano Xavier Maukoski, André Auler e Thays Schneider for companionship and help in soil and plant samplings and laboratory analysis.

To my family and friends Cleusa Burgardt, Ilda and Rogério Nogaroli, Rafaela Daiane de OLIVEIRA and Cynthia Hlataki for the encouragement and companionship during all this time.

And to all the people who somehow made it possible to carry out this work.

ABSTRACT

NOGAROLI, J.A. A**cidity control of a Typic Distrudept, under no-tillage, after surface application of micronized liming materials: yield and soil reaction.** 2019. Thesis of doctorate degree in Agronomy - University State of Ponta Grossa.

We measured the relative yield (RY), relative yield change (RYG) and production efficiency (PE) of wheat, soybean, black oat and maize, during the years 2012 to 2016; and also evaluate the effect after 5, 11, 23, 34 and 45 months of the surface application of dose of liming materials (LM), in various soil layers (0-5, 5-10, 10-20, 20-40 and 40-60 cm) of a Typic Distrupedt, of attributes: active acidity (pH), soil base saturation (V), exchangeable calcium (Ca), magnesium (Mg) and potassium (K), the percentage (%) of Ca and Mg in the cation exchange capacity at pH 7.0 (CEC) and cationic relationship (CR) as Ca/Mg and (Ca+Mg)/K. The experimental design used was completely randomized blocks in split-plot with four replications. In the plots were studied the dolomitic limestone (DL) and the micronized liming material (MLM): granulated micronized calcite (GMC) and dolomite (GMD) and carbonated suspension (CS). In the subplots were studied three doses of each the LM aiming to increase V to 50, 70 and 90 %, besides of control treatment. The MLM presented major RY and PE along the time than DL. Besides, the major RYG of MLM major residual effect and major/maintenance crops yield. If we consider only PE, better results are found in the dose aiming V to 61 % for all the LM, showing that it is the adequate V for acidity control of a Typic Distrudept. Despite the MLM are more fineness than DL, the effectiveness for control soil acidity in subsoil were inefficient. However, the MLM present lower gap between the V estimated and obtained, manly in the 0-5 cm layer than DL. LM in the V to 50-70 % increased Ca, Mg and K, in 0-5 cm layer, up to 34 months after application. In the 0-20 cm layer, the better CR occurred at 11 months after application. The K increased as it decreased the % of Mg in the CEC.

Keywords: soil reaction, soil with variable charge, soil base saturation, nutrient available, crops yield.

RESUMO

NOGAROLI, J.A. **Controle da acidez de um Cambissolo Háplico, sob plantio direto, após aplicação superficial de corretivos micronizados: rendimento e reação do solo.** 2019. Tese de doutorado em Agronomia – Universidade Estadual de Ponta Grossa.

Nós mensuramos o rendimento relativo (RR), a diferença de rendimento relativo (DRR) e a eficiência de produção (EP) de trigo, soja, aveia preta e milho, durante os anos de 2012 a 2016; e avaliamos o efeito após 5, 11, 23, 34 e 45 meses da aplicação superficial da dose de corretivos, em diversas camadas do solo (0-5, 5-10, 10-20, 20-40 e 40-60 cm) de um Cambissolo Háplico, dos atributos: acidez ativa (pH), saturação por bases do solo (V), cálcio (Ca), magnésio (Mg) e potássio (K) trocáveis, o percentual (%) de Ca e Mg na capacidade de troca catiônica a pH 7,0 (CEC) e relações catiônicas (RC) como Ca/Mg e (Ca+Mg)/K. O delineamento experimental utilizado foi o de blocos ao acaso, em parcelas subdivididas, com quatro repetições. Nas parcelas foram estudados o calcário dolomítico (CD) e os corretivos micronizados (CM): calcita (CMG) e dolomita (DMG) micronizada granulada e suspensão carbonatada (SC). Nas subparcelas foram estudadas três doses de cada corretivo a fim de elevar a V para 50, 70 e 90%, além do tratamento controle. Os CM apresentaram maiores RR e EP ao longo do tempo do que CD. Além disso, a maior DRR do CM refere-se ao maior efeito residual e maior/manutenção do rendimento das culturas. Se considerarmos apenas EP, melhores resultados são encontrados na dose que visa V a 61 % para todo os corretivos, mostrando que é o V adequado para o controle da acidez de um Cambissolo Háplico. Apesar do CM apresentarem maior finura do que CD, a eficiência no controle da acidez do subsolo foi ineficiente. No entanto, os CM apresentam menor diferença entre o V estimado e obtido, principalmente na camada de 0-5 cm do que CD. Os corretivos na dose de V entre 50-70 % aumentam a concentração de Ca, Mg e K trocáveis, na camada 0-5 cm e por até 34 meses após a aplicação. Na camada 0-20 cm, as melhores RC ocorreram aos 11 meses após a aplicação. A concentração de K aumentou à medida que diminuiu a % de Mg na CTC.

Palavras-chave: reação do solo, solo com carga variável, saturação por bases do solo, disponibilidade de nutrientes, rendimento das culturas.

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1. Introduction

The increase of the productivity of the mainly agricultural crops – soybean, maize and wheat – associate to the intense exploitation of the soil, is due to the increase of the demand for food by the world population (SPIERTZ, 2012). However, it has been increasingly common to grow these plants in soils with fertility restrictions.

In the tropics and subtropics - domain of soils with charge variable - the greatest limitation of yield increase has been the acidity and toxicity of aluminum (Al) (CASTRO and CRUSCIOL, 2013; VENDRAME et al., 2013). The correction of the acidity of these soils is not limited only to exchangeable-Al neutralization but also in the increase of pH that results in the consumption of protons from surface functional groups (mainly silanol, aluminum, OH-iron oxide radicals, OH-aluminum oxide, carboxylic and phenolic), generating negative electric charge (SPARKS, 2003). Once corrected, the soil naturally tends to acidify (CHO et al., 2019). Therefore, adequate management and control of soil acidity in soils with variable charge is a premise for sustainable agriculture (KIRKHAM et al., 2014) and food security in developing countries (SPIERTZ, 2012; CURTIS and HALFORD, 2014).

The acidification can be more intense in the surface layers of the soil in no-tillage (NT) (CIOTTA et al., 2004), and the acidification may occur towards the deeper layer. This fact may be due to the greater deposition of crops residues and renewal of the root system, intensive use of nitrogen fertilization, and release of H^+ ions that can reduce the pH (ANGHINONI, 2007). Thus, affects the nutrients availability, root development and yield of the main agricultural crops (CAIRES et al., 2005, SORATTO and CRUSCIOL, 2008, ÁLVAREZ et al., 2009, CASTRO and CRUSCIOL, 2013, JORIS et al. 2013).

The liming material has been the most used for soil acidity correction. However, this material has low solubility in water (1.4 mg L^{-1} – ALCARDE, 1992) and needs to be applied in advance to obtain satisfactory results in the crop of main economic interest (RAIJ, 2011). Thus, it is important to study micronized liming materials (MLM) that present greater reactivity and solubility, in short term, plausible to be used, efficiently, in conservationist systems, as in NT. The MLM, due to the fact that they have a larger specific surface area (SSA) (1055-1559 m^2 kg^{-1}), are more effective in the control of acidity soil and supply of calcium (Ca) and magnesium (Mg), in short term (DOS SANTOS et al., 2016a, DOS SANTOS et al., 2016b).

The soil acidity control improves the nutrition and yields of wheat (*Triticum aestivum*) (COSTA and ROSOLEM, 2007), soybean (*Glycine max*) (BARBIERI et al., 2015), maize (*Zea mays*) (CAIRES et al., 2015) and black oats (*Avena Strigosa*) (ERNANI et al., 2001). However, there is a lack of information on the reactivity and efficiency of MLM in soils with variable charge (as Typic Distrudept), as well as their effects on the yield of the main crops in Campos Gerais region of Paraná, under NT.

2. Objectives

The general objective this work is measured (i) the reactivity and agronomic efficiency of micronized liming materials (granulated micronized calcite – GMC; granulated micronized dolomite – GMD and carbonated suspension – CS) when compared with dolomitic limestone (DL), applied only once in the surface of a Typic Distrudept (soil with variable charge), under no-tillage, along of time.

2.1. Specifics objectives:

- to measure yield index (relative yield, relative yield change and production efficiency) of wheat, soybean, black oat and maize for four years consecutive (during the years of 2012 up to 2016).
- to evaluate the pH and soil base saturation values, exchangeable-Ca, Mg and K concentrations and percentage of Ca and Mg in the cationic exchangeable capacity at pH 7.0 for up to 45 months, in the soil profile (0-5, 5-10, 10-20, 20-40 and 40-60 cm layers).

3. Literature review

3.1. Acidity control of soil with variable charge under no-tillage

In Brazil, around 66 million of hectares are growing with grains, fibers and pastures. However, most of these areas are degraded with high soil acidity. The soil acidity affects the development of plants and organisms and favors environmental degradation (BOLAN et al., 2008). Therefore, there is a need to build fertility, starting with the control of soil acidity.

The acidification occurs due to following factors: rainfall higher; basic cations displaced by H^+; basic cations leached; use of nitrogen (N) fertilizer and/or N fixation (HAVLIN et al., 2014); oxides-Al and oxides-Fe accumulation; higher aluminum (Al) and manganese (Mn) concentration; release of H^+ from soil organic; Al and Fe hydrolysis; uptake of cations favoring extrusion of H^+ (HUE, 2008; HUE, 2011); and acidity deposition by fossil fuel combustion (LAWRENCE et al., 2016). Besides, the acidity favors the accumulation of materials rich in aluminum (Al) and iron oxides (Fe), toxicity of Al and manganese (Mn), and deficiency of calcium (Ca), magnesium (Mg), potassium (K) and phosphorus (P) in the soil (HUE, 2011). Therefore, the soil acidity control is important for keeping of crop yield and reduce of soil fertility loss, mainly in variable charge soils (as Typic Distrudept).

The correct commonly used to control soil acidity are carbonates of calcium ($CaCO_3$ - calcite - $\log K_0 = 9.74$) and of magnesium ($(Ca,Mg)CO_3$ - dolomite - $\log K_0 = 18.46$), known commercially as liming materials. The carbonates ($CaCO_3$ or $(Ca,Mg)CO_3$) originate from sedimentary rocks and present solubility in water containing carbon dioxide (GEYSSANT, 2001). These rocks were deposited (rhombohedral form with crystals of size 0.1 mm) during biochemical processes dependent of temperature and sea water, favoring the formation of calcites with 4-15% of Mg and 10-20 % retention of in the pores (GEYSSANT, 2001).

The liming materials can increase crop yields and fertilizer efficiency, providing greater nutrient availability and decreased concentrations of potentially toxic elements (SORATTO and

CRUSCIOL, 2008; CASTRO and CRUSCIOL, 2013). The most important factors determining the efficiency of liming materials to control soil acidity are: release of neutralizers (OH^- or HCO_3^-), particle size and specific surface area (SSA) of the particles, crystalline structure of source material and Ca concentration (HAVLIN et al., 2014, CHAI et al., 1995).

The control soil acidity with carbonates ($CaCO_3$ or $(Ca,Mg)CO_3$) occurs as follows: carbonates when interacting with water (H_2O) release cations (Ca^{2+} and/or Mg^{2+}), bicarbonates (HCO_3^-) and hydroxyls (OH^-) (SPARKS, 2003). The bicarbonates (HCO_3^-) and hydroxyls (OH^-) react with the protons (H^+) forming H_2O and CO_2 (SPARKS, 2003) and, with the Al^{3+} precipitating in the form of Al hydroxide ($Al(OH)_3$) (SOUZA et al., 2007). These factors increase the pH value of the soil. The cations (Ca^{2+} and/or Mg^{2+}) are adsorbed at the soil exchange sites unbalancing the surface charges of the colloids due to the substitution between Al and Ca (ALBUQUERQUE et al., 2000; SPERA et al., 2008). Besides, with increase of soil pH, the hydroxyls (OH^-) present in the face-to-edge bonds of 1:1 clay mineral (silanol, aluminol, OH-iron oxide, OH-aluminum oxide), and in the carboxylic and phenolic groups of organic matter, release H^+ for soil solution generating negative charges (FONTES et al., 2001). These factors favor the cation exchange capacity (CEC), the dynamics of the natural acidification process and the carbonates solubility (RAIJ, 2011).

In no-tillage (NT), the most significant effects of the application of liming materials are observed in soil surface layer (GATIBONI et al., 2003). Thus, in NT used the crops wheat, soybean, black oat and maize, the soil acidification process can be attributed the following factors: (i) the export of basic cations (Ca, Mg and K) from the soil by grain-legume rotation (equivalent to 135-196 kg of $CaCO_3$ ha^{-1} $year^{-1}$ – SLATTERY et al., 1991), (ii) fertilizer contribution (2.3; 2.9 and 3.4 million of tons of nitrogen – N, P_2O_5 and K_2O, respectively in the Brazilian agriculture – IPNI, 2010) and (iii) biological fixation of N (up to 450 kg of N ha^{-1}, according to the leguminous species – OJIEM et al, 2014), capable of releasing protons (H^+)

for environment. However, over time, the liming material applied in the surface soil under NT, can improved acidity control in the deeper layers, due to the following factors: (i) movement of fine particles in biopores (AMARAL et al., 2004); (ii) inorganic anions (MARSCHNER, 1995); (3) water-soluble organic compounds (FRANCHINI et al., 1999; CIOTTA et al., 2004) and (iv) anions HCO_3^- (OLIVEIRA and PAVAN, 1996).

Then, the reaction of the liming material in NT is lower and gradual (CAIRES et al., 2005), but can resulting, along the time in amelioration of the soil fertility below the point of placement (OLIVEIRA and PAVAN, 1996). The liming materials provide ideals conditions of change in the pH and exchange complex, favoring the crops yield and amelioration of soils attributes (BOLAN et al., 2008; CAIRES et al., 2015). Besides, in soils with controlled acidity there is increase of crops yield due to greater crops yield and carbon input (PARADELO et al., 2015) and this influence the soil reaction (HUE, 2008; HUE, 2011).

However, the liming material conventionally employed in agriculture (limestone) has low solubility in water (1.4 mg L^{-1} - ALCARDE, 1992) and needs to be applied in advance (about three months in a soil conventional preparation system) to obtain satisfactory agronomic results (RAIJ, 2011). Besides, in production systems (high nutrients input), is need to apply, with more often (< 3 years) liming materials in order to avoid decrease in crop yields, especially in soils with variable charge (ERNANI et al., 2004). Therefore, it is important to study liming materials that have a higher reactivity, in short term, and have efficient use in conservation agriculture systems (as NT) and in precision agriculture.

These liming materials, considered as "micronized liming materials – MLM", are characterized by the presence of particles with lower diameters (< 10 μm) and higher SSA (1055-1559 m^2 kg^{-1}) when compared to conventional limestones (DOS SANTOS et al., 2016b). However, due to the small granulometry they are presented in a form of pelletized (or granulated) or fluid (in suspension with water), facilitating the application in the field and reducing losses with drift. Besides, there are few studies showing that MLM are capable of soil acidity control (OLIVEIRA et al., 2014; DOS SANTOS et al., 2016b), to source and/or nutrients available (FRASER and SCOTT, 2011; HOU et al., 2012; DOS SANTOS et al., 2016a) and to reduce the variability (vertical) of the acidity in soils with variable charge, as the Typic Distrudept.

There are most works that measured the efficiency of liming materials in Oxisol (other typic of soil with variable charge), under NT, in relation to decrease in the acidity and increase in the soil base saturation (V) such as studies of CAIRES et al. (2000), CAIRES et al. (2004), FIDALSKI and TORMENA (2005), CORRÊA et al. (2007) and among others. However, in Typic Distrudept there are lack of work, even though one of the main soils of Brazil, mainly in Campos Gerais Region, experimental local this work. This region presented around 389 thousand hectares of Oxisol and 436 thousand hectares of Typic Distrudept (SÁ, 2007). The Typic Distrudept present different characteristics and are representative for grain and pasture production in southern Brazil (EMBRAPA, 2006).

3.2. Characteristics of liming materials

The liming materials are products capable of neutralizing the acidity and providing nutrients to the soil, mainly Ca and Mg (ALCARDE, 1992). For calcium and/or magnesium carbonates to be registered with the Ministry of Agriculture, Livestock and Supply (MAPA) there are basic requirements to be met.

The fineness factor (FF) of the liming materials must meet the following criteria: (i) the liming material particles must pass 100 % in a sieve of 2.00 mm (ABNT nº10), (ii) pass at least 70 % in a sieve of 0.84 mm (ABNT nº20) and (iii) pass at least 50 % in a 0.30 mm sieve (ABNT nº50) (Brasil, 2006). The neutralizing power (NP) of liming materials, which is calculated by the formula: [CaO (%) x 1.79 + MgO (%) x 2.48], must be at least 67 % and the sum of percentage of CaO and MgO of at least 38 %. The effective calcium carbonate (ECC), calculated by the formula: [(NP x FF) / 100], must be at least 45 % (BRASIL, 2006). The liming materials can be classified as calcitic and dolomitic when they present a lower and higher concentration at 5 % of magnesium oxide (MgO), respectively (BRASIL, 2006).

Other factors that determine the efficiency of liming materials are granulometry and SSA of the particles (HAVLIN et al, 2014). Liming materials with small particle size and high SSA have uniform distribution, faster reactivity and application of small doses in the soil (HAVLIN et al, 2014). Thus, liming materials with small particle sizes (< 0.25 μm) are more efficient in the increase of pH values and in the decrease Al concentrations after three years of application in Typic Haplic (Inceptisol) (ÁLVAREZ et al, 2009).

The liming material can to increase soil pH value and exchangeable-Ca and Mg concentrations and favor the adjustment of the soil Ca/Mg relationship (BARBIERI et al., 2015; CHATZISTATHIS et al., 2015). Besides, the liming material increase the soil base saturation and reduced the loss of exchangeable-K (HAVLIN et al., 2014). However, in deep layer, occur the exchangeable-Al increase while decrease the pH value and exchangeable-Ca and Mg concentrations (BORTOLUZZI et al., 2014). Therefore, is important the soil acidity control and provide Ca and Mg in deep layer using liming materials. Also, the effects of liming materials can influence the exchangeable-K concentration in soil deep layer. However, the distribution of exchangeable-K in deep layer is high influence by plant uptake (JAMES et al., 2016), mobility in soil profile and cation exchange capacity (CEC) (HAVLIN et al., 2014). The high K uptake by plants can suppress more the Mg uptake than Ca (RHODES et al., 2018) and during the uptake by plants, near roots, occur more exchange selectivity in soil of K relative to Ca (SCHNEIDER and MOLLIER, 2016). These facts can influence the K available in soil.

The MLM present SSA between 1055 to 1559 m^2 kg^{-1} (DOS SANTOS et al., 2016b) and easier to application (found pelletized or in fluid). Those characteristics influence in the reaction velocity and soil distributions liming material (ÁLVAREZ et al., 2009; HIGGINS et al., 2012). In controlled conditions, the MLM decreased soil acidity and increased the exchangeable-Ca, Mg and K concentrations in a Typic Distrudept and a Rhodic Hapludox (DOS SANTOS et al., 2016a; DOS SANTOS et al., 2016b). However, is important understand the size of the exchangeable pool (Ca, Mg and K) and nutrient dynamic in farming production systems (KOPITTKE et al., 2017), mainly after application of MLM. Besides, after liming material application on soil, can to occur increase crops grains yield due to improvement plants nutrition, as major uptake of Ca, Mg and K (JORIS et al., 2013; CRUSCIOL et al., 2016), influencing your available in soil. Therefore, is need knowledge the effects of liming materials in soils with charge variable, as a Typic Distrudept. And then, found the optimal liming material requirement for efficient stabilization these soils (CHERIAN et al., 2018).

3.3. Soil acidity control and amelioration in crops yield

The soil acidity is a serious limited of crops yield – as wheat, soybean, black oat and maize – in various world regions (VALENTINUZZI et al., 2015). Acids soil have high concentrations of Al^{3+} (at $pH < 5.0$) and can cause changes in the crops root system (HAVLIN et al., 2014). These changes may decrease nutrient and water absorption and inhibit root and aerial growth (KOPITTKE et al., 2009; TOSELLI et al., 2009). However, after application of liming material in the soil, there is an increase in pH and V values, cation exchange capacity (CEC) and nutrients availability, mainly Ca^{2+} and Mg^{2+}. These nutrients are more easily uptake by crops than toxic potentially elements of same valence, favoring the development of crops (LUO et al., 2008). Therefore, the increase in the grain yield of soybean and wheat may be more closely linked to the increase in V and the availability of Ca^{2+} provided by the liming material (BARBIERI et al., 2015). However, in wheat, soybean and maize production systems, which use a greater amount of fertilizers, mainly N, the soil acidification occurs more quickly. Thus, the application of liming materials to control soil acidity can increase grain yield of wheat, soybean and maize (CAIRES et al., 2015). Besides, the increase grain yield and dry matter are directly related to the availability and uptake of nutrients from the soil by the crops after liming (CASTRO and CRUSCIOL, 2013).

The yield of crops is the result of various interactions between environments, climate, soil attributes, agronomic management, genetic material, rainfall, solar radiation, photoperiod and a lot more (VAN ITTERSUM and RABBINGE, 1997; ANDREA et al., 2018). However, for greater knowledge, the crops yield index are important for agriculture, mainly when employed technology for world or national food security (FISCHER et al., 2014; LIU et al., 2016). These crops yield index can be relative yield (RY), relative yield change (RYG) and production efficiency (PE). The RY taking into account the crops yield data after each treatment (i.e. after application of liming material). Already, the RYG taking into account the relative yield change between the years of crops growth (EWERT et al., 2005). And, the PE taking into account the crops yield sum after each treatment (i.e. after application of liming material). Same factors, as soil acidity control, can to increase or loss reduces in the crops yield index (GRASSINI et al., 2013; MERLOS et al., 2015).

There are few studies regarding the MLM grains and dry matter yields index (RY, RYG, and PE) of wheat/soybean/black oat/maize cropped in succession under NT. This index helps the measured the yield evolution in space and temporal scale in the actual conditions of weather, soil, farmer's knowledge and technologies (FAO, 2015, GUILPART et al., 2017). In this way, in the future can use more the yield index to soil fertility science using soil acidity as limiting factor and not only for some limiting factors, as water and weather, as mentioned in VAN OORT et al. (2017).

4. Material and Methods

4.1. Physical environment characterization

The experiment was carried out in Palmeira, Paraná state, Brazil, region of Campos Gerais of Paraná (S25º24'37.8'' W49º58'22,8'' (± 3 m) alt. 900 m) (Figure 1) in a soil Typic Distrudept (Inceptisol). This region presents 37% (436 thousand ha) of your area fill with Typic Distrudept (SÁ, 2007) and its characteristics by higher grains yields in Brazil.

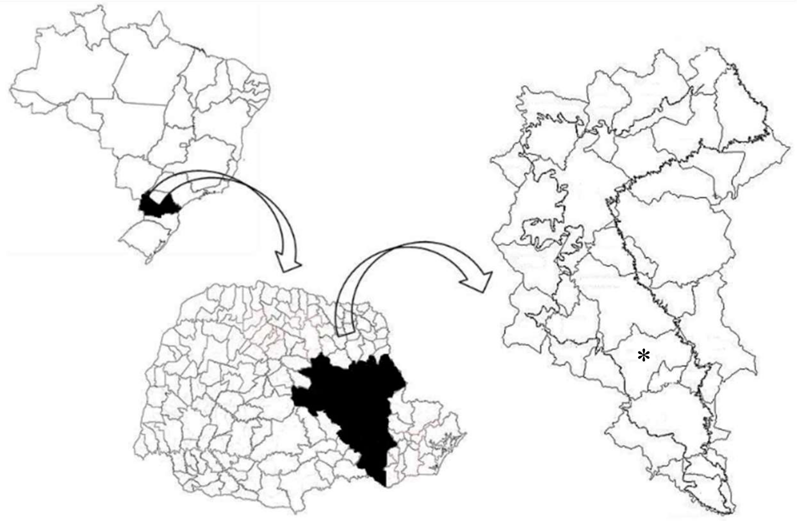


Figure 1. Map of the Campos Gerais Region - Paraná – Brazil (around 1.17 million ha). The soils predominant are Typic Distrudept (around 436 thousand ha) and Oxisol (around 389 thousand ha), being in the Palmeira municipality (*) the Typic Distrudept is more representative for grains production. Adapted from SÁ (2007).

The experimental area was under NT in the past 15 years, cropping black oat, in the fall, and soybean, in the summer. In the beginning of the experiment, the soil showed following attributes in the 0-20 cm layer (according Pavan et al., 1992): 4.3 of pH ($CaCl_2$), 23 % of aluminum saturation (m), 30.8, 9.3, 2.3 and 145.6 $mmol_c$ dm^{-3} of Ca, Mg, K and CEC, respectively, 29 % of base saturation (V), 23 mg dm^{-3} of available phosphorus (Mehlich-1) and 21.0 g dm^{-3} of organic carbon (Walkey-black); 200.0, 255.2 and 544.8 g kg-1 of clay, silt and sand, respectively.

The local weather is Cfb (humid subtropical climate), according to Köppen-Geiger classification (ALVARES et al., 2013). Monthly rainfall and temperature of the site, over the experimental period (May/2012 to Apr/2016) are presented in Figure 2.

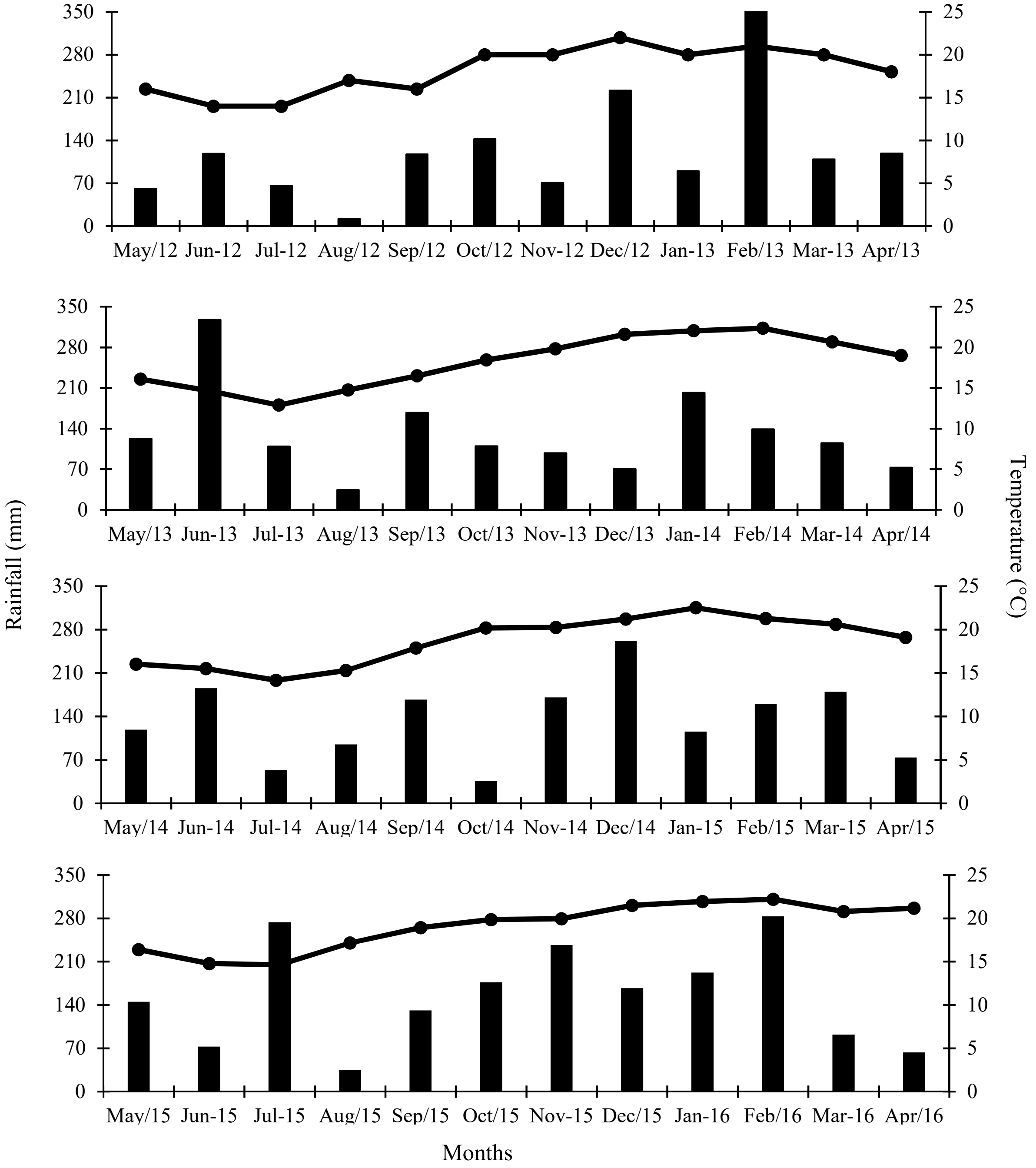


Figure 2. Monthly rainfall and temperature during the experimental period (may/2012 to apr/2016) in the Palmeira municipality. The line is temperature and the column is rainfall. In September/2014 occurred hail rain. Source: SIMEPAR (2016).

4.2 Design experimental and liming materials

The experimental design was completely randomized blocks in split-plot with four replications. In the plots (384 m^2) were studied four liming materials: dolomitic limestone (DL), granulated micronized calcite (GMC), granulated micronized dolomite (GMD) and carbonated suspension (CS). In the subplots (96 m^2) four doses of the liming materials were applied aiming to increase V to 50, 70 and 90%, besides of control treatment (without liming material). All the liming materials doses were applied in the soil surface, without incorporation, only once, in jun/2012. After this, no was applied liming material in the experimental area.

The doses estimated to increase V (to 50, 70 and 90 %) was obtained through the equation according CANTARELLA et al. (1998) and can be observed in Table 1. The effective calcium carbonate (ECC) of liming materials results of calcium carbonate equivalent (CCE), fineness factor (FF) of the liming and neutralizing power (HAVLIN et al., 2014). As the MLM used are pelletize, as the CMG and DMG, or fluid limes, as the CS, present finer particle size (Figure 3), these materials do not increase their neutralizing value (HAVLIN et al., 2014) and FF value adopted was 100%, according to DOS SANTOS et al. (2016b).

Table 1. Doses of the liming materials applied on the soil surface, without incorporation, aiming the soil base saturation (V) to 50, 70 and 90%.

Aimed V (%)	Liming materials			
	DL^2	GMC^3	GMD^4	CS^5
	Mg ha^{-1}			
50^1	3.22	3.18	3.05	3.98
70^1	6.28	6.21	5.94	7.76
90^1	9.34	9.23	8.83	11.54

(1)The estimated doses of each liming material to estimate the need for liming were obtained through the equation (according to CANTARELLA et al., 2008): $LR = [CEC*(V_2 - V_1)/10*ECC]$, where: LR: lime requirement (Mg ha^{-1}) for layer 0-20 cm; CEC: cation exchange capacity ($mmol_c\ dm^{-3}$); V_1: base saturation (%) obtained; and V_2: base saturation (%) aimed. The ECC was estimated through the equation (according to HAVLIN et al., 2014): $ECC = (NP \times RE)/100$, where: ECC: effective calcium carbonate – %; NP: neutralizing power and RE: relative efficiency of the liming; (2)DL: dolomitic limestone; (3)GMC: granulated micronized calcite; (4)GMD: granulated micronized dolomite; (5)CS: carbonated suspension with 1.89 kg L^{-1} of density and 740 g kg^{-1} of solid.

The calcium (Ca), magnesium (Mg) and ECC values of liming materials studied are 216.6, 135.1 and 952.0 g kg^{-1} for DL; 330.4, 9.3 and 962.7 g kg^{-1} for GMC; 247.2, 73.28 and 1006.5 g kg^{-1} for GMD; 258.1, 5.0 and 770.0 g kg^{-1} for CS, respectively. More information about the physical and chemical attributes of liming materials are presented in DOS SANTOS et al. (2016a and b), except for DL. The DL this work present 952 g kg^{-1}; 1099 g kg^{-1} and 303 m^2 kg^{-1} of the ECC, CCE and specific surface area, respectively.

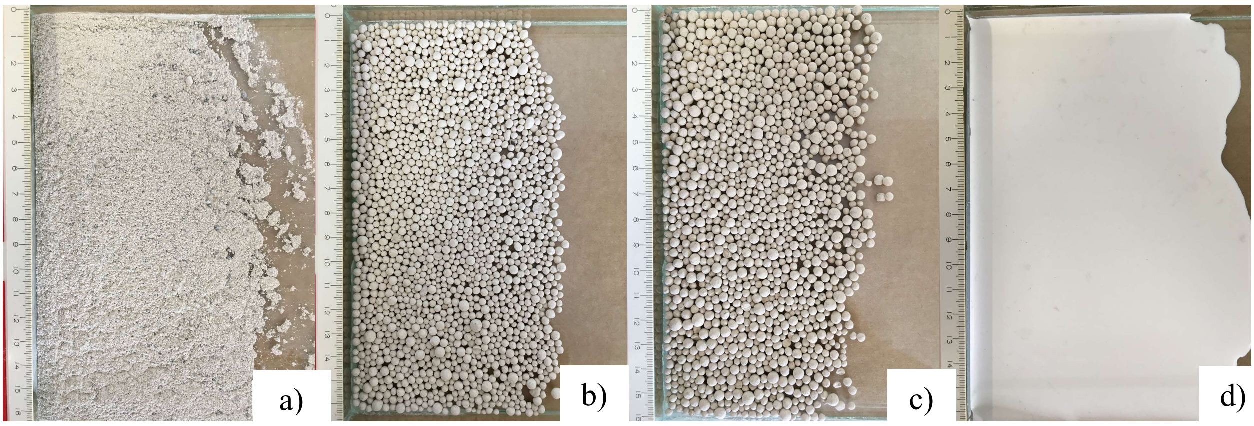


Figure 3. Granules size (cm) and arrangement of dolomitic limestone (DL) (a), granulated micronized calcite (GMC) (b), granulated micronized dolomite (GMD) (c) and carbonated suspension (CS) (d).

4.3. Crops growth and sampling

After the application of the treatments, wheat, soybean, black oat and maize were cropped along 45 months, as showed in Figure 4. These crops are the most representative in Campos Gerais Region (Paraná State) and Southern Brazil. The input of mineral fertilizers for these crops was showed in Table 2. All the crop protection strategies commonly employed in the region were used.

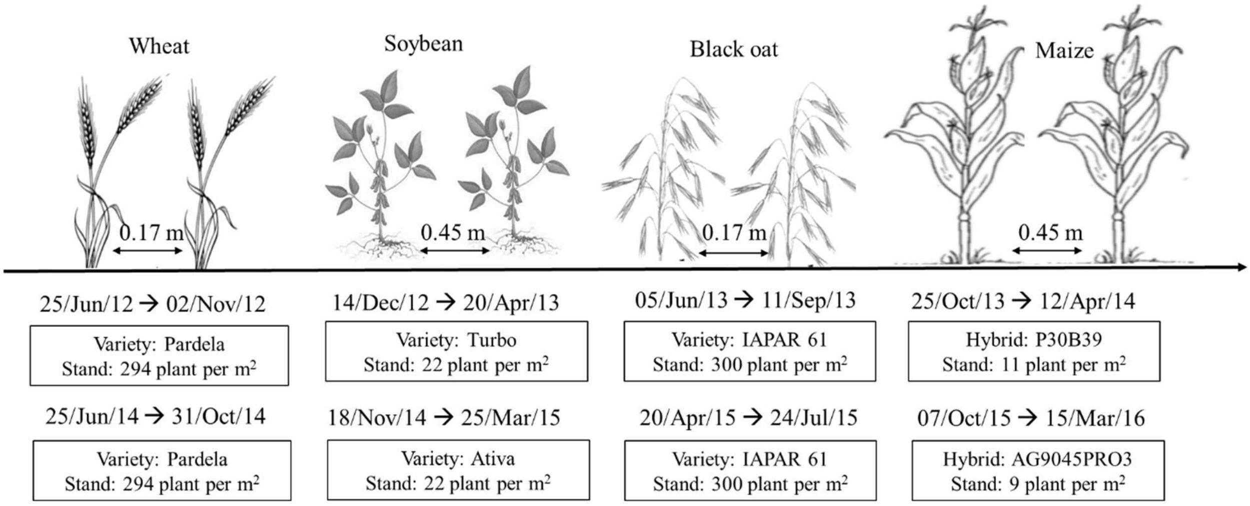


Figure 4. Two cycles of crop succession and information about the events along the experimental period, under no-tillage. The crops growth under no-tillage were wheat, soybean, black oat and maize during the years 2012 to 2016.

When the grains crops were in the physiologic maturity stage, the harvest was performed sampling 6.0 m^2 per subplots (taking into account only middle rows). The wheat, soybean and maize grains were threshed (BC-80 III model), weighed, and the expressed their yields by 130 g water kg^{-1}. Regarding the dry matter, samples of the black oat were collected from randomized 1.0 m^2 per subplots. The samples were oven-dried at 65 °C until take constant dry matter, weighed and measured dry matter yield.

Table 2. Nutrients input by mineral fertilizers applied in wheat, soybean, black oat and maize cropped along the experimental period (jun/2012 to mar/2016).

Crops	**Nutrients input**		
	N$^{(1)}$	**$P_2O_5$$^{(2)}$**	**$K_2O$$^{(3)}$**
	kg ha^{-1}		
	Base fertilization		
Wheat	22.5	120.0	-
Soybean	7.0	70.0	70.0
Black oat	18.0	96.0	-
Maize	25.6	64.0	64.0
	Topdressing fertilization		
Wheat:			
- After emergence	82.5	-	55.0
- 20 days after emergence	45.0	-	-
- Elongation	22.5	-	-
Maize:			
- 30 days after emergence	120.0	-	80.0
Sum	686.2	700.0	538.0

(1)N as urea (450 g kg^{-1} N) or as monoammonium phosphate (MAP) (110 g kg^{-1} N); (2)P_2O_5 water soluble as single superphosphate (SSP) and triple superphosphate (TSP) or MAP (480 g kg^{-1} P_2O_5); (3)K_2O as potassium chloride (KCl – 600 g kg^{-1} K_2O).

4.4. Analyses yield trends

The relative yield (RY), relative yield change (RYG) and production efficiency (PE) of wheat, soybean, black oat and maize were estimated after 5, 10, 15, 22, 28, 33, 37 and 45 months after liming materials surface application in the soil. The RY was calculated by equation 1:

$$RY = \frac{T0}{Tn} x\, 100 \qquad (1)$$

where RY: Relative yield (%); T_0: grains and dry matter yield in the control treatment (without application of liming material) (kg ha^{-1}); T_n: grains and dry matter yield after application of liming material doses (kg ha^{-1}).

The RYG was estimated by equation 2, according to EWERT et al. (2005):

$$RYG = \frac{Ye\ (ty)}{Ye\ (ty-1)} \tag{2}$$

where RYG: relative yield change; Y_e: yield of grains and dry matter (kg ha^{-1}); t_y: year of crop growth; $t_y - 1$: previous growth year of the same crop.

The PE was measured by equation 3:

$$PE = \frac{Ys}{D} \tag{3}$$

where, PE: production efficiency (kg of grains or dry matter / Mg of liming material); Y_s: yield sum of grains and dry matter up to 45 months after soil surface application of liming materials (kg ha^{-1}); D: dose of liming material applied on soil in jun/2012 (Mg ha^{-1}) (Table 1).

4.5. Soil samples and chemical analyze

The aleatory soil samples from 0-5, 5-10, 10-20, 20-40 and 40-60 cm were sampled by augers. Twelve simple samples were collected for performed a composite sample, in each layer of the subplot. The soil was sampled in 0 (at the beginning of the experiment), 5 (after the harvest of wheat 2012), 11 (after the harvest of soybean 2012/13), 23 (after the harvest of maize 2013/14), 34 (after the harvest of soybean 2014/15) and 45 (after the harvest of maize 2015/16) months after surface application of liming materials.

These samples were taken to the laboratory, dried in an oven at 40ºC with forced air circulation over a period of 48 hours, ground and sieved in a 2.0 mm mesh sieve. Afterwards, pH, exchangeable-Ca, Mg and K values was performed according to regional methods (Pavan et al.,1992). The pH value was determined in a 0.01 mol L^{-1} $CaCl_2$ solution using a 1:2.5 (v:v) soil-to-solution ratio suspension. The exchangeable-Ca and Mg values were determined in a 1.0

mol L^{-1} potassium chloride (KCl) solution and titration using a standard 0.025 mol L^{-1} EDTA (Ethylenediaminetetraacetic acid). The exchangeable-K value was determined in Mehlich-1 (0.05 mol L^{-1} chloride acid (HCl) and 0.0125 mol L^{-1} sulfuric acid (H_2SO_4)) solution. The V was calculated by the relationship between the Ca, Mg and K-exchangeable values sum and cation exchange capacity (in pH = 7.0) (HAVLIN et al., 2014).

4.6. Statistical analyses

Data were submitted for statistical analysis employing the computer program SAS Version 9.1.2 (SAS, 2004). All results were sphericity and the Huynh-Feldt (H-F) conditions met, ensuring that univariate test statistics could be each attribute measured. The effects of liming materials (DL, GMC, GMD and SC), of doses applied (to increase V to 50, 70 and 90% besides to the control treatment) on crops yield index, pH and V values and exchangeable-Ca, Mg and K concentrations and percentual of Ca and Mg in the CTC were assessed using: (i) the analysis of variance employing the PROC GLM and Tukey test ($\alpha = 0.05$); (ii) the analysis of regression employing the PROC REG and least significant difference (LSD) to compare the liming materials. The effects of liming materials (DL, GMC, GMD and SC), of doses applied (to increase V to 50, 70 and 90% besides to the control treatment) and periods (0, 5, 11, 23, 34 and 45 months) after application on pH, V, exchangeable-Ca, Mg and K and % of Ca and Mg in the CEC were assessed using (iii) the analysis of profile using the PROC GLM and REAPEATED. Just the wheat 2014 RY date was transformed to Log_{10}. For equation of quadratic regression was used the derived of second-degree equation. The control treatment for liming material is the DL and for doses is without application of liming materials.

5. Yield index of crops grown under no-tillage after soil superficial application of micronized liming materials

Abstract

The superficial application of micronized liming materials (MLM) in no-tillage (NT), without incorporation, for the acidity control in soil can be a strategic, in short-term, avoiding yield losses. We measured the relative yield (RY), relative yield change (RYG) and production efficiency (PE) of wheat, soybean, black oat and maize during four consecutive years (2012 up to 2016), in a Typic Distrudept under NT, treated with MLM. The experimental design used was completely randomized blocks in split-plot with four replications. In the plots were studied the dolomitic limestone (DL) and MLM (granulated micronized calcite – GMC; granulated micronized dolomite – GMD and carbonated suspension – CS). In the subplots were studied four doses of each the liming materials aiming to increase soil base saturation (V) to 50, 70 and 90 %, besides of control treatment. The MLM presented major RY and PE along experimental period than DL. Besides, the major RYG of MLM refer lower responsiveness, major residual effect as well as major or maintenance crops yield. If we consider only PE, better results was found in the dose aiming V to 61 % for all the liming materials studied, showing that it is the adequate V for acidity control of a Typic Distrudept.

Keywords: soil reaction; relative yield; relative yield gap; production efficiency; Typic Distrudept.

Índices de rendimento das culturas cultivadas sob plantio direto após aplicação superficial de corretivos micronizados

Resumo

A aplicação superficial de corretivos micronizados (CM) em plantio direto (PD), sem incorporação, para o controle da acidez pode ser uma estratégia, em curto tempo, de reduzir as perdas de rendimento. Nós mensuramos o rendimento relativo (RR), mudanças de rendimento relativo (MRR) e eficiência de produção (EP) de trigo, soja, aveia preta e milho durante 4 anos consecutivos (2012 a 2016), em um Cambissolo Háplico sob PD, tratado com CM. O delineamento experimental usado foi de blocos casualizados, em parcela subdividia, com quatro repetições. Nas parcelas foram estudados o calcário dolomítico (CD) e os CM (calcita micronizada granulada – CMG; dolomita micronizada granulada – DMG e suspensão carbonatada – SC). Nas subparcelas foram estudadas quatro doses de cada corretivo visando elevar a saturação por bases do solo (V) para 50, 70 e 90%, mais o tratamento controle. Os CM apresentaram maior RR e EP, ao longo do período experimental, do que o CD. Além disso, a maior MRR do CM indicam baixa reatividade, maior efeito residual bem como maior ou manutenção do rendimento das culturas. Se considerarmos apenas a EP, melhores resultados foram encontrados na dose visando V para 61% para todos os corretivos estudados, mostrando que é o V mais adequado para controlar a acidez de um Cambissolo Háplico.

Palavras-chave: reação no solo; rendimento relativo; mudança de rendimento relativo; eficiência de produção; Cambissolo Háplico.

5.1. Results

The yield index of all crops studied considered the absolute yield (in kg ha^{-1}). Therefore, for calculations of yield index were used the absolute data of crops yield (Table 3) after application of liming materials in all the doses.

5.1.1. Relative Yield (RY)

For RY results there were some interactions between liming materials and doses, as for wheat 2012 ($F = 7.08$; $p < 0.0001$), soybean 2012/13 ($F = 3.58$; $p = 0.0034$), black oat 2013 ($F = 6.53$; $p < 0.0001$) and 2015 ($F = 3.97$; $p = 0.0018$). The control treatment (DL and without liming materials) for RY was of 110 % (Figures 5 and 6). For wheat 2012, higher RY was observed in MLM than DL (Figure 5A). Major RY of wheat 2014 were observed in DL than MLM, and also, in the doses that aimed to increase V to between 50 and 70 % (Figure 5B). For wheat 2014, after obtaining of equation derivative, the higher GRY was in the dose 5.95 Mg ha^{-1} of DL or the dose aiming V to 68 % (Figure 5B). The RY of maize 2013/14 was major in CS following of DL, GMD and GMC (Figure 5C). For maize 2015/16 there is no differences for liming materials applied (Figure 5D). However, for maize 2013/14, higher RY was observed in the doses that aimed to increase V to between 50 and 70 % (Figure 5C). For maize 2013/14, after obtaining of equation derivative, the higher RY was in the dose 5.02 Mg ha^{-1} of CS or the dose aiming V to 55 % (Figure 5C). The RY was major for soybean 2012/13 after application of DL and CS than the others (Figure 6A). Already, for soybean 2014/15 was observed major RY in GMC and CS than DL and GMD (Figure 6B). For black oat 2013 was observed major RY in GMD than others liming materials (Figure 6C). Major RY of black oat 2015 were observed in DL than the MLM (Figure 6D).

Table 3. Absolute yield of wheat (2012 and 2014), maize (2013/14 and 2015/16), soybean (2012/13 and 2014/15) and black oat (2013 and 2015) after application of liming materials (DL – dolomitic limestone; GMC – granulated micronized calcite; GMD – granulated micronized dolomite – GMD and CS- suspension carbonated) in the doses aiming soil base saturation (V) to 50, 70 and 90 %, besides control treatment (dose 0).

	Wheat 2012	Wheat 2014	Maize 2013/14	Maize 2015/16	Soybean 2012/13	Soybean 2014/15	Black oat 2013	Black oat 2015
	Kg ha^{-1}							
DL								
0	2482*	1225	9696	12061	2727	3945	5015	6145
50	2477	694	10539	13180	2867	4831	6691	4791
70	3263	963	10620	11634	2766	3619	6586	5611
90	2891	671	10660	11812	2580	3916	5737	4278
GMC								
0	3668	700	10447	11479	2713	4023	2741	2994
50	3350	658	13291	13138	2681	3812	6327	5102
70	2612	767	11136	11904	2689	3829	5951	5872
90	3309	563	12070	12550	3238	4648	5633	4672
GMD								
0	3452	863	10824	12483	2392	3829	5758	4013
50	2515	1200	11113	13683	2755	4333	6034	4734
70	3136	1481	10262	12570	2663	4017	4639	4526
90	2913	1279	11188	13355	2676	3730	4797	5431
CS								
0	3458	940	11398	12284	2449	4523	5329	4312
50	3562	758	10004	12318	2398	4702	8535	5023
70	2427	604	10330	14526	2578	3360	6438	4942
90	2901	642	12973	14104	2283	3878	7393	4715

*Mean of four reapplications.

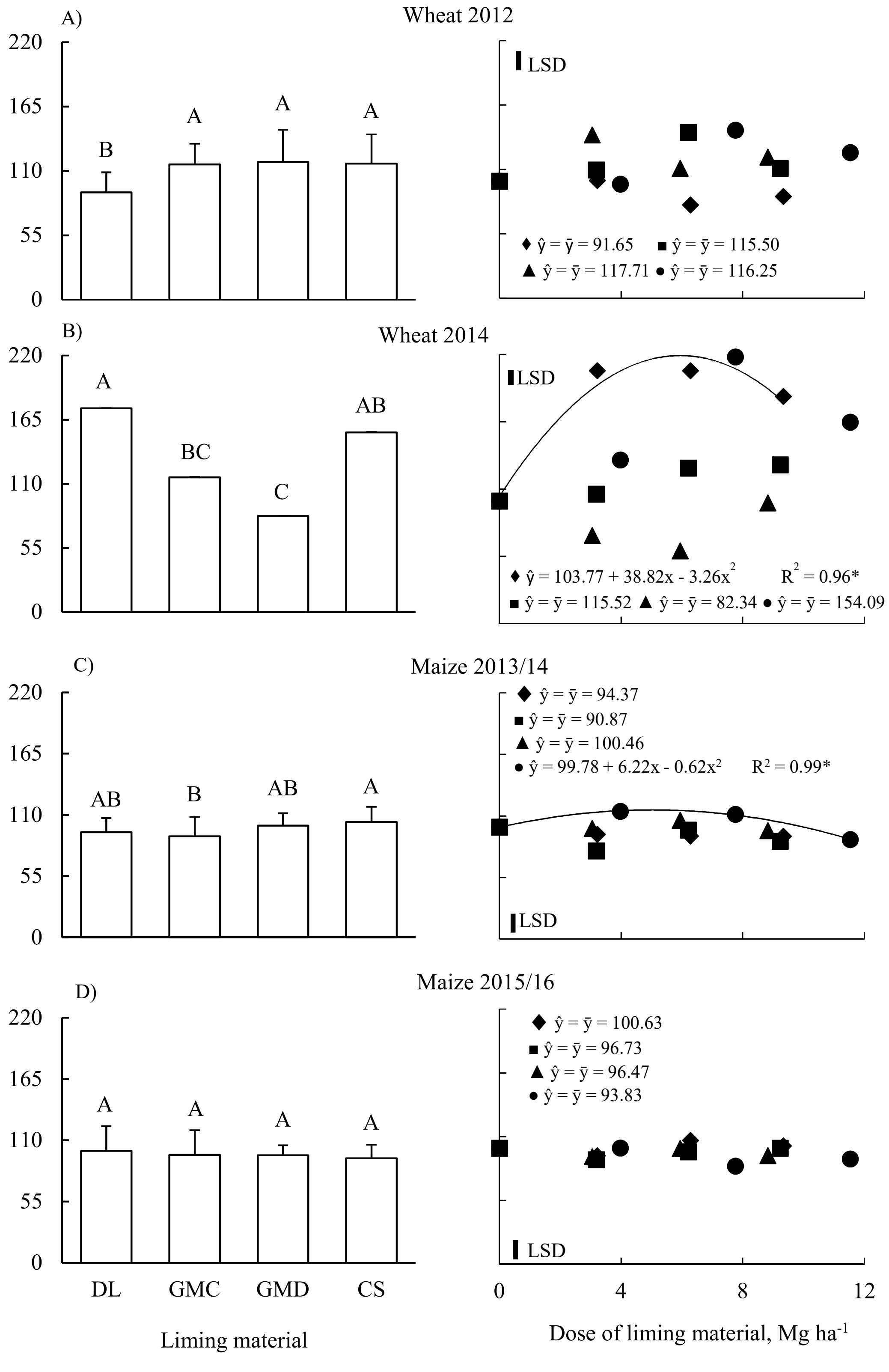


Figure 5. Grains (GRY) relative yield (%) (*n* = 16 ± standard deviation) of wheat and maize cropped under no-tillage, 5, 10, 15 and 22 months after surface application of the liming material doses (in jun/2012). (♦) Dolomitic limestone – DL. (■) Granulated micronized calcite – GMC. (▲) Granulated micronized dolomite – GMD. (●) Carbonated suspension – CS. Averages followed by the same letter do not differ statistically (Tukey test, $\alpha = 0.05$). Vertical bars indicate the least significant difference (LSD). *: $P < 0.05$. **: $P < 0.01$.

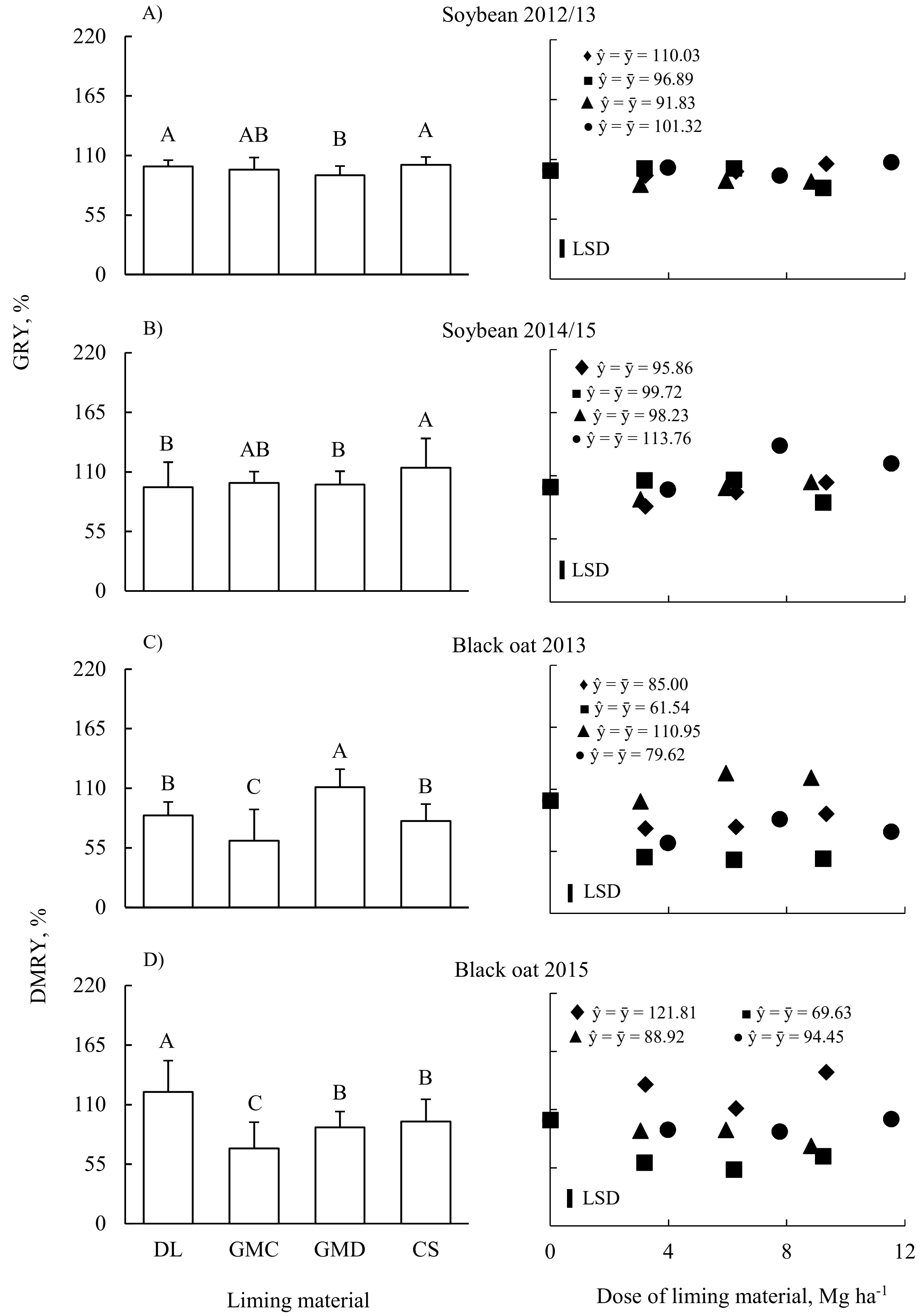


Figure 6. Grains (GRY) and dry matter relative yield (DMRY) (%) (*n* = 16 ± standard deviation) of soybean and black oat cropped under no-tillage 28, 33, 37 and 45 months after surface application of the liming material doses (in jun/2012). (♦) Dolomitic limestone – DL. (■) Granulated micronized calcite – GMC. (▲) Granulated micronized dolomite – GMD. (●) Carbonated suspension – CS. Averages followed by the same letter do not differ statistically (Tukey test, α = 0.05). Vertical bars indicate the least significant difference (LSD). *: $P < 0.05$. **: $P < 0.01$.

5.1.2. Relative Yield Change (RYG) and Production Efficiency (PE)

For RYG results there was an interaction between liming materials and doses, as for black oat ($F = 3.18$; $p = 0.0074$). The control treatment (DL and without liming materials) for RYG was of 0.3; 1.5; 1.0 and 1.0 % for wheat, soybean, black oat and maize, respectively (Figure 7). We considered the effect of liming materials and of doses applied in each crop studied in two cycles of crop succession. For the wheat the GMD and DL presented major RYG that the others liming materials but, only DL decrease RYG as far as increased the doses applied (Figure 7). Already for soybean the CS performed major RYG followed DL > GMD > GMC (Figure 7). Major RYG of black oat was observed in GMC and GMD, which presented similar and upper results than DL and CS (Figure 7). Also, there is decrease of black oat RYG as far as increased the doses applied of DL (Figure 7). There were no differences between the liming materials in maize (Figure 7).

For PE results there was an interaction between liming materials and doses, as for grains ($F = 7.64$; $p < 0.0001$). The control treatment DL for PE was of 4500 and 1500 kg of grains and dry matter, respectively, by Mg of liming materials applied on the soil (Figure 8). In the control treatment, without liming material, the PE was of 0.0 kg of grains and dry matter (Figure 8). For grains was observed higher PE in GMC and GMD up to 45 months than others liming materials (Figure 8). Already for dry matter PE there was no differences between the liming materials (Figure 8). However, for grains and dry matter higher PE was observed in the dose of liming material aiming V to 50% (Figure 8). For grains, after obtaining of equation derivative, the higher PE was in the dose 4.93; 4.88; 4.69 and 6.22 Mg ha^{-1} to DL, GMC, GMD and CS, respectively (Figure 8). Theses doses aiming V to 61%. For dry matter, after obtaining of equation derivative, the higher PE was in the dose 4.91; 4.86; 4.68 and 6.03 Mg ha^{-1} to DL, GMC, GMD and CS, respectively (Figure 8). Theses doses aiming V to 61%.

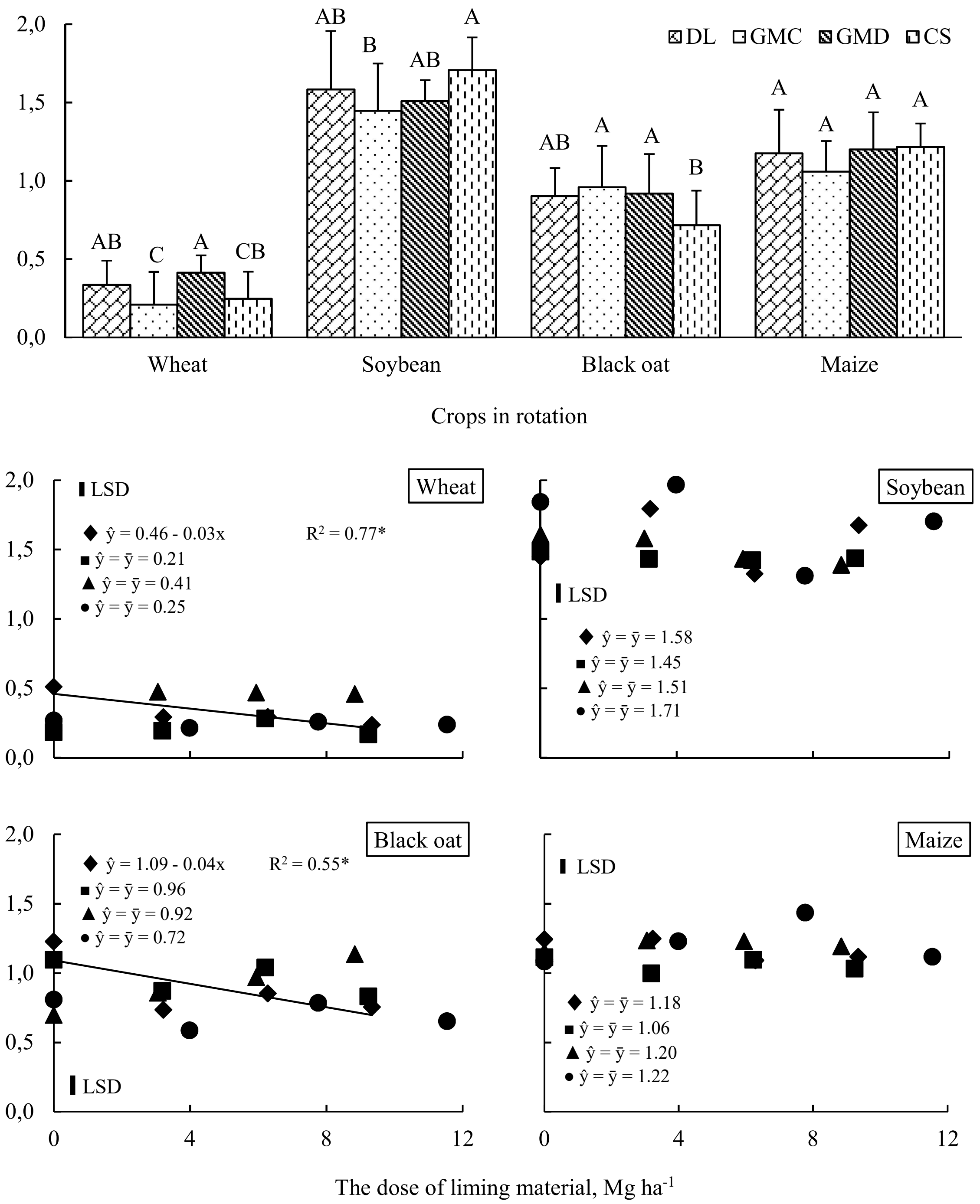


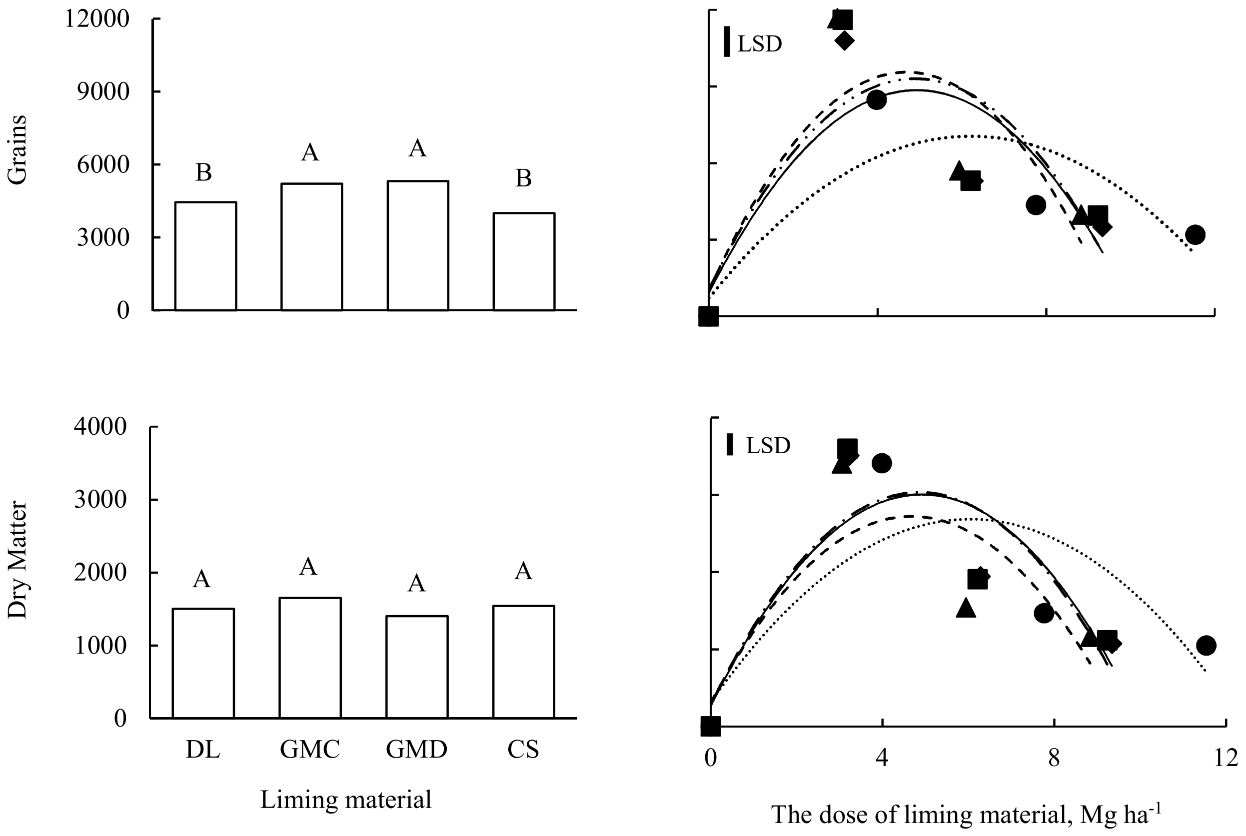
Figure 7. Relative yield change (%) (*n* = 16 ± standard deviation) of grains of wheat, soybean and maize; and of dry matter of black oat growth in two cycles of crops succession under no-tillage up to 45 months after surface application of doses of liming material (in jun/2012). (♦) Dolomitic limestone – DL. (■) Granulated micronized calcite – GMC. (▲) Granulated micronized dolomite – GMD. (●) Carbonated suspension – CS. Means followed by the same letter do not differ statistically by Tukey test (α = 0.05). Vertical bars indicate the least significant difference (LSD). *: $P < 0.05$. **: $P < 0.01$.

5.2. Discussion

5.2.1. Knowing the soil acidity control on relative yield

Thus, can be observed, using RY, that the MLM react much faster but present little residual effect than DL, in short-term (5-10 months after application), when we observe wheat 2012 and soybean 2012/13 (Figures 5 and 6). However, in the experimental soil (Typic Distrudept), the DL, in all doses studied, started your effect as from maize 2013/14 (or after 24 months of surface application) (Figure 6C). Little studies are found in Typic Distrudept wherefore we will argue with other soils. The same did not occur in an Oxisol, under NT, treatment with dolomitic limestone (surface application and ECC = 850 g kg^{-1}) in the dose aiming V to 70%, in which takes about 72 months for acidity control (CAIRES et al., 2015). The GMC and CS, generally, presented better RY than DL and GMD due to significant concentration of calcites than dolomites and this confers greater solubility (Vargas et al., 2019). The application of MLM resulted in Typic Distrudept acidity control (DOS SANTOS et al., 2016b). However, the soil acidity control favored the crop growth (BOLAN et al., 2008; CAIRES et al., 2015) and increase RY (LIU et al., 2004; BARBIERI et al., 2015).

However, this experiment was observed high yields, including in control treatment, when compared with Brazilian mean. The Brazilian mean yield (estimated) of years 2017/18 for wheat, soybean, black oat and maize is of 2431; 3276; 2210 and 5556 kg ha^{-1}, respectively (CONAB, 2018). This because the rainfall and the temperature of Palmeira City (Figure 2), as well as the crops rotation (Figure 4), can be influenced all the results this work. The rainfall and temperature influence the liming material dissolution in soil and the growth of crops, already crops rotation indicate a greater input of fertilizers and phytomass accumulation (VAN ITTERSUM and RABBINGE, 1997; CAIRES et al., 2005; BOLAN et al., 2008; ANDREA et al., 2018). The crop rotation in NT is important for maintenance of crops yield (JOKELA and NAIR, 2016). For example, if considered only wheat on agricultural planning, the loss can be around 500 kg ha^{-1} (MAZZILLI et al., 2016). Therefore, crop rotation can keep the crop yield, to reduce yield risks (ERNST et al., 2016) and to reduce yield gap.



Equations grains:

♦ $\hat{y} = 923.1 + 3219.8x - 326.7x^2$ $R^2 = 0.69^{**}$

■ $\hat{y} = 1059.6 + 3374.7x - 345.2x^2$ $R^2 = 0.64^{**}$

▲ $\hat{y} = 1004.7 + 3650.1x - 389.2x^2$ $R^2 = 0.68^{**}$

● $\hat{y} = 716.9 + 2037.8x - 163.9x^2$ $R^2 = 0.69^{**}$

Equations dry matter:

♦ $\hat{y} = 265.1 + 1114.5x - 113.4x^2$ $R^2 = 0.76^{**}$

■ $\hat{y} = 285.1 + 1130.1x - 116.3x^2$ $R^2 = 0.74^{**}$

▲ $\hat{y} = 310.7 + 1030.3x - 110.1x^2$ $R^2 = 0.64^{**}$

● $\hat{y} = 317.8 + 785.1x - 65.1x^2$ $R^2 = 0.63^{**}$

Figure 8. Production efficiency (kg grains or dry matter by Mg of liming material applied on the soil, without incorporation) ($n = 16$ ± standard deviation) of grains of wheat, soybean and maize; and of dry matter of black oat growth under no-tillage up to 45 months after surface application of doses of liming material (in jun/2012). (♦ and solid line) Dolomitic limestone – DL. (■ and segmented line) Granulated micronized calcite – GMC. (▲ and dashed line) Granulated micronized dolomite – GMD. (● and asterisks line) Carbonated suspension – CS. Averages followed by the same letter do not differ statistically (Tukey test, $\alpha = 0.05$). Coefficient of variation was of 9.86 and 18.24% for grains and dry matter, respectively. Vertical bars indicate the least significant difference (LSD). *: $P < 0.05$. **: $P < 0.01$.

Besides, yet than the experimental area soil presented (Typic Distrudept) lower pH (4.3), aluminum saturation (23%) and V value (29%) in the meantime presented medium CEC value (146 $mmol_c$ dm^{-3}) and higher organic carbon (21 g dm^{-3}) (interpretation according to SBCS, 2017). This fact can justify the higher yield crops as well as the absence of crop responses the major doses applied of liming material (V aiming to 70 and 90 %). Therefore, the Typic Distrudept diversify its chemical attributes until the liming material dose that is aiming V between 55-68 % (after equation derivate), if we consider only wheat and maize RY.

5.2.2. Yield index applied in the soil acidity control

The wheat was influenced by hail rain in 2014 (Figure 2) resulting in a lower yield in the second crop. Already, the significant variability of soybean RYG may have been the difference of crop water availability between the two years of growth (Figure 2).

Thus, the lower gap between two years of growth of a crop can be due to superior responsiveness in short-term, major residual effect of liming material and yield maintenance in a crop rotation up four years. However, the major gap between two years of growth of a crop can be due to slow liming material dissolution over the years and a significant increase of yield only in the last crop. Also, we can suggest that the soil acidity control with MLM, mainly GMC and CS, promote smaller gap and yield maintenance between two years of growth of a crop.

However, in variable charge soils and constant rainfall, the acidity control is more important than others factors studied around the world as (i) crop rotation with plants species C3 and C4 under NT (FARMAHA et al., 2016), (ii) integrated soil-crop system management (LIU et al., 2016) and (iii) the crop water availability may impact on RYG of wheat, soybean, and maize (GRASSINI et al., 2015; MERLOS et al., 2015). Already, in maize, the not differences between the liming materials and your doses, is due to yield keeping and upper plateaus (GRASSINI et al., 2013; ZHAO et al., 2015) (average of maize grains on experiment 11863 Mg ha^{-1}) generally found in Campos Gerais Region. For both, grain and DM, the dose that aimed to increase V to 50% (Table 1) presented major PE than the doses that aimed to increase V to 70 and 90% (Figure 8) in a Typic Distrudept. However, the V to 50 %, after the equation derivative, become 61 % (Figure 8). This result is different of others soils, as Oxisol, cropped with same crops this study (V aiming 70 % - CAIRES et al., 2000). Even the lime requirement (LR) is dependent of each crop (FARHOODI and COVENTRY, 2008), for the Typic Distrudept (conditions of this study) and independently of the type of liming material, the V recommended is aiming 61 %.

Other point is economic viability this MLM, which presented the cust of until (mean during 2012 to 2016) 0.40; 0.42 and 0.94 $ per kg of grains or dry matter produced for GMC, GMD and CS. Already the DL presented the cust of until (mean during 2012 to 2016) 0.03 $ per kg of grains or dry matter produced. However, this data need of further studied considering the price fluctuation of grain, dollar quotation, raw material value of MLM and policies.

5.3. Conclusions

The micronized liming materials (calcite > carbonated suspension > dolomite) presented major relative yield, relative yield change and production efficiency of wheat, soybean, black oat and maize up to 45 months than the dolomitic limestone.

The doses of micronized liming materials that aimed to increase the soil base saturation to 55 and 68 % resulted in major relative yield. When, lower relative yield gap between two years of growth of a crop, major responsiveness and lower residual effect of micronized liming material, mainly calcite micronized granulated and carbonated suspension, and yield maintenance in a crop succession of four years.

The production efficiency of grains was major after application of calcite and dolomite micronized granulated. If we consider only production efficiency of grains and dry matter, better results were found in the dose aiming soil base saturation to 61 % for all the liming materials applied, showing that it is the recommended dose for acidity control of a Typic Distrudept.

6. Acidity control after surface application of micronized liming material in a Typic Distrudept under no-tillage

Abstract

The acidity control of soil with variable charge is factor essential for the adequate development and growth. We objected to evaluate the pH and soil base saturation (V) values, during 45 months after surface application and without incorporation of the liming materials in deeper layers of soil. The experimental design was completely randomized blocks in split-plot with four replications. In the plots were studied the dolomitic limestone (DL) and micronized liming materials (MLM) – granulated micronized calcite (GMC), granulated micronized dolomite (GMD) and carbonated suspension (CS). In the subplots were studied doses of all the liming materials aiming to increase V to 50, 70 and 90 % besides of control treatment. We measured the pH and soil base saturation (V) values in 0-5, 5-10, 10-20, 20-40 and 40-60 cm soil layers along the time (5, 11, 23, 34 and 45 months after application of liming materials). The MLM when compared to DL were more efficient to increase and maintain the pH and V values along the time. The doses of MLM aiming V to 50-70% resulted increasing of the pH and V values of Typic Distrudept and keeping of these in a range considered adequate for the major crops. Despite of the MLM are more fineness than DL, the effectiveness for control soil acidity in subsoil were inefficient, because theses pH and V increases/maintains were observed just in 0-5 cm layer. However, the MLM present lower gap between the V estimated and obtained, manly in the 0-5 cm layer than DL.

Keywords: soil reaction, soil with variable charge, soil base saturation, pelletized limes, fluid lime.

Controle da acidez após aplicação superficial de corretivos micronizados em um Cambissolo Háplico, sob plantio direto

Resumo

O controle da acidez de solo com carga variável é fator essencial para o adequado desenvolvimento e crescimento das culturas. Nosso objetivo foi avaliar os valores de pH e saturação por bases do solo (V), durante 45 meses após a aplicação superficial e sem incorporação de corretivos, nas camadas mais profundas do solo. O delineamento experimental usado foi o de blocos casualizados em parcelas subdivididas com quatro repetições. Nas parcelas foram estudados o calcário dolomítico (CD) e corretivos micronizados (CM) – calcita micronizada granulada (CMG); dolomita micronizada granulada (DMG) e suspensão carbonatada (SC). Nas subparcelas foram estudadas doses de todos os corretivos visando elevar a V para 50, 70 e 90 %, além do tratamento controle. Nos mensuramos os valores de pH e V das camadas do solo 0-5, 5-10, 10-20, 20-40 e 40-60 cm, ao longo do tempo (5, 11, 23, 34 e 45 meses após aplicação de corretivos). Os CM quando comparados com CD foram mais eficientes em aumentar e manter os valores de pH e V ao longo do tempo. As doses de CM visando V para 50-70 % aumentaram o pH e V do Cambissolo Háplico e mantiveram esses valores em níveis considerados adequados para a maioria das culturas. Apesar dos CM serem mais finos do que o CD, a eficácia para controlar a acidez no subsolo foi ineficiente, pois esses aumentos/manutenções de pH e V foram observados apenas na camada 0-5 cm. Os CM apresentam baixa diferença entre o V estimado e o V obtido, principalmente na camada 0-5 cm, do que o CD.

Palavras-chave: reação no solo; solo com carga variável; saturação por bases, corretivos peletizados; corretivos fluídos.

6.1. Results

There were interactions between liming materials, doses and periods after application for pH and V values (Table 4). In the control treatment there was increase of the pH, in the all layers, along the time (Figure 9). However, the application of liming materials resulted in the pH changes more in the 0-5 cm layer than in others layers (Figure 9). In the 0-5 cm layer, all the doses of liming materials increased and remained the pH along the time, when compared with the control treatment (Figure 9).

In the 0-5 cm layer, the pH increased and remained as from 23 months after application of DL in the dose V to 50 % (Figure 9). Being that, after 45 months, the pH measured was of 5.7 (the biggest pH for DL) (Figure 9). Already for MLM, the pH increased and remained as from 5 months of application in the dose V to 50 % (Figure 9). Whereas the highest pH was observed, in the 0-5 cm layer, 23 months after the application of MLM in the dose V to 50 % (Figure 9). These pH values were of 6.2, 5.6 and 6.1 to GMC, GMD and CS, respectively (Figure 9). Already, the pH, after 45 months, were of 5.0, 5.4 and 5.5 to GMC, GMD and CS, respectively (Figure 9).

The pH increased and remained during 5 up to 34 months of liming materials application in the dose V to 70 % and in the 0-5 cm layer (Figure 9). However, the major increased in the pH were observed for GMC, GMD and CS than for DL (Figure 9). Already, the highest pH observed was 23 and 11 months after application of DL (pH = 6.0) and GMC (pH = 6.4), respectively (Figure 9). And, the pH, after 45 months, were of 5.0 and 4.8 to DL and GMC, respectively (Figure 9). The highest pH was observed after 5 months of GMD and CS application and were of 6.1 and 6.7, respectively, both in the dose V to 70 % (Figure 9). After 45 months, the pH was of 5.4 and 5.5 to DL and GMC, respectively (Figure 9).

Table 4. ANOVA significance for soil pH and base saturation (V).

Layer (cm)	Liming materials (LM)		Doses (D)		Months after application (M)		LM x D		LM x M		M x D		LM x D x M	
	F	Pr > F	F	Pr > F	F	Pr > F	F	Pr > F	F	Pr > F	F	Pr > F	F	Pr > F
pH														
0-5	9.97	0.0032	129.70	<0.0001	95.65	<0.0001	2.61	0.0065	4.71	<0.0001	12.82	<0.0001	0.93	0.6005
5-10	0.59	0.6354	9.23	<0.0001	7.87	<0.0001	0.99	0.4493	1.17	0.2935	1.34	0.1753	0.66	0.9545
10-20	1.58	0.2619	3.47	0.0168	125.14	<0.0001	0.57	0.8236	2.40	0.0028	0.83	0.6453	0.31	1.0000
20-40	0.52	0.6768	7.03	0.0001	10.23	<0.0001	1.70	0.0884	1.04	0.4132	2.53	0.0015	0.56	0.9890
40-60	1.48	0.2841	9.45	<0.0001	16.80	<0.0001	0.56	0.8265	0.84	0.6346	1.98	0.167	0.45	0.9990
V														
0-5	24.86	0.0001	304.47	<0.0001	523.88	<0.0001	10.25	<0.0001	9.44	<0.0001	38.27	<0.0001	7.69	<0.0001
5-10	3.09	0.0826	23.18	<0.0001	60.57	<0.0001	7.41	<0.0001	4.57	<0.0001	3.91	<0.0001	1.96	0.0006
10-20	3.77	0.0528	8.99	<0.0001	194.49	<0.0001	5.62	<0.0001	2.48	0.0020	2.60	0.0011	2.56	<0.0001
20-40	1.78	0.2207	21.70	<0.0001	216.79	<0.0001	2.07	0.0320	1.34	0.1772	2.65	0.0009	2.24	<0.0001
40-60	2.35	0.1406	11.22	<0.0001	303.02	<0.0001	1.68	0.0949	2.13	0.0090	3.01	0.0002	1.35	0.0806

Yet, in the 0-5 cm layer, the pH increased and remained as from 5 months of MLM application in the dose V to 90 % (Figure 9). However, the major increased in the pH were observed in the following order GMC < GMD < CS < DL (Figure 9). Yet after 5 months, the highest pH values were of 5.7, 6.9, 6.5 and 6.9 to DL, GMC, GMD and CS, respectively (Figure 9). Already, after 45 months of DL, GMC, GMD and CS application in the dose to 90 %, the pH was of 5.5, 5.9, 5.1 and 5.5, respectively (Figure 9).

The V in control treatment and in the all layers was increased along the time (Figure 10). However, after the application of liming material doses, the more variations in the V occurred in the 0-5 cm layer than 5-60 cm layer (Figure 10). In the 0-5 cm layer, the V increased and remained of 23 up to 45 months of DL application in the dose to 50 % (Figure 10). Besides, the V measured after 45 months after application of DL was of 44 % more than V estimated (Figure 10). Yet, in the 0-5 cm layer, the V increased and remained as from 5 months after application of MLM in the dose to 50 % (Figure 10). Being that, the highest V in the dose to 50 % was observed 23 months after application of GMC (V measured was 58 % more than V estimated) and after 34 months of GMD and CS application (V measured was of 38 and 52 % more than V estimated, respectively) (Figure 10). Already, the V measured, after 45 months, by GMC was 42 % and by GMD and CS was 30 % more than the V estimated 50 % (Figure 10).

The V, in the 0-5 cm layer, increased and remained of 5 up to 34 months after application of DL and GMC in the dose V to 70% (Figure 10). Already, the highest V measured was observed 28 months after the application of DL and GMC in the order of 2 and 14 % more than V estimated, respectively (Figure 10). Besides, the V measured, after 45 months and in the 0-5 cm layer, by DL and GMC, for both, it was reached 82 % of the V estimated (Figure 10). And, the only treatment that the V measured equal the estimated of 70 %, was the GMC after 34 months (Figure 10). Still in the 0-5 cm layer, the V increased and remained as from 5 months of GMD and CS application in the dose V to 70 % (Figure 10). The highest V measured was observed 23 and 34 months after application of GMD and CS, in the order of 14 % more than V estimated, for both (Figure 10). Already, the V measured, after 45 months, by GMD and CS, was reached 97 % of the V estimated of 70 % (Figure 10).

The V, in the 0-5 cm layer, increased and remained as from 5 months after application of all liming materials in the dose V to 90 % (Figure 10). The highest V measured, was observed 34 months of DL and GMD application, both reached 88 % of V estimated (Figure 10). Already, the V measured, after 45 months, by DL and GMD reached 73 and 65 % of V estimated, respectively (Figure 10). Besides, the highest V was observed 23 months after application of GMC and CS, both reached 93 % of V estimated (Figure 10). Already, the V measured, after 45 months and in the 0-5 cm layer, by GMC and CS, both reached 82 % of the V estimated of 90 % (Figure 10).

The pH was more influenced by doses of liming material in the 0-5 cm layer (Figure 11). The linear increases the pH was observed of 5 up to 34 months of application of liming materials, except for 23 months (Figure 11). Thus, the higher pH was observed in the dose V to 90 % after 5 months of DL and GMC application; after 11 months of all liming materials application, after 23 months of GMC, GMD and CS application; and after 34 months of DL and GMC application (Figure 11). The increase pH occurred 23 months after application of DL in the doses V to 50-70 % (Figure 11).

The V was influenced by doses of liming material up to 20 cm depth than 20-60 cm (Figure 12). In the 0-5 cm layer, higher V was observed in the dose V to 90 % after 5, 23, 34 and 45 months of DL, GMD, GMC and CS application, respectively (Figure 12). In the 0-5 cm layer and in the dose V to 50-70 %, higher V was observed after 5 months of GMC, GMD and CS application; after 11 months of all liming material application; after 23 months of DL, GMC and CS application; after 34 months of CS application; and after 45 months of GMD application (Figure 12). Already, in the 5-10 cm layer, higher V was observed in the dose V to 50-70 %

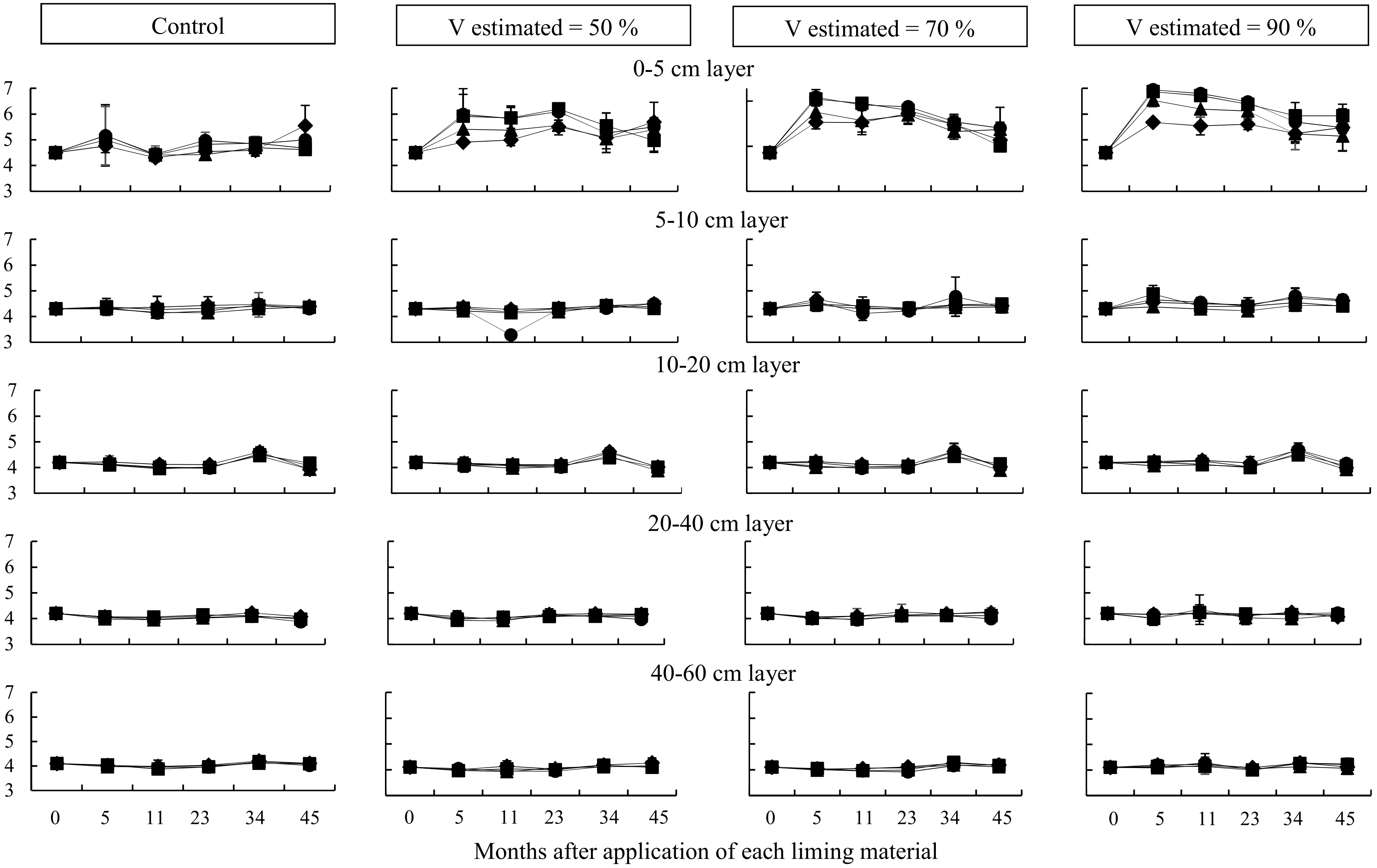


Figure 9. pH values (in $CaCl_2$ 0.01 mol L^{-1}) of a Typic Distrudept (n = 16 ± standard deviation), after 0, 5, 11, 23, 34 and 45 months after the surface application of liming materials in the doses aiming the increase of the soil base saturation (V estimated) to 50, 70 and 90% besides control treatment, in each soil layer. (♦) Dolomitic limestone. (■) Granulated micronized calcite. (▲) Granulated micronized dolomite. (●) Carbonated suspension.

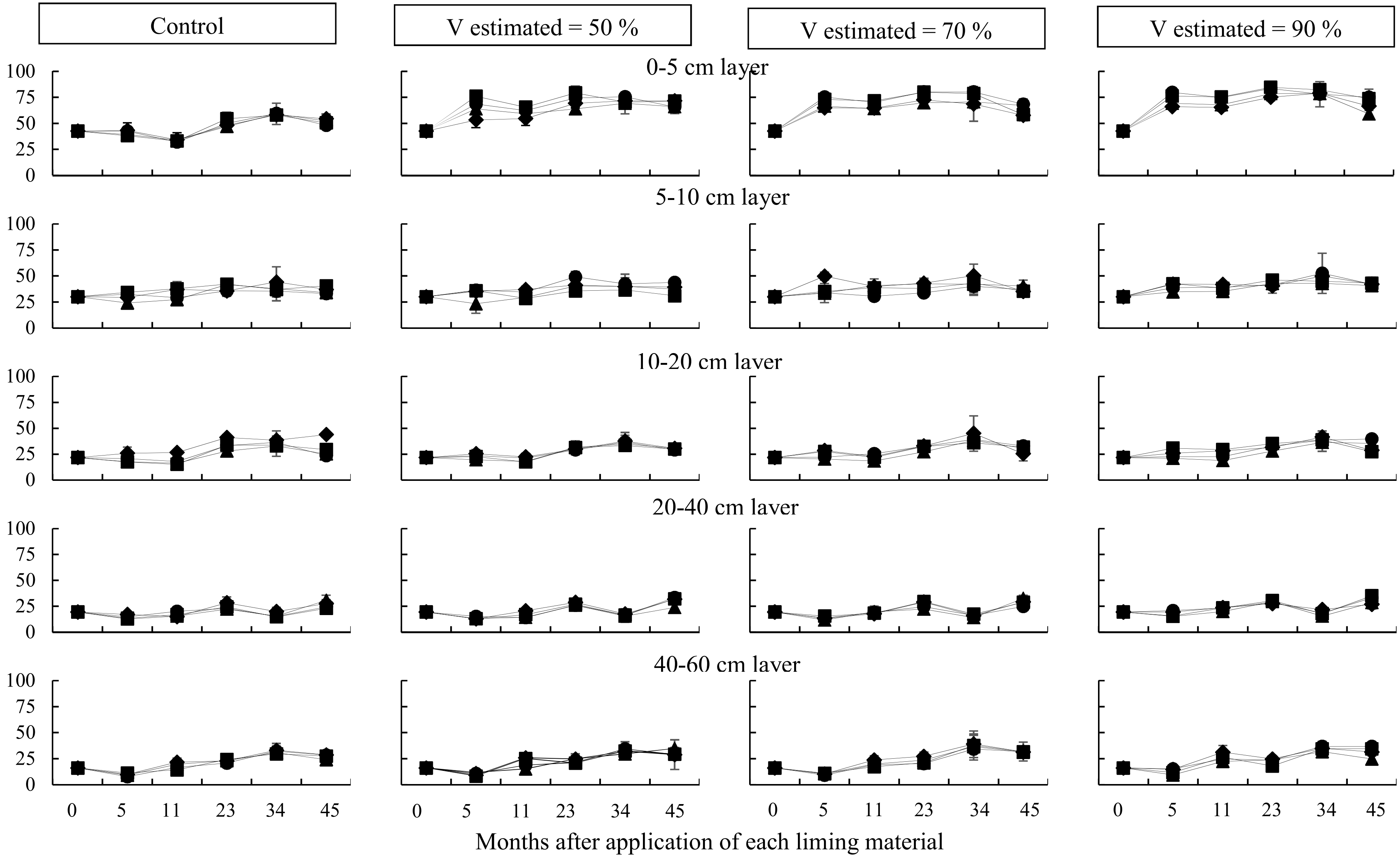


Figure 10. Soil base saturation (V), % (*n* = 16 ± standard deviation) of a Typic Distrudept, after 0, 5, 11, 23, 34 and 45 months after the surface application of liming materials in the doses aiming the increase of the soil base saturation (V estimated) to 50, 70 and 90% besides control treatment, in each soil layer. (♦) Dolomitic limestone. (■) Granulated micronized calcite. (▲) Granulated micronized dolomite. (●) Carbonated suspension.

after 5 and 23 months of DL application (Figure 12). And, in the 10-20 cm layer, higher V was observed in the dose V to 50-70 % after 11 months of CS application (Figure 12). Besides, after 5 months of GMC application, in the 10-20 cm layer, higher V value was observed in the dose V to 90 % (Figure 12).

6.2. Discussion

The MLM (GMC, GMD and CS) increased the pH and V as from 5 months of your application while the DL increased as from 23 months of your application, in all doses applied (Figures 9 to 12). This fact shows that, the MLM presented faster reaction and higher responsiveness than DL, in soil with high buffering power and variable charge under NT, under field conditions. Similar results also were observed in soils under controlled conditions, where the MLM are able to increase the pH and the V in the first month of application (DOS SANTOS et al., 2016a; DOS SANTOS et al., 2016b). Therefore, in short-term, the MLM can be strategic more efficient to soil acidity control and then, reduce loss of crops yield. These results, also point to differences of Typic Distrudept with others soils, as the Oxisol under NT, whom the DL (with 840 g kg^{-1} of ECC) reacted after 48 months of application (JORIS et al., 2016). And also, as the Typic Hapludox under NT, whom the DL (with 710 g kg^{-1} of ECC) reacted after 12 months of application (CRUSCIOL et al., 2016). However, the highest pH and V observed along the time, was only 23 months of MLM application and 45 months of DL application (Figures 9 and 10). Begging that, after 23 months of MLM application there was slight decrease in the pH and V, until 45 months (Figures 9 and 10). Hence, we concluded that, the MLM presented lower residual effect than DL.

All the major increased in the pH and V occurred more in the 0-5 cm layer than 5-60 cm layer, for all the liming materials and doses applied (Figures 9 to 12). This fact suggests that, the reaction of liming material applied in a Typic Distrudept (high buffering power and variable charge) under NT, occur only in the surface layer and not below the point of placement. Even though the MLM present fineness particles much lower than DL (MLM of 1.91 to 6.58 μm and DL of 269 μm) this fact not favored your reaction in deep layers (5-60 cm). In others soils, as the Haplic Umbisol, the reaction of DL (878 g kg^{-1} of ECC) with fineness particle (< 0.25 μm) was much faster than with DL of coarsest particle (2-4 mm), during 36 months and 0-20 cm layer (ÁLVAREZ et al., 2009). Already, the absence of liming material effect in 5-60 cm layer can be attributed the following factors that (i) the soil presented higher potential acidity (RHEINHEIMER et al., 2018), (ii) the dissolution/dissociation as far from acidity zone and reaction time (VARGAS et al., 2019); (ii) subsoil pH is adequate (HAVLIN et al., 2014), (iii) the neutralization of aluminum (Al^{3+}) and of hydrogen (H^+) on soil functional groups is limited (VARGAS et al., 2019), (iv) the soil buffering power is strongly by Al and iron (Fe) oxides (CHO et al., 2019), (v) lower water infiltration via macroporos (AMARAL et al., 2004a) and (vi) lower adsorption/desorption of cations by organic anions soluble (MIYAZAWA et al., 2002).

Also, in Typic Distrudept, can occur the reprecipitation of carbonate due to decrease of partial pressure of CO_2 (by microbial activity) and increase of solute concentration, limiting the acidity control only in 0-5 cm layer (AMARAL et al., 2004b). This layer may have occurred increase of microbial activity by liming material, favoring the organic matter mineralization and the decrease of the carbon stocks (less CO_2) (PARADELO et al., 2015).

The majority of Brazil, especially in the Paraná State, the liming requirement by V is calculated for 0-20 cm layer of soil in conventional tillage, but this also is used for NT (SBCS, 2017). However, in NT, with surface application and without incorporation of liming materials, the V estimated is not reached, across the 0-20 cm layer. But, only, in some part of 0-20 cm layers, as the 0-5 cm layer. All the major increased in the V occurred more in the 0-5 cm layer than 5-60 cm layer, for all the liming materials and doses applied (Figures 10 and 12). For the

MLM in the dose of V to 50 %, the highest V observed along the time as much as the V after 45 months of application, it was of V measured > V estimated, approximately 40 % greater. Already, in the dose of V to 70 %, the highest V observed, along the time, it was of V measured > V estimated, approximately 10 % greater. Yet, in the dose of V to 70 %, the V after 45 months of application was of V measured < V estimated, approximately 20 % smaller. For the MLM in the dose of V to 90 %, the highest V observed along the time as much as the V after 45 months of application, was of V measured < V estimated, approximately 80 % smaller. This fact was stronger in MLM than DL. Begging that, among the MLM, the GMC was the only where V measured equal the V estimated of 70 % (Figures 10 and 12). Therefore, the gap between the V estimated and measured is smaller in soil treatment with MLM than DL. This way, the MLM present greater assurance that what was applied really reacted. But, when the V measured is higher than V estimated, can be occur a problem with the overliming in the pH in surface layer. This fact was common with surface application of CS in all the doses (Figures 10 and 12). The overliming in the pH may cause, in short-time, micronutrient unavailability (HAVLIN et al., 2014). Therefore, in short-term, the MLM can be strategic more efficient to increase and remain the V and then, reduce loss of crops yield.

As from results obtained, the doses of all liming materials more recommended is aiming V between 50 and 70 % for a Typic Distrudept under NT (Figures 9 to 12). Therefore, the dose aiming V over 70 % and below 50 % will not occur interesting results. In these doses and among the MLM, the GMC and CS were more efficient than others liming materials studied with regard to increase of pH and V. However, for Typic Distrudept the dose aiming V to 70 %, commonly used in Oxisol (CAIRES et al., 2015), may not be appropriate.

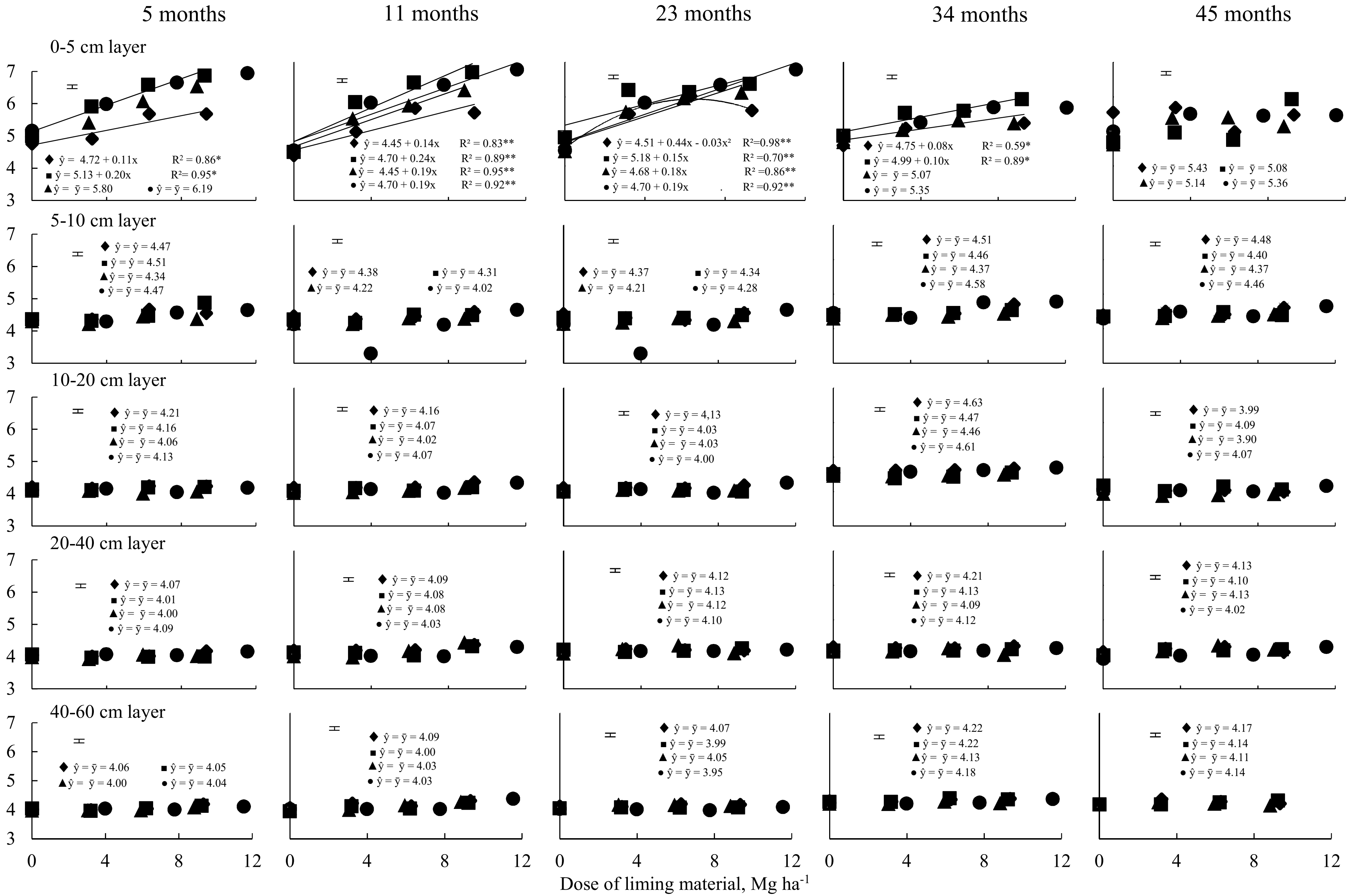


Figure 11.pH values (n = 4) of a Typic Distrudept, after 5, 11, 23, 34 and 45 months after the surface application of liming materials in the doses aiming the increase of the soil base saturation (V estimated) to 50, 70 and 90% besides control treatment, in deep layer. (♦) Dolomitic limestone. (■) Granulated micronized calcite. (▲) Granulated micronized dolomite. (●) Carbonated suspension. Vertical bars indicate the least significant difference (LSD). *: $P < 0.05$. **: $P < 0.01$.

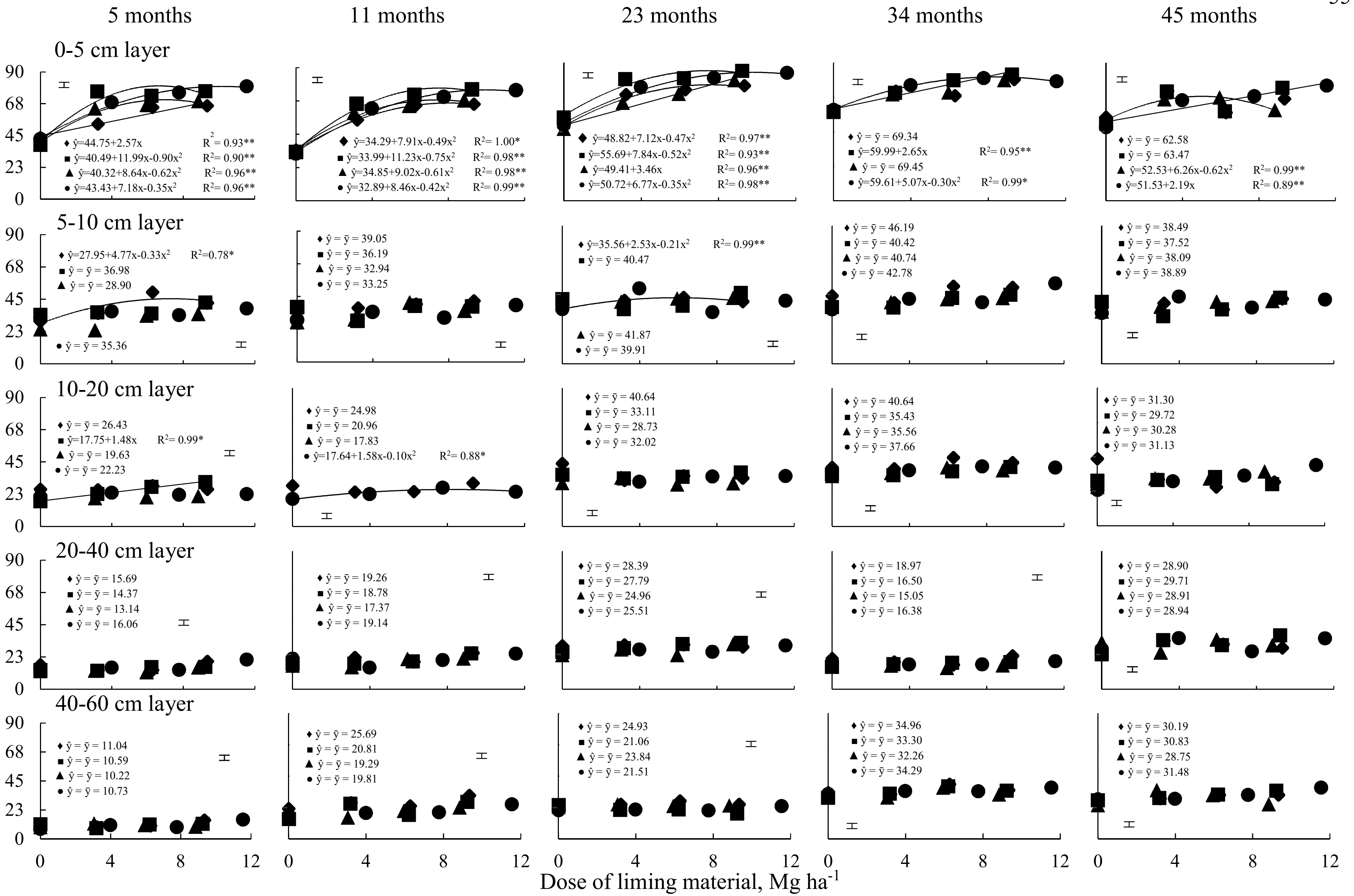


Figure12. Soil base saturation (V) values (n = 4), %, of a Typic Distrudept, after 5, 11, 23, 34 and 45 months after the surface application of liming materials in the doses aiming the increase of the soil base saturation (V estimated) to 50, 70 and 90% besides control treatment, in deep layer. (♦) Dolomitic limestone. (■) Granulated micronized calcite. (▲) Granulated micronized dolomite. (●) Carbonated suspension. Vertical bars indicate the least significant difference (LSD). *: $P < 0.05$. **: $P < 0.01$.

6.3. Conclusions

The micronized liming material increase and keeps pH and V values, only in the 0-5 cm layer, during 5 up to 45 months after surface application, without incorporation, in a Typic Distrudept under no-tillage. However, the fineness particles of micronized liming material do not favor the soil reaction in the 5-60 cm layer. The doses of all liming materials more recommended is aiming base saturation between 50 and 70 % for a Typic Distrudept. The gap between the soil base saturation estimated and measured is smaller in soil treatment with micronized liming material than dolomitic lime, manly in the 0-5 cm layer. Therefore, the liming materials, applied superficially and without incorporation, were not efficient to increase and keep the pH and V values below the point of placement, in soils high buffering power and variable charge, as the Typic Distrudept.

7. Calcium, magnesium and potassium dynamic in Typic Distrudept treated with micronized liming materials, under no-tillage

Abstract

The objective this study was evaluate the micronized liming material (MLM) as source of calcium (Ca) and magnesium (Mg) as well as provisioning agent of potassium (K), over time, after surface application (without incorporation) in a Typic Distrudept under no-tillage (NT). The experimental design was completely randomized blocks in split-plot with four replications. In the plots were studied the liming materials (LM) – dolomitic limestone (DL), granulated micronized calcite (GMC), granulated micronized dolomite (GMD) and carbonated suspension (CS). In the subplots, the applied doses aiming to increase soil base saturation (V) to 50, 70 and 90 % of each liming material, besides of control treatment. Soil samples of the 0-5, 5-10, 10-20, 20-40 and 40-60 cm layers were collected in 0, 5, 11, 23, 34 and 45 months after the LM application, and the exchangeable Ca, Mg and K concentrations were measured. Also, were measured the percentage (%) of Ca and Mg in the cation exchange capacity at pH 7.0 (CEC) and cationic relationship (CR). The GMC and CS inputted more Ca and DL and GMD inputted more Mg in the soil. LM in the V to 50-70 % increased Ca, Mg and K, in 0-5 cm layer, up to 34 months after application. In the 0-20 cm layer, the better CR occurred at 11 months after application. The K increased as it decreased the % of Mg in the CEC.

Keywords: soil with variable charge, nutrients source, nutrients available, pelletized lime, fluid lime.

Dinâmica do cálcio, magnésio e potássio em Cambissolo Háplico tratado com corretivos micronizados, sob plantio direto

Resumo

O objetivo desse trabalho foi avaliar os corretivos micronizados (CM) como fontes de cálcio (Ca) e magnésio (Mg) bem como agente disponibilizador de potássio (K), ao longo do tempo, após aplicação superficial (sem incorporação) em um Cambissolo Háplico sob plantio direto (PD). O delineamento experimental utilizado foi blocos casualizados em parcelas subdivididas, com quatro repetições. Nas parcelas foram estudados os corretivos – calcário dolomítico (CD), calcita micronizada granulada (CMG), dolomita micronizada granulada (DMG) e suspensão carbonatada (SC). Nas subparcelas, as doses aplicadas visaram elevar a saturação por bases do solo (V) para 50, 70 e 90 %, mais o tratamento controle. Amostras de solo das camadas 0-5, 5-10, 10-20, 20-40 e 40-60 cm foram coletadas em 0, 5, 11, 23, 34 e 45 meses após aplicação de corretivos, e as concentrações de Ca, Mg e K trocáveis foram mensuradas. Também, foram mensurados o percentual (%) de Ca e Mg na capacidade de troca catiônica a pH 7,0 (CTC) e relações catiônicas (RC). O CMG e o SC aportaram mais Ca e CD a DMG aportaram mais Mg no solo. Os corretivos nas doses de V para 50-70% aumentaram Ca, Mg e K, na camada 0-5 cm, por até 34 meses após aplicação. Na camada 0-20 cm, a melhor RC ocorreu aos 11 meses após aplicação. O K aumentou a medida que diminuiu o % de Mg na CTC.

Palavras-chave: solo com carga variável, fonte de nutrientes, disponibilidade de nutrientes, corretivos peletizados, corretivos fluidos.

7.1. Results

There were interactions between liming materials, doses and periods after application for exchangeable-Ca, Mg and K and percentage of Ca (% Ca-CEC) and Mg (% Mg-CEC) in the CEC pH 7.0 (Table 5). In the 0-5 cm layer, the major increase and maintain of exchangeable-Ca occurred up to 45 months after application of MLM in the dose V to 50, 70 and 90 %, follow of DL (Figure 13). Already, in the 5-10 cm layer, the increase of exchangeable-Ca was observed after 5 months of DL application in the dose V to 70 and 90 % (Figure 13). In the 10-20 and 40-60 cm layer, the major increase in the exchangeable-Ca occurred after 34 months of liming materials application in the doses V to 70 and 90 %, (Figure 13). Already, in the 20-40 cm layer, the higher exchangeable-Ca was obtained after 45 months of DL application in the dose V to 70 % (Figure 13). The same occurred with GMC in the dose V to 50 % (Figure 13).

In the 0-20 cm layer, the major increase of exchangeable-Mg occurred after 34 months of DL and GMD application than GMC and CS, in all doses applied (Figure 14). Already, in the 20-40 cm layer, the higher increase of exchangeable-Mg occurred 23 and 45 months after DL and GMD surface application, in all doses applied (Figure 14). However, in the 40-60 cm layer, all the doses applied increased the exchangeable-Mg up to 45 months after liming materials application (Figure 14).

In the 0-5 cm layer, the increase of exchangeable-K was observed up to 45 months after application of all the doses of liming materials, except after 34 months (Figure 15). Besides, in the dose V to 70 %, higher exchangeable-K was obtained after 5 months of CS application and 23 and 34 months of GMC application (Figure 15). In the 5-10 and 10-20 cm layers, the major exchangeable-K were obtained only after 5 and 23 months of liming materials surface application, in all the doses applied, respectively (Figure 15). Already, in the 20-40 and 40-60 cm layer, increased exchangeable-K was observed after 45 months of GMD surface application in all the doses applied (Figure 15).

In the 0-5 cm layer, the increase of exchangeable-Ca was observed as it increases the doses CS applied of 5 up to 23 months after application (Figure 16). Also, the major exchangeable-Ca was observed 11 and 34 months after application of GMC and CS, respectively, both in the dose V to 50 and 70 % (Figure 16). In the 5-10 cm layer, it was observed increase of exchangeable-Ca, as it increases the doses applied of GMC and CS, after 23 and 34 months of application, respectively (Figure 16). In the same layer, it was observed increase in the exchangeable-Ca after 5 and 45 months of DL and GMD application, respectively, both in the dose V to 50 and 70 % (Figure 16). Already, in the 10-20 and 20-40 cm layer, major exchangeable-Ca was observed 5 and 45 months after application of DL and GMC, and CS respectively, in the dose V to 50 and 70 % (Figure 16). In the 40-60 cm layer, the major increase of exchangeable-Ca was observed 11 and 23 months after application of GMD and CS, and GMD, respectively, in the major dose applied (Figure 16). Still on the same layer, major exchangeable-Ca was observed of 23, 34 and 45 months after application of DL, GMC and DL, GMD and CS, respectively, in the dose V to 50 and 70 % (Figure 16).

In the 0-5 cm layer, the increased of exchangeable-Mg occurred after 5 months of GMC, GMD and CS application and after 11 months of DL application, in the doses V to 50 and 70 % (Figure 17). However, major exchangeable-Mg was observed 5 months after the application of DL in the dose V to 90 % (Figure 17). In the 5-10 cm layer, was observed increase in the exchangeable-Mg in the major dose applied after 23 months application of DL (Figure 17). Already, in the 10-20 cm layer, there was increase in the exchangeable-Mg in the major dose after 5 and 11 months of CS application; after 15 and 45 months of GMC and CS of application, respectively (Figure 17). In the 20-40 cm layer, was observed increase of exchangeable-Mg in the doses V to 50 and 70 % after 5 months of GMC application, after 11 months of DL and GMC application and after 45 months of CS application (Figure 17). The same occurred, in the

40-60 cm layer, after 23 and 45 months of GMC and GMD application, respectively (Figure 17).

In the 0-5 cm layer, there was increase in the exchangeable-K in the major dose applied after 5 months of CS application (Figure 18). In the 5-10 cm layer, the increase of exchangeable-K occurred in the doses V to 50 and 70 % after 11 months of GMC and CS application (Figure 18). In the 10-20 cm layer, major increase of exchangeable-K occurred after 11 months of GMC application in the higher dose applied (Figure 18). Already, in the 20-40 cm layer, higher exchangeable-K was observed after 11 months of GMC application (Figure 18). Also, the increase of exchangeable-K occurred in the 40-60 cm layer and in the doses V to 50 and 70 % after 5 months of GMC and GMD application, after 11 months of CS application and after 34 months of GMC application (Figure 18).

The increase in the % Ca-CEC was observed up to 23 months after application of all the doses of liming materials, and only in the 0-5 cm layer (Figure 19). However, in the same layer, the GMC and CS more increased the % Ca-CEC than GMD and DL (Figure 19). In the 5-60 cm layer, the % Ca-CEC not was influenced by liming materials and doses applied (Figure 19). There was naturally increase (control treatment) of the % Mg-CEC of 23 up to 34 months measured in the 0-20 cm (Figure 20). Only in the 0-5 cm layer, the increase in the % Mg-CEC was observed up to 34 months after application of all the doses of liming materials (Figure 20). The DL and GMD more increased the % Mg-CEC than GMC and CS, in all the doses applied and in the 0-5 cm layer (Figure 20). However, in the 5-60 cm layer, the % Mg-CEC not was influenced by liming materials and doses applied and the increased were similar to control treatment (Figure 20).

In the 0-5 cm layer, the increase in the % Ca-CEC was observed in the major dose applied after 5, 11, 23 and 34 months of DL, GMD and GMC application, respectively (Figure 21). Also, in the 0-5 cm layer, increase in the % Ca-CEC was observed in the doses V to 50 and

70 % after 5 months of GMC, GMD and CS application, after 11 months of GMC and CS application, after 23 months of DL, GMD and CS application, after 34 months of CS application, and after 45 months of GMD and CS application (Figure 21). Already, in the 5-10 cm layer, there was increase in the % Ca-CEC in the major dose applied after 23 and 34 months of GMC and CS application, respectively, (Figure 21). In the same layer, the % Ca-CEC was increased in the doses V to 50 and 70 % after 5 months of DL application and after 45 months of GMD application (Figure 21). The same occurred in the 10-20 cm layer, where the % Ca-CEC was increased in the doses V to 50 and 70 % after 5 months of DL and GMC application (Figure 21). Already, in the 40-60 cm layer, the higher % Ca-CEC was observed in the major dose applied, 5 months after application of GMD, and in the dose V to 50 and 70 %, 45 months after application of DL, GMD and CS (Figure 21).

In the 0-5 cm layer, the increase in the % Mg-CEC was observed in the major dose applied after 5 and 23 months of DL application (Figure 22). Yet this layer, the % Mg-CEC was increased in the doses V to 50 and 70 % after 5 months of GMC, GMD and CS application, after 11 months of DL application, after 45 months of DL application (Figure 22). In the 5-10 cm layer, there was increase in the % Mg-CEC in the major dose applied after 5 and 45 months of GMC and GMD application, respectively (Figure 22). The same layer, the % Mg-CEC was increased in the doses V to 50 and 70 % after 5 months of GMD application and after 23 months of DL application (Figure 22). The increase the % Mg-CEC was observed in the doses V to 50 and 70 % after 11 months of CS application in the 10-20 cm layer, and after 23 months of GMD application and after 45 months of GMD application in the 40-60 cm layer (Figure 22). There was increase in the % Mg-CEC in the major dose applied after 11 months of GMC in the 10-20 cm layer, after 5 months of GMC and CS in the 20-40 cm layer and after 45 months of GMC in the 40-60 cm layer, (Figure 22).

Table 5. ANOVA significance for soil attributes exchangeable calcium (Ca), magnesium (Mg) and potassium (K) and percentage (%) of Ca and Mg in the cation exchangeable capacity (CEC) at pH = 7.0.

Depth layer (cm)	Liming materials (LM)		Doses (D)		Months after application (M)*		LM x D		LM x M		M x D		LM x D x M	
	F	Pr > F	F	Pr > F	F	Pr > F	F	Pr > F	F	Pr > F	F	Pr > F	F	Pr > F
Exchangeable-Ca														
0-5	19.80	0.0030	55.28	<0.0001	189.55	<0.0001	7.28	<0.0001	8.74	<0.0001	19.54	<0.0001	5.94	<0.0001
5-10	3.19	0.0770	20.67	<0.0001	15.00	<0.0001	6.13	<0.0001	4.55	<0.0001	2.98	0.0002	2.58	<0.0001
10-20	14.87	0.0008	1.93	0.1253	22.84	<0.0001	7.10	<0.0001	3.58	<0.0001	8.19	<0.0001	3.43	<0.0001
20-40	0.39	0.7609	15.98	<0.0001	18.52	<0.0001	2.06	0.0329	2.16	0.0078	2.81	0.0004	3.83	<0.0001
40-60	6.76	0.0111	5.47	0.0012	143.75	<0.0001	1.59	0.1173	2.65	0.0009	3.00	0.0002	1.20	0.1926
Exchangeable-Mg														
0-5	11.33	0.0021	5.94	0.0006	142.56	<0.0001	4.13	<0.0001	3.74	<0.0001	3.89	<0.0001	2.32	<0.0001
5-10	1.61	0.2536	2.44	0.0644	70.04	<0.0001	1.69	0.0907	3.22	<0.0001	1.13	0.3271	1.22	0.1674
10-20	0.02	0.9970	1.78	0.1516	460.96	<0.0001	1.54	0.1335	1.93	0.0207	0.96	0.5025	1.85	0.0015
20-40	15.32	0.0007	0.19	0.9029	318.99	<0.0001	2.94	0.0024	1.76	0.0404	2.47	0.0020	2.63	<0.0001
40-60	1.59	0.2586	0.53	0.6626	240.99	<0.0001	3.54	0.0004	4.87	<0.0001	1.24	0.2445	2.21	<0.0001
Exchangeable-K														
0-5	1.22	0.3585	1.62	0.1860	43.44	<0.0001	0.46	0.9015	2.28	0.0048	1.85	0.0287	1.17	0.2280
5-10	2.10	0.1704	0.42	0.7421	63.91	<0.0001	1.31	0.2316	3.23	<0.0001	2.21	0.0065	1.35	0.0777
10-20	1.21	0.3606	0.88	0.4511	2.70	0.0210	1.05	0.3986	1.03	0.4291	0.95	0.5133	1.02	0.4412
20-40	2.21	0.1568	0.19	0.9059	29.24	<0.0001	0.74	0.6704	3.64	<0.0001	0.78	0.6979	0.98	0.5061
40-60	2.06	0.1761	5.55	0.0010	45.82	<0.0001	2.46	0.0103	3.18	<0.0001	1.43	0.1332	2.23	<0.0001
% of Ca in the CEC														
0-5	108.01	<0.0001	247.65	<0.0001	90.73	<0.0001	6.05	<0.0001	13.91	<0.0001	14.27	<0.0001	2.38	<0.0001
5-10	2.48	0.1277	39.54	<0.0001	2.82	0.0168	4.83	<0.0001	5.82	<0.0001	4.34	<0.0001	2.72	<0.0001
10-20	10.59	0.0026	4.37	0.0050	13.79	<0.0001	8.16	<0.0001	3.30	<0.0001	6.49	<0.0001	3.06	<0.0001
20-40	1.31	0.3289	30.41	<0.0001	42.22	<0.0001	2.15	0.0256	2.65	0.0009	3.97	<0.0001	3.53	<0.0001
40-60	10.31	0.0029	6.76	0.002	118.16	<0.0001	1.64	0.1052	3.18	<0.0001	3.76	<0.0001	1.28	0.1252
% of Mg in the CEC														
0-5	27.46	<0.0001	2.99	0.0314	170.75	<0.0001	6.10	<0.0001	3.66	<0.0001	3.25	<0.0001	1.61	0.0118
5-10	3.40	0.0670	1.65	0.1777	66.40	<0.0001	2.43	0.0115	2.91	0.0003	1.83	0.0308	1.39	0.0594
10-20	0.13	0.9414	6.09	0.0005	451.51	<0.0001	2.44	0.0109	2.81	0.0004	2.38	0.0031	2.64	<0.0001
20-40	3.48	0.0635	0.73	0.5330	366.10	<0.0001	3.53	0.0004	1.17	0.2938	2.25	0.0054	3.14	<0.0001
40-60	1.43	0.2981	2.88	0.0364	303.83	<0.0001	2.58	0.0072	5.52	<0.0001	1.54	0.0906	2.13	0.0001

*The data of months after application were analyzed by profile analysis.

7.2. Discussion

7.2.1. Effect of liming materials doses along the time about exchangeable-Ca and Mg

The increase in the exchangeable-Ca and Mg concentrations were more evidenced in the 0-5 cm layer than 5-60 cm layer, of a Typic Distrudept, under no-tillage (NT), after application of liming materials (Figures 13 to 22). Bellow of point of application, there was difference between the doses in the exchangeable-Ca, Mg and K concentrations; however, magnitude was little. Therefore, the main results are in the 0-5 cm layer and will be approached in writing. The not vertical distribution of soil exchangeable-Ca, Mg and K can be the failure of one of these processes of the weathering of primary minerals, atmospheric input, leaching and biological cycling (JAMES et al., 2016). In all the doses applied of liming materials were observed increase in the exchangeable-Ca concentration (Figures 13 and 16). However, of 5 up to 45 months after application, the intensity of increase in the exchangeable-Ca concentration was in the following order, aiming V to 50 < 70 < 90 %. The GMC and CS resulted in major exchangeable-Ca concentration in the Typic Distrudept under NT than the DL and GMD. The variation in the exchangeable-Mg concentration, in a Typic Distrudept under NT, after application of liming material doses were similar the variation in the control treatment (Figures 14 and 17). However, major increase of exchangeable-Mg concentration was observed up to 45 months after application of DL and GMD than of GMC and CS, in the dose aiming V to 50 and 70 %. Besides, we can observe that up to 34 months of study, occurred increase in the exchangeable-Mg concentration in the 0-20 cm layer (Figure 14). Already, in the 20-40 cm layer, the increase in the exchangeable-Mg concentration occurred after 45 months of study (Figure 14). This fact, can be assigned the exchangeable-Mg leaching and nutrient cycling by crops. Unlike our study, in others soils types the increase of exchangeable-Ca and Mg in soil surface layer (0-10 cm) can occur up to 24 months after application of DL (CAIRES et al., 2000; DOS ANJOS et al., 2011) and reach the deep layer (up to 80 cm) after 13 years of liming material application (BLUM et al., 2013). In variable charge soil of type Oxisol, the better dose of DL is the dose aiming V to 70 % (CAIRES et al., 2005). However, take into account variable charge soil of type Inceptisol, the DL, GMC, GMD and CS presented higher exchangeable-Ca, Mg and K in the doses aiming V between 50 and 70 %.

Besides, we can be suggested that GMC and CS are source of exchangeable-Ca and that the DL and GMD source of exchangeable-Mg. However, the amount and available of Ca and Mg added in soil by each liming material are different. This difference of results between the liming materials can be due to the Ca and Mg concentrations. The amount of Ca and Mg added is of 216.6 and 952.0 kg Mg^{-1} by DL; 330.4 and 9.3 kg Mg^{-1} by GMC; 247.2 and 73.3 kg Mg^{-1} by GMD; 258.1 and 5.0 kg Mg^{-1} by CS, respectively. This data, indicate that in jun/2012 (the beginning of the experiment) was applied in 0-20 cm layer of soil the following amount of Ca in the doses V to 50, 70 and 90 %: 698, 1360 and 2013 kg ha^{-1} when DL; 1051, 2052 and 3050 kg ha^{-1} when GMC; 754, 1468 and 2183 kg ha^{-1} when GMD; 1027, 2003 and 2979 kg ha^{-1} when CS, respectively; and the following amount of Mg in the doses V to 50, 70 and 90 %: 3065, 5979 and 8892 kg ha^{-1} when DL; 30, 58 and 86 kg ha^{-1} when GMC; 223, 435 and 647 kg ha^{-1} when GMD; 20, 39 and 58 kg ha^{-1} when CS, respectively. However, in the 0-20 cm layer, after 45 months of liming material application, had in the soil the following amount of Ca in the doses V to 50, 70 and 90 %: 1550, 1515 and 1569 kg ha^{-1} when DL; 1659, 1679 and 1781 kg ha^{-1} when GMC; 1552, 1672 and 1454 kg ha^{-1} when GMD; 1575, 1649 and 2063 kg ha^{-1} when CS, respectively; and the following amount of Mg in the doses V to 50, 70 and 90 %: 778, 630 and 763 kg ha^{-1} when DL; 659, 635 and 736 kg ha^{-1} when GMC; 737, 754 and 905 kg ha^{-1} when GMD; 582, 683 and 594 kg ha^{-1} when CS, respectively. Therefore, we can observe that the gap between the Ca and Mg input in jun/2012 (experimental initial) and the Ca and Mg after 45 months was positive and more increase in the dose V to 50 % for all liming material. In the dose V to 50 % probably occurred the better adjustment in the pH and V value and nutrients available, favoring the increase crops yield and nutrient cycling.

7.2.2. Cationic relationship

The fact that influenced the exchangeable-Ca and Mg is the relationship between Ca, Mg and K overtime. When we consider only relationship Ca/Mg (value ideal = 4-5:1 – HAVLIN et al., 2014), was observed, in 0-20 cm layer and after 0, 5, 11, 23, 34 and 45 months of application of all doses and liming materials, the following values 3, 2, 5, 2, 1 and 1:1, respectively. Already, when we consider only relationship (Ca+Mg)/K (value ideal = 15-40:1 1 – HAVLIN et al., 2014), was observed, in 0-20 cm layer and after 0, 5, 11, 23, 34 and 45 months of application of all doses and liming materials, the following values 19, 27, 28, 30, 57 and 68:1, respectively. Therefore, is evident the decrease in the Ca/Mg (except after 11 months) and increase in the (Ca+Mg)/K, along the time. Thus, in the 0-20 cm layer of Typic Distrudept, the doses of liming materials reached the ideal Ca/Mg relationship at 11 months after application, increased (Ca+Mg)/K and decrease exchangeable-K (Figure 15) in the long time. Besides, we observed that the GMC and CS more increased the cationic relationship than DL and GMD. Thus, we conclude that the higher Ca concentration in the liming material its greater influence in the cationic relationship. This fact can be attributed the higher solubility and dissolution of calcites (GMC and CS) than dolomites (DL and GMD) (HAVLIN et al., 2014). Therefore, the GMC and CS application is important in soils with lower cationic relationship. However, in soils with higher CEC (as that of this study) generally did not change over time of Ca, Mg and K available, in 0-10 cm layer (KOPITTKE et al., 2017).

7.2.3. Effect of liming materials in the exchangeable-K

There were changes in the exchangeable-K concentrations, which was intensified up to 45 months after application of liming materials doses than in control treatment (Figure 15 and 18). Over time, there was natural decrease in the exchangeable-K concentration except at 45 months in the 0-5 and 20-60 cm layer (Figure 15). This fact, can be assigned the exchangeable-K leaching and nutrient cycling by crops. When it was observed major % Ca-CEC, also was observed decrease in the exchangeable-K concentration (Figures 15, 19 and 20). In this study, the increase in the % Mg-CEC influenced more the K concentration than the % Ca-CEC. Thus, the decrease of exchangeable-K in soil can be due to: (i) uptake by crops and (ii) so the K uptake suppress the Mg uptake (RHODES et al., 2018) and (iii) increase of % Mg-CEC.

After the liming materials application on soil, the $CaCO_3$ or $CaMg(CO_3)_2$, can to dissociate and to release exchangeable-Ca and Mg (HAVLIN et al., 2014). However, the soil acidity control with liming material of faster reaction and fineness, as the MLM, increase the pH (and reduce aluminum) (ÁLVAREZ et al., 2009; DOS SANTOS et al., 2016b), favor the Ca uptake and positive influence in the root growth of crops (CAIRES et al., 2006; CAIRES et al., 2008; HAVLIN et al., 2014), and increase o % Ca and Mg-CEC (BARBIERI et al., 2015). The higher exchangeable-Ca and Mg concentration in the soil can to reduce the uptake of exchangeable-K, and this occur, because the exchangeable-Ca and Mg competed with exchangeable-K (HAVLIN et al., 2014).

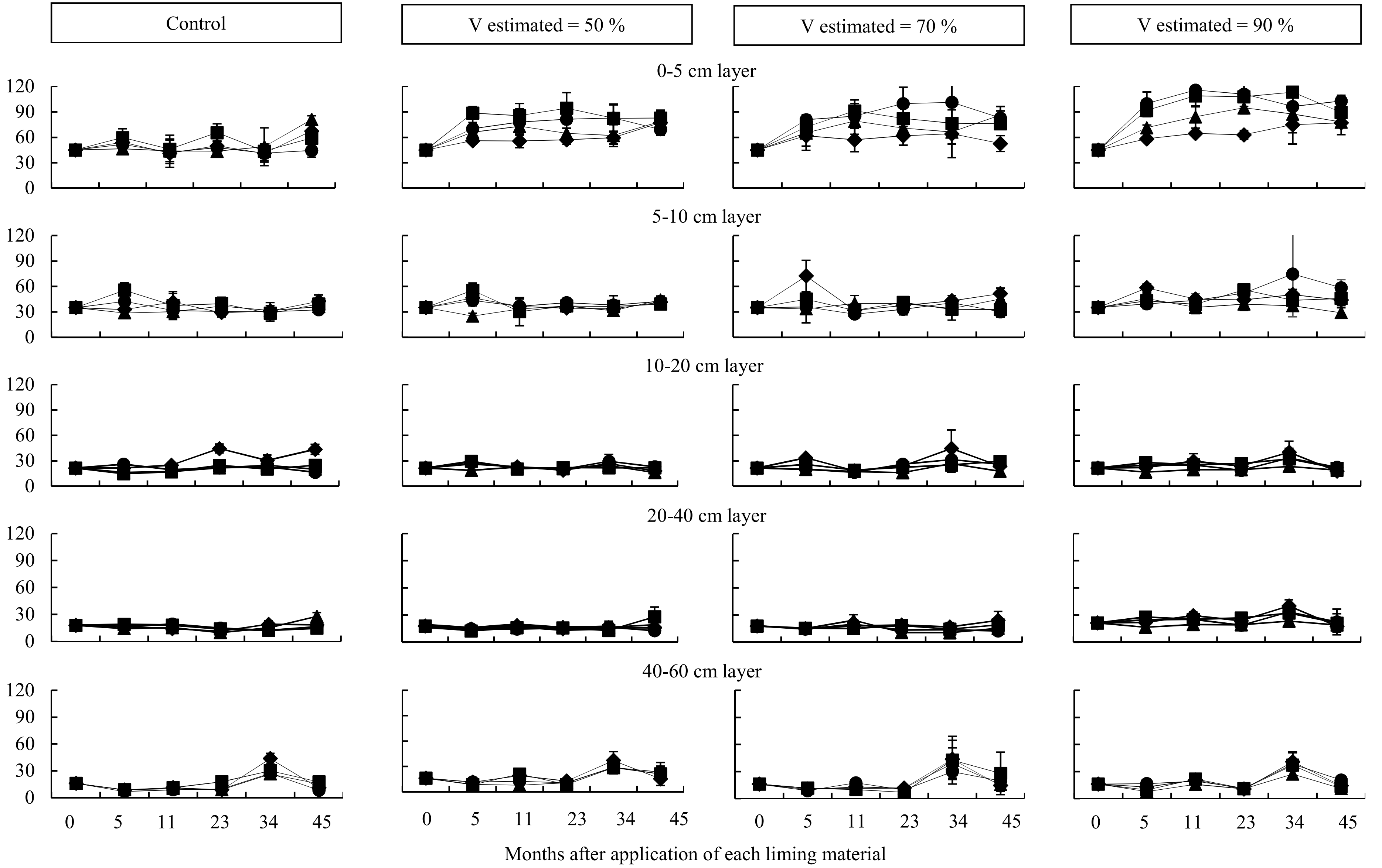


Figure 13.Exchangeable calcium (Ca) concentration, mmol$_c$ dm^{-3} (n = 16 ± standard deviation), after 0, 5, 11, 23, 34 and 45 months after the surface application of liming materials in the doses aiming the increase of the soil base saturation (V estimated) to 50, 70 and 90% besides control treatment, in each soil layer. (♦) Dolomitic limestone. (■) Granulated micronized calcite. (▲) Granulated micronized dolomite. (●) Carbonated suspension.

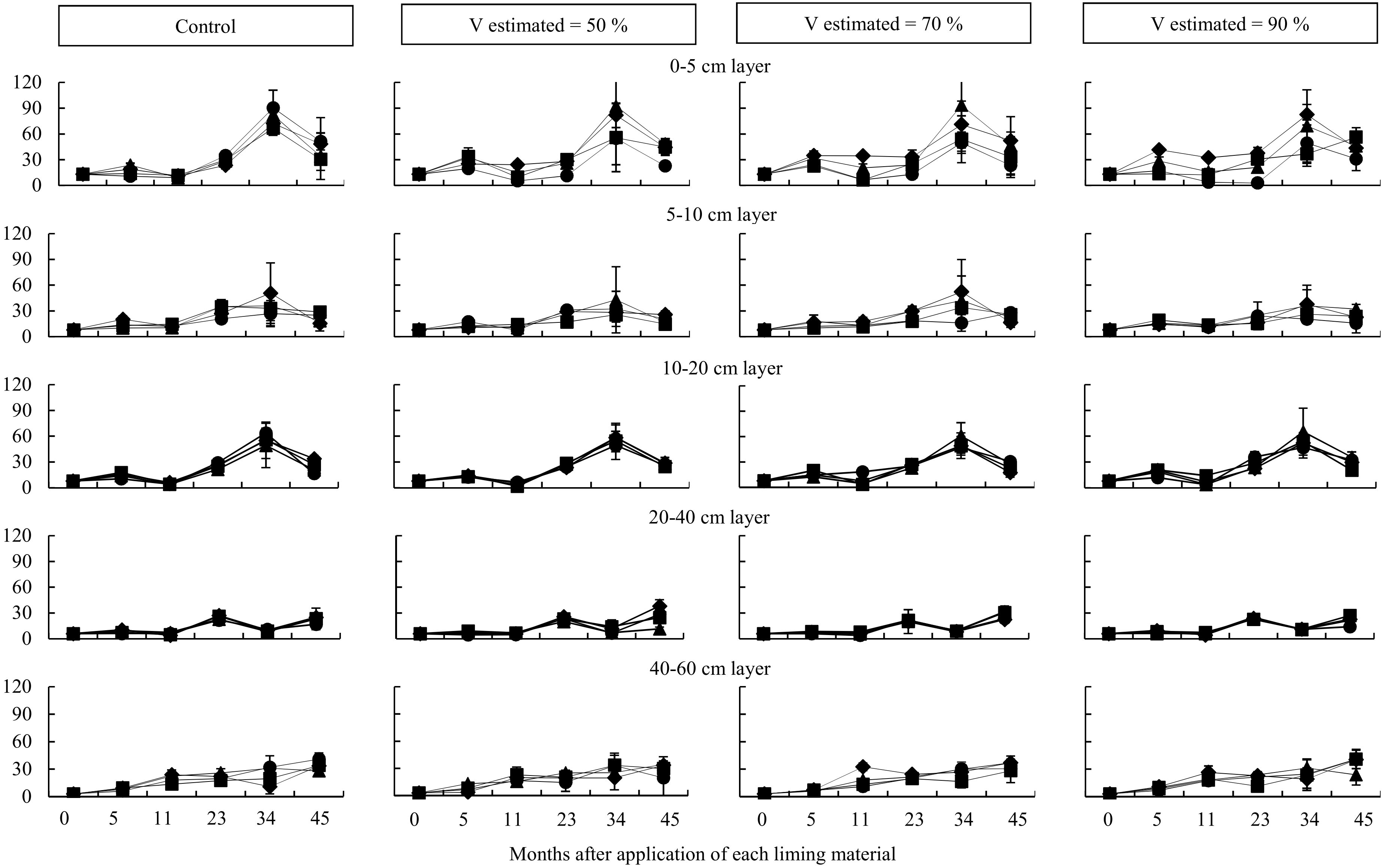


Figure 14.Exchangeable magnesium (Mg) concentration, mmol$_c$ dm^{-3} (n = 16 ± standard deviation), after 0, 5, 11, 24, 34 and 45 months after the surface application of liming materials in the doses aiming the increase of the soil base saturation (V estimated) to 50, 70 and 90% besides control treatment, in each soil layer. (♦) Dolomitic limestone. (■) Granulated micronized calcite. (▲) Granulated micronized dolomite. (●) Carbonated suspension.

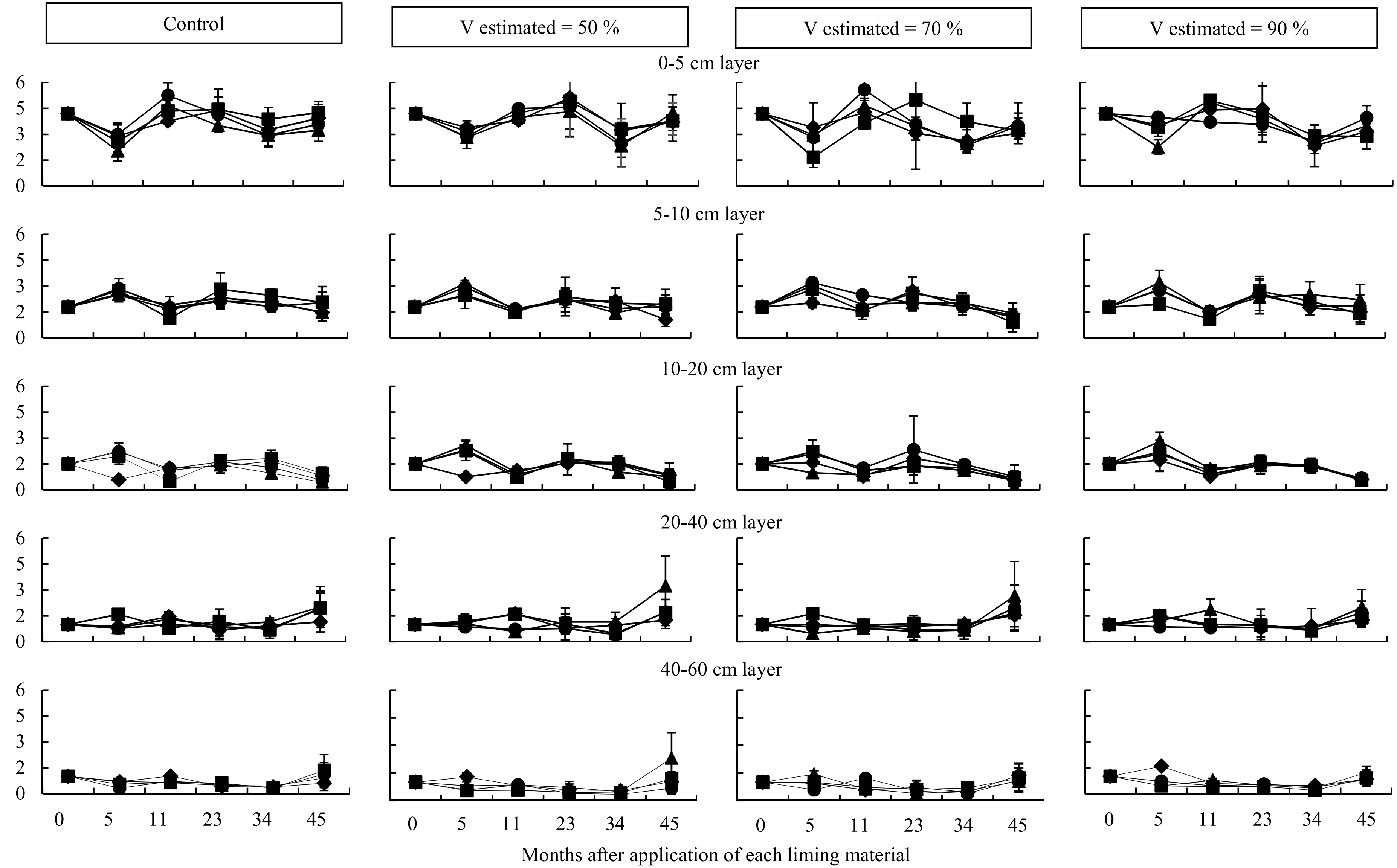


Figure 15. Exchangeable potassium (K) concentration, mmol$_c$ dm^{-3} (n = 16 ± standard deviation), after 0, 5, 11, 23, 34 and 45 months after the surface application of liming materials in the doses aiming the increase of the soil base saturation (V estimated) to 50, 70 and 90% besides control treatment, in each soil layer. (♦) Dolomitic limestone. (■) Granulated micronized calcite. (▲) Granulated micronized dolomite. (●) Carbonated suspension.

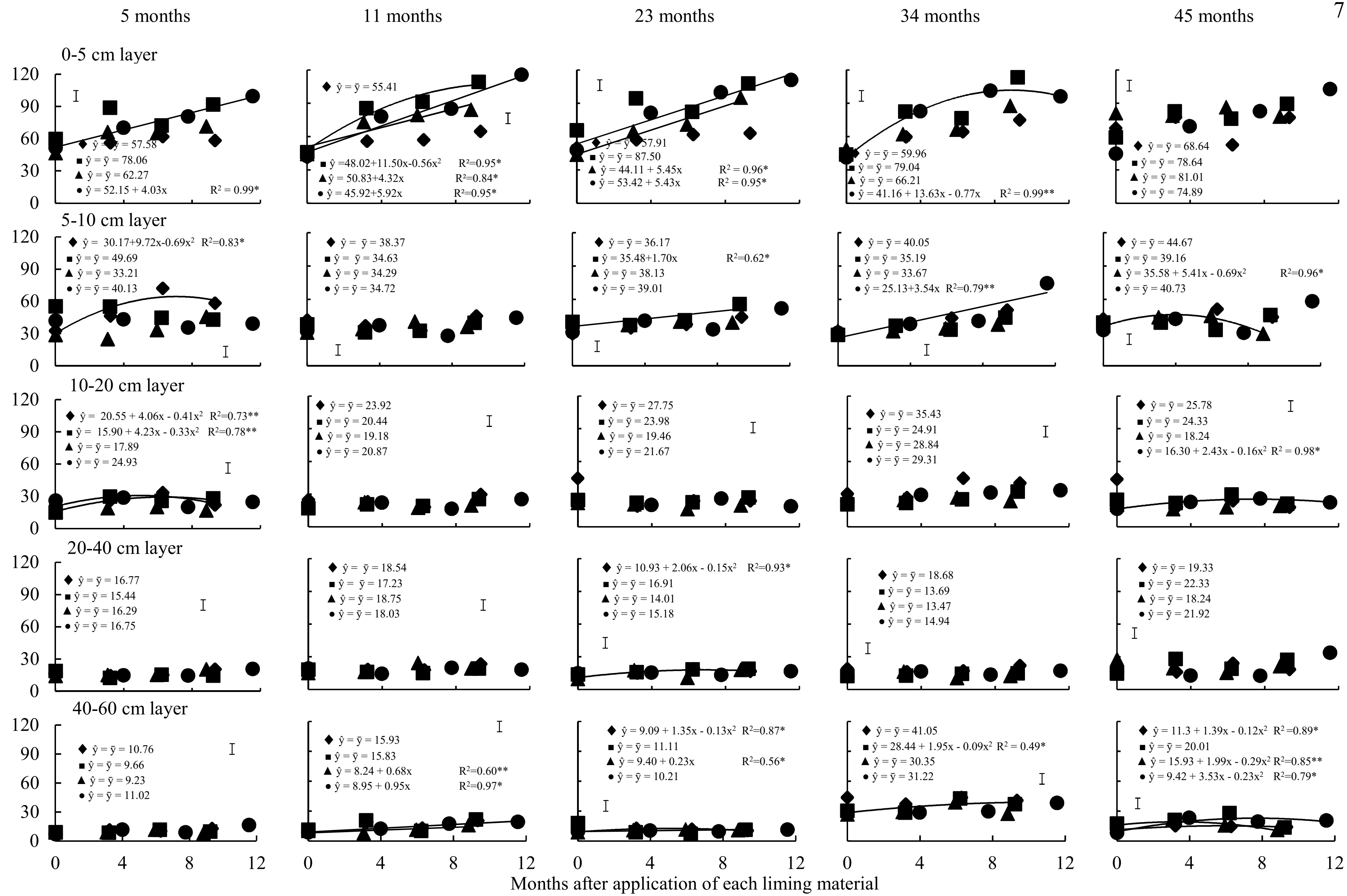


Figure 16.Exchangeable calcium concentration (n = 4), mmol$_c$ dm^{-3}, of a Typic Distrudept, after 5, 11, 23, 34 and 45 months after the surface application of liming materials in the doses aiming the increase of the soil base saturation (V estimated) to 50, 70 and 90% besides control treatment, in deep layer. (♦) Dolomitic limestone. (■) Granulated micronized calcite. (▲) Granulated micronized dolomite. (●) Carbonated suspension. Vertical bars indicate the least significant difference (LSD). *: $P < 0.05$. **: $P < 0.01$.

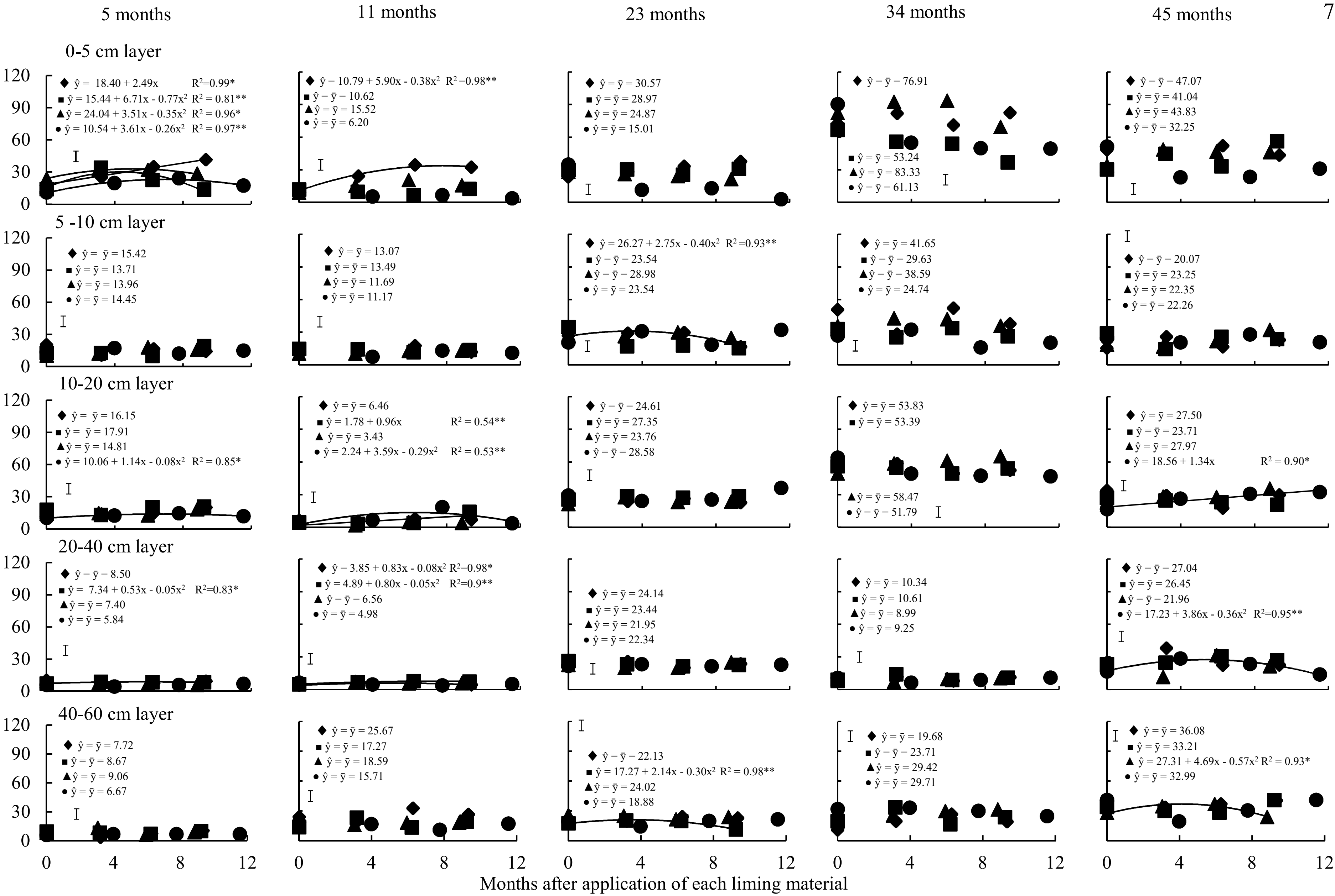


Figure 17. Exchangeable magnesium concentration (n = 4), mmol$_c$ dm^{-3}, of a Typic Distrudept, after 5, 11, 23, 34 and 45 months after the surface application of liming materials in the doses aiming the increase of the soil base saturation (V estimated) to 50, 70 and 90% besides control treatment, in deep layer. (♦) Dolomitic limestone. (■) Granulated micronized calcite. (▲) Granulated micronized dolomite. (●) Carbonated suspension. Vertical bars indicate the least significant difference (LSD). *: $P < 0.05$. **: $P < 0.01$.

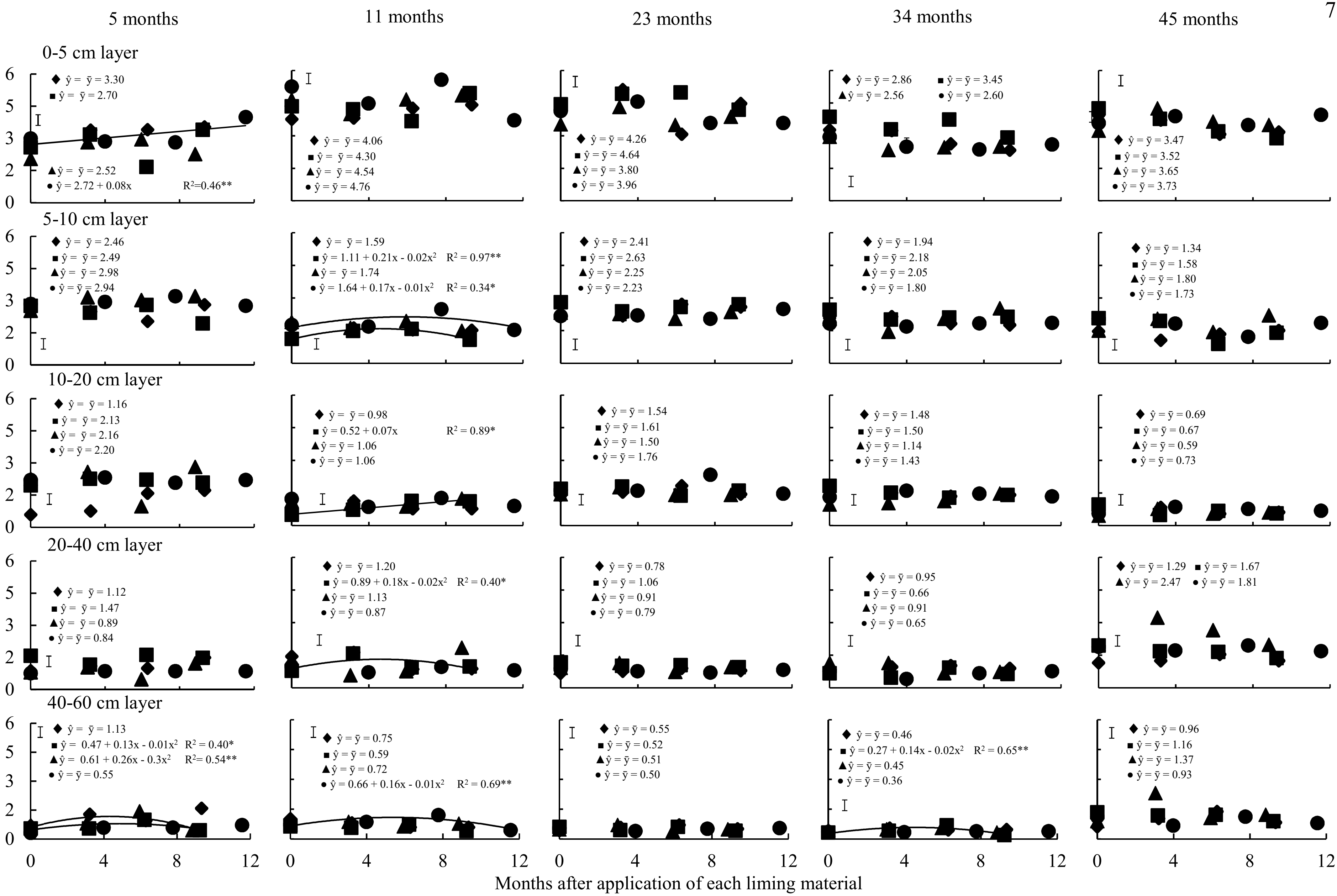


Figure 18. Exchangeable potassium concentration (n = 4), mmol$_c$ dm^{-3}, of a Typic Distrudept, after 5, 11, 23, 34 and 45 months after the surface application of liming materials in the doses aiming the increase of the soil base saturation (V estimated) to 50, 70 and 90% besides control treatment, in deep layer. (♦) Dolomitic limestone. (■) Granulated micronized calcite. (▲) Granulated micronized dolomite. (●) Carbonated suspension. Vertical bars indicate the least significant difference (LSD). *: $P < 0.05$. **: $P < 0.01$.

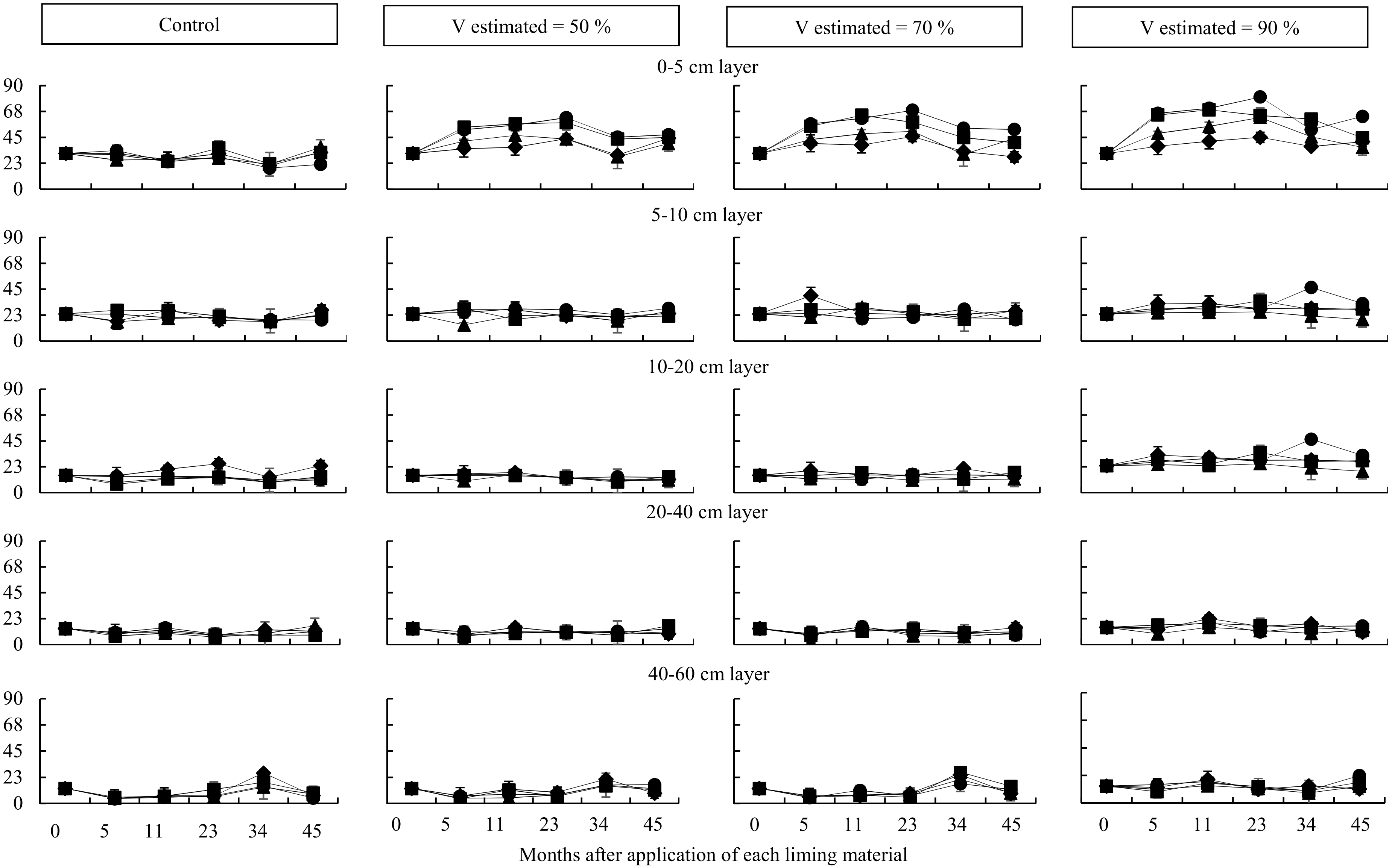


Figure 19. Percentage of calcium in the cation exchangeable capacity at pH = 7.0, % (*n* = 16 ± standard deviation) after 0, 5, 11, 23, 34 and 45 months after the surface application of liming materials in the doses aiming the increase of the soil base saturation (V estimated) to 50, 70 and 90% besides control treatment, in each soil layer. (♦) Dolomitic limestone. (■) Granulated micronized calcite. (▲) Granulated micronized dolomite. (●) Carbonated suspension.

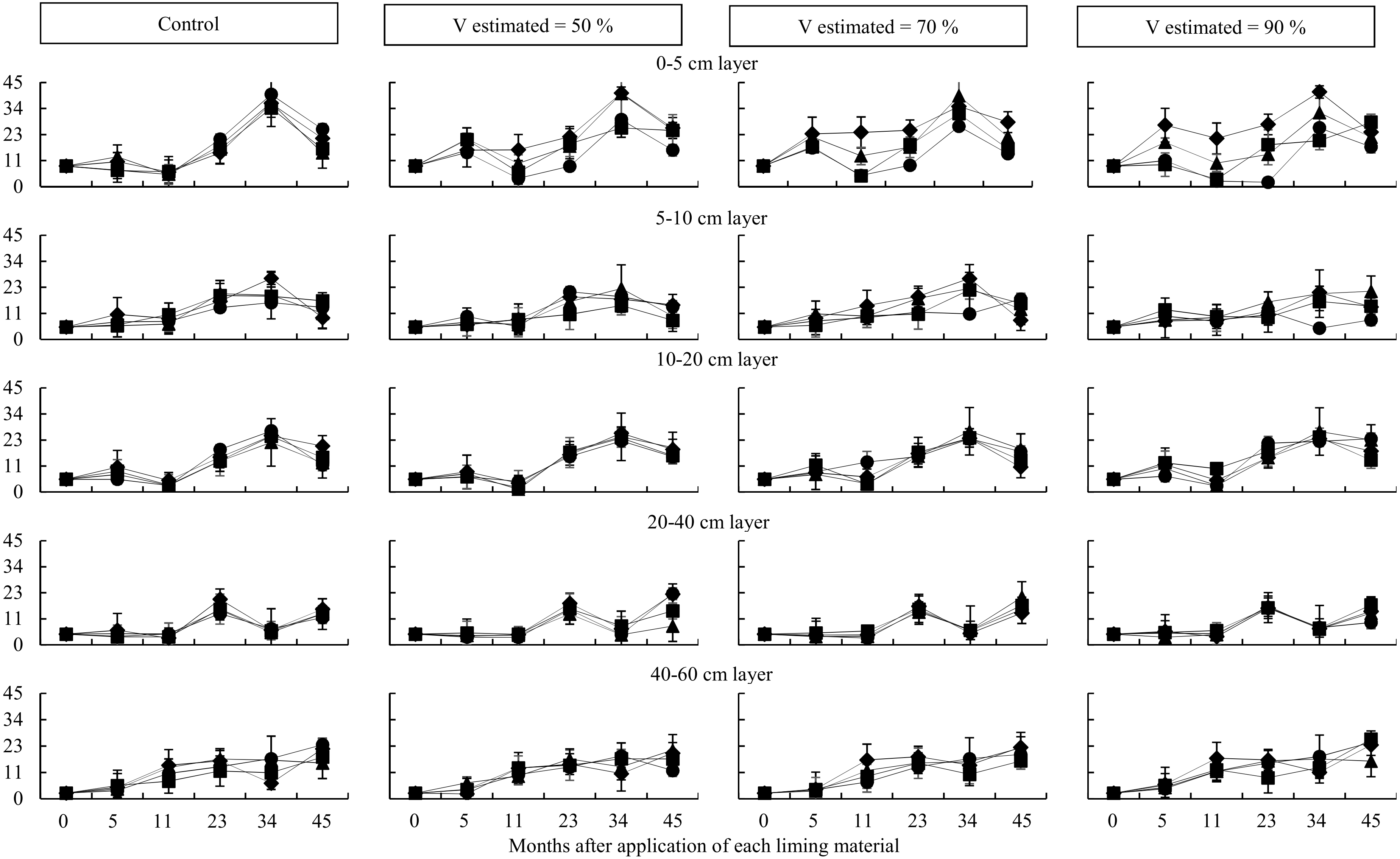


Figure 20. Percentage of magnesium in the cation exchangeable capacity at pH = 7.0, % (n = 16 ± standard deviation) after 0, 5, 11, 23, 34 and 45 months after the surface application of liming materials in the doses aiming the increase of the soil base saturation (V estimated) to 50, 70 and 90% besides control treatment, in each soil layer. (♦) Dolomitic limestone. (■) Granulated micronized calcite. (▲) Granulated micronized dolomite. (●) Carbonated suspension.

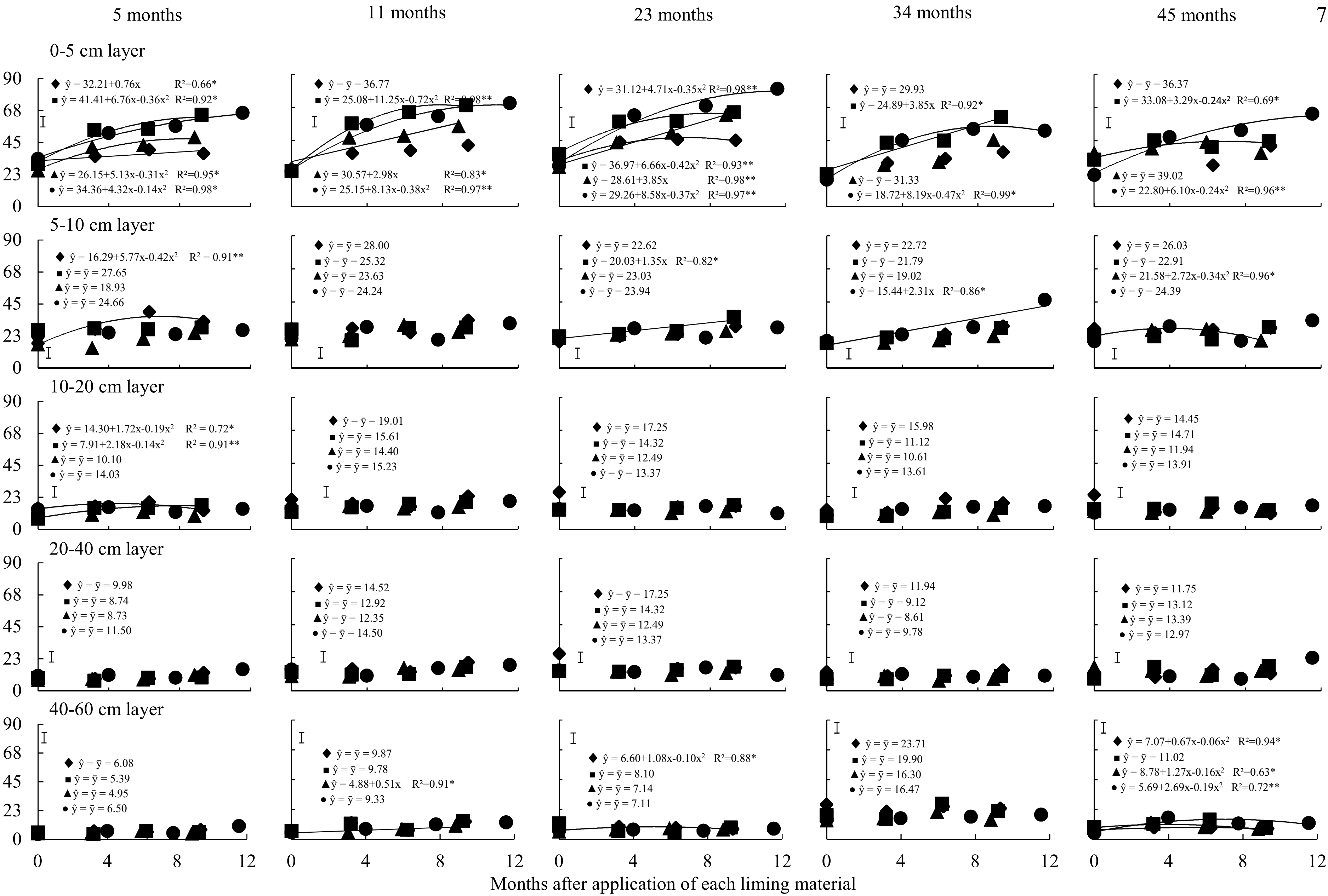


Figure 21. Percentage of calcium in the cation exchangeable capacity at pH = 7.0, (n = 4), %, of a Typic Distrudept, after 5, 11, 23, 34 and 45 months after the surface application of liming materials in the doses aiming the increase of the soil base saturation (V estimated) to 50, 70 and 90% besides control treatment, in deep layer. (♦) Dolomitic limestone. (■) Granulated micronized calcite. (▲) Granulated micronized dolomite. (●) Carbonated suspension. Vertical bars indicate the least significant difference (LSD). *: $P < 0.05$. **: $P < 0.01$.

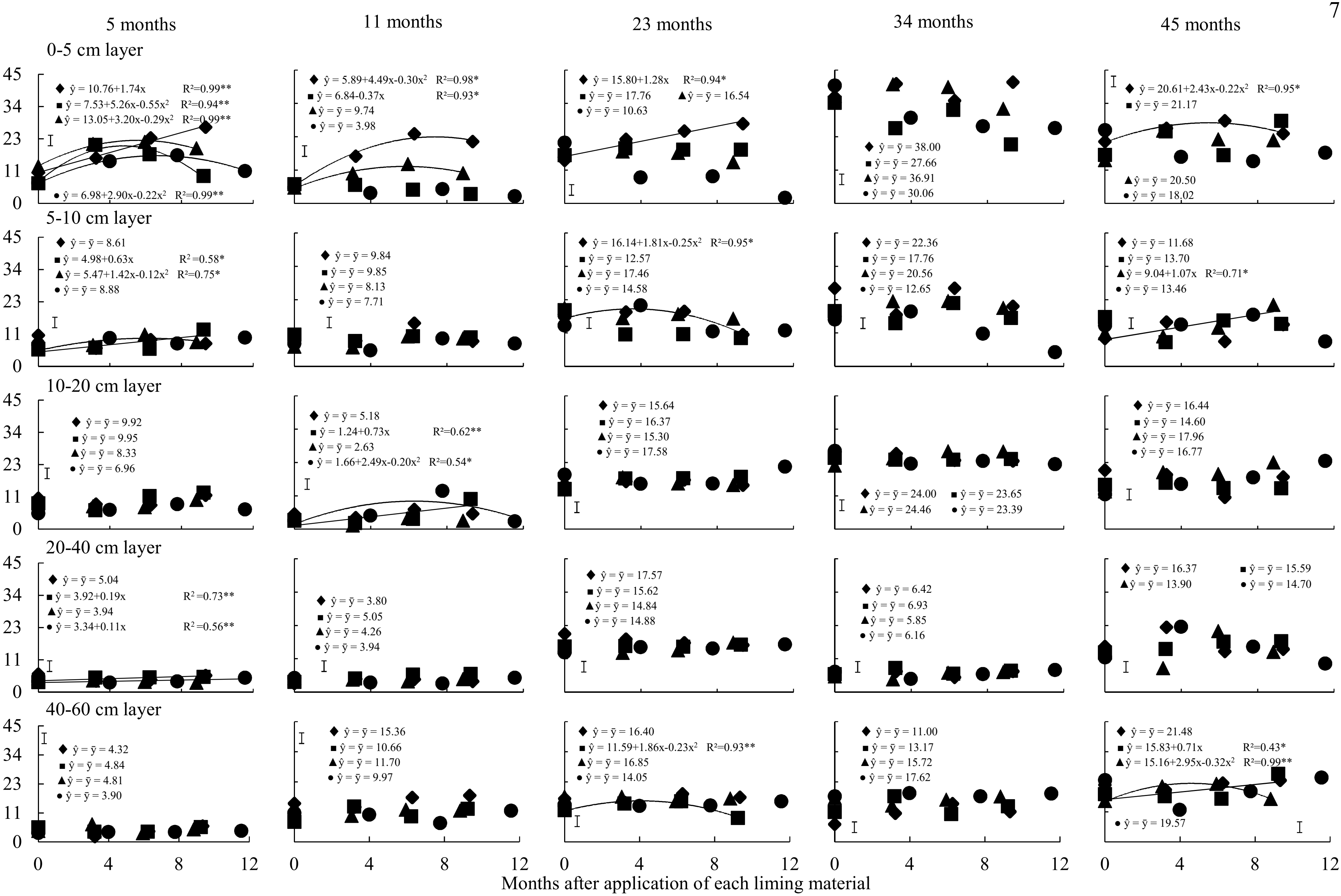


Figure 22. Percentage of magnesium in the cation exchangeable capacity at pH = 7.0, (n = 4), %, of a Typic Distrudept, after 5, 11, 23, 34 and 45 months after the surface application of liming materials in the doses aiming the increase of the soil base saturation (V estimated) to 50, 70 and 90% besides control treatment, in deep layer. (♦) Dolomitic limestone. (■) Granulated micronized calcite. (▲) Granulated micronized dolomite. (●) Carbonated suspension. Vertical bars indicate the least significant difference (LSD). *: $P < 0.05$. **: $P < 0.01$.

7.3. Conclusions

In a Typic Distrudept, under no-tillage, the increase in the exchangeable calcium, magnesium and potassium concentrations were higher in the surface (0-5 cm) up to 34 months after superficial application of liming materials, in the doses aiming soil base saturation to 50-70 %. However, in the 0-20 cm layer, the doses of liming materials reached the ideal cationic relationship at 11 months after surface application and the higher calcium concentration in the liming material its greater influence in the cationic relationship. Thus, the granulated micronized calcite and carbonated suspension application is important in soils with lower cationic relationship. The exchangeable potassium concentration, in a Typic Distrudept under no-tillage, treated with liming material, was increased as it decreased the percentage of magnesium in the cationic exchange capacity at pH 7.0.

8. Final considerations

The micronized liming materials, applied in a Typic Distrudept under no-tillage, without incorporation, presented (i) major relative yield, relative yield change and production efficiency of wheat, soybean, black oat and maize up to 45 months; (ii) increase and keeps pH and soil base saturation values, only in the 0-5 cm layer, during 5 up to 45 months after surface application; (iii) increase in the exchangeable calcium, magnesium and potassium concentrations in the soil surface (0-5 cm) up to 34 months after superficial application; mainly and always in the doses aiming soil base saturation to 50-70 % and when compared with dolomitic limestone.

When, the relative yield change is lower between two years of growth of a crop, major responsiveness and lower residual effect of a micronized liming material and yield maintenance in a crop succession of four years. This fact occurred, mainly, with calcite micronized granulated and carbonated suspension. Also, if we consider only production efficiency of grains and dry matter, better results were found in the dose aiming soil base saturation to 61 % for all the liming materials applied, showing that it is the recommended dose for acidity control of a Typic Distrudept.

Others conclusions important, were that: (i) the gap between the soil base saturation estimated and measured is smaller on soil treatment with micronized liming material than dolomitic lime, manly in the 0-5 cm layer; (ii) in the 0-20 cm layer, the doses of liming materials reached the ideal cationic relationship at 11 months after surface application and the higher calcium concentration in the liming material its greater influence in the cationic relationship. Thus, the granulated micronized calcite and carbonated suspension application is important in soils with lower cationic relationship; and (iii) the exchangeable potassium concentration, in a Typic Distrudept under no-tillage, treated with liming material, was increased as it decreased the percentage of magnesium in the cationic exchange capacity at pH 7.0.

The liming materials, applied superficially and without incorporation, were not efficient to increase and keep the pH and soil base saturation values as well as the exchangeable-calcium and magnesium concentrations, below the point of placement, in soils high buffering power and variable charge, as the Typic Distrudept. In this soil the fact more important that prevent the acidity control in deep layers are: (i) higher potential acidity; (ii) dissolution/dissociation as far from acidity zone and reaction time; (iii) the neutralization of aluminum and of hydrogen on soil functional groups is limited; and (iv) the soil buffering power is strongly by aluminum and iron oxides. Therefore, is a soil that need of more monitoring by chemical analyze, use of micronized liming material and practices of deep layers conditioning.

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