

*Full Length Research Paper*

# Exchangeable cations and available phosphorus in soils with variable charge after application of special liming materials

Jessica Alves dos Santos<sup>1\*</sup>, Adriel Ferreira da Fonseca<sup>1</sup>, Domenico Zocco<sup>2</sup> and Igor Vieira<sup>3</sup>

<sup>1</sup>State University of Ponta Grossa, Av. Carlos Cavalcanti, Ponta Grossa, Paraná, Brazil.

<sup>2</sup>Omya International AG, PO Box 335, Baslerstrasse 42, 4665 Oftringen, Switzerland.

<sup>3</sup>Omya do Brasil Ltda, Av. Angélica, 2220, 2º andar, São Paulo, São Paulo, Brazil.

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Special liming materials have the potential to control soil acidity and constitute a source of nutrients for plant development. In this study, the efficiency of special liming materials was evaluated. Their effects in soil exchangeable cations and available P concentrations were compared with the ones of dolomitic limestone (DL). Samples of Typic Distrudept and Rhodic Hapludox were collected from 0 to 20 cm layer. Two experiments were conducted in a completely randomized block of 4x4x8 factorial design. Four liming materials were studied: DL, granulated micronized calcite (GMC), granulated micronized dolomite (GMD) and carbonated suspension (CS). The liming materials were added to the soils doses that increase the soil bases saturation (V) to 50, 70 and 90%; and a control treatment. The treated soil samples were incubated at  $23 \pm 2^\circ\text{C}$  and 60% of soil water retention capacity for eight periods (0, 7, 15, 30, 45, 60, 75 and 90 days). Exchangeable Ca, Mg and K, and available P were determined. All liming materials increase exchangeable Ca and Mg, and available P. However, the most efficient source that increased exchangeable Ca in the studied soils were CS followed by GMC.

**Key words:** Special liming materials, micronized limestone, carbonated suspension, availability of nutrients, Inceptisol, Oxisol.

## INTRODUCTION

Soil acidity is a severe agricultural problem in the world. Firstly, soil acidity is mainly due to: the removal of basic cations ( $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$  and  $\text{K}^+$ ), cation exchange capacity (CEC) from the soil and their substitution with exchangeable aluminum ( $\text{Al}^{3+}$ ) and non-dissociated

hydrogen ( $\text{H}^+$ ). Secondly, soil acidity is caused by Ca, Mg and K uptake and exportation by the harvested crops (Nagy and Kónya, 2007; Souza et al., 2007; Raij, 2011). Acidity might result in accumulation of rich soil particles in  $\text{Al}^{3+}$  and iron (Fe) oxide,  $\text{Al}^{3+}$  and manganese (Mn)

\*Corresponding author. E-mail: [jessicaalvesdossantos@bol.com.br](mailto:jessicaalvesdossantos@bol.com.br).

toxicity and Ca, Mg, K and phosphorus (P) deficiency in the soil (Hue, 2011). Therefore, in acid soils, the plants have no opportunity to grow adequately and their yields are negatively affected, mainly in situations of water stress (Joris et al., 2013).

Liming controls acidity, reestablishes or provides high productivity, make nutrients available, reduce  $\text{Al}^{3+}$  and consequently supply the soil with Ca and Mg (Caires et al., 2001). However, the most used liming material in the Brazilian agriculture presents low solubility as compared to the special liming materials for soil acidity control (Oliveira et al., 2014). The special liming materials comprised calcium and/or magnesium carbonates [ $\text{CaCO}_3$ ,  $\text{MgCO}_3$  and  $(\text{Ca,Mg})\text{CO}_3$ ] called granulated micronized calcite or dolomite and carbonated suspension. However, there are few studies that show the capacity of providing nutrients such as Ca and Mg, and make K and P available as a result of special liming material application in soils with variable charges (such as the Typic Distrudept and Rhodic Hapludox). Also, these special liming materials can be a strategy to fast increase the soil relationship Ca/Mg, due to the present of very fine particle size ( $< 7.0 \mu\text{m}$ ) as compared to a limestone ( $< 500.0 \mu\text{m}$ ) (Coelho, 2004).

The objective of this study was to evaluate the efficiency of special liming materials as compared to dolomitic limestone (DL), on exchangeable Ca, Mg, and K and available P concentrations in Typic Distrudept and Rhodic Hapludox.

## MATERIALS AND METHODS

Two soils with variable charges, Typic Distrudept and Rhodic Hapludox, were collected in the region of Paraná Campos Gerais, Brazil. Typic Distrudept had the follow attributes in the 0-20 cm layer: 4.3 of pH ( $\text{CaCl}_2$ ), 103.3, 11.3, 30.8, 9.3 and 2.3  $\text{mmol}_c \text{dm}^{-3}$  of H+Al, Al, Ca, Mg and K, respectively; and 23.4  $\text{mg dm}^{-3}$  of P; 21.0  $\text{g dm}^{-3}$  and 29.0% of organic carbon (OC) by Walkey-black method (Pavan et al., 1992) and soil base saturation (V), respectively; 200.0, 255.2 and 544.8  $\text{g kg}^{-1}$  of clay, silt and sand, respectively; 1.2  $\text{g cm}^{-3}$  and 1.5  $\text{cm}^3 \text{cm}^{-3}$  of bulk density (BD) and water saturation (S) (EMBRAPA, 1997), respectively. This soil was managed in no-tillage for 15 years and crops succession between black oat and soybean for the last 4 years. The other soil (without previous cropping), Rhodic Hapludox, had the follow attributes in the 0-20 cm layer: 3.8 of pH ( $\text{CaCl}_2$ ), 151.6, 26.0, 6.0, 7.0 and 1.5  $\text{mmol}_c \text{dm}^{-3}$  of H+Al, Al, Ca, Mg and K, respectively; and 1.6  $\text{mg dm}^{-3}$  of P; 33.0  $\text{g dm}^{-3}$  and 8.7% of OC by Walkey-black method (Pavan et al., 1992) and V, respectively; 736.0, 174.2 and 89.8  $\text{g kg}^{-1}$  of clay, silt and sand, respectively; 1.0  $\text{g cm}^{-3}$  and 1.0  $\text{cm}^3 \text{cm}^{-3}$  of BD and S (EMBRAPA, 1997), respectively. After collection, the soil samples were dried in oven with forced air circulation at  $40^\circ\text{C}$  for 48 h. Thereafter, they were ground and sieved in a 2.0 mm mesh sieve. Each experimental unit consisted of 500 g of the sieved soil, weighed on a precision scale (Balmak ELP 10 and 5000.0 g of maximum and 20.0 g of minimum  $\pm 1.0$  g). Two experiments were conducted separately with Typic Distrudept and Rhodic Hapludox.

The design used in both experiments, was completely randomized in a  $4 \times 4 \times 8$  in factorial design with four replications. Four liming materials were studied: dolomitic limestone (DL – 898.7

$\text{g kg}^{-1}$  of effective calcium carbonate (ECC)), granulated micronized calcite (GMC – 962.7  $\text{g kg}^{-1}$  of ECC), granulated micronized dolomite (GMD – 1006.5  $\text{g kg}^{-1}$  of ECC) and carbonated suspension (CS – 770.0  $\text{g kg}^{-1}$  of ECC), whose physical and chemical characteristics liming materials were performed according to MAPA (2007). The specific surface area (SSA) of the liming materials determined with the method of França and Couto (2007) were 306.6; 1055.0; 1099.0 and 1559  $\text{m}^2 \text{kg}^{-1}$  for DL, GMC, GMD and CS, respectively. The liming materials contents in CaO and MgO, analyzed according to MAPA (2007), were respectively 265.9 and 257.6  $\text{g kg}^{-1}$  for DL; 462.2 and 15.5  $\text{g kg}^{-1}$  for GMC; 345.9 and 121.5  $\text{g kg}^{-1}$  for GMD and 361.1 and 8.30  $\text{g kg}^{-1}$  for CS.

For each liming material, three doses that are supposed to increase V to 50, 70 and 90% were studied. Also, a control treatment was included, that is, untreated check. The doses of the liming material were determined using the equation of Raji et al. (1996):

$$\text{LR} = \frac{\text{CEC} \times (V_2 - V_1)}{(10 \times \text{ECC})}$$

Where: LR: lime requirement ( $\text{Mg ha}^{-1}$ ) for layer 0-20 cm; CEC: cation exchange capacity ( $\text{mmol}_c \text{dm}^{-3}$ );  $V_1$ : base saturation (%) obtained; and  $V_2$ : targeted base saturation (%). The ECC was estimated using the equation according to Raji (1977):

$$\text{ECC} = \frac{(\text{NP} \times \text{RE})}{100}$$

Where: ECC (%): effective calcium carbonate; NP: neutralizing power, calculated with the equation [ $\text{CaO} (\%) \times 1.79 + \text{MgO} (\%) \times 2.48$ ] and RE: relative efficiency of the liming.

The 100% RE was adopted for the special liming materials, due to the fact that they present very low particle size ( $< 7.0 \mu\text{m}$ ) as compared to good quality limestone with particles size  $< 300.0 \mu\text{m}$  – according to the scale of MAPA (2007). The doses of each liming materials applied in each experimental unit and in each soil were calculated taking into consideration the soil volume and BD of each soil study.

The doses estimated to increase V to 50, 70 and 90% of Typic Distrudept were of 3.41, 6.65 and 9.89  $\text{Mg ha}^{-1}$  for DL, respectively; 3.18, 6.21 and 9.23  $\text{Mg ha}^{-1}$  for GMC, respectively; 3.05, 5.94 and 8.83  $\text{Mg ha}^{-1}$  for GMD, respectively; and 3.98, 7.76 and 11.54  $\text{Mg ha}^{-1}$  for CS, respectively. The doses estimated to increase V to 50, 70 and 90% of Rhodic Hapludox were of 7.63, 11.33 and 15.03  $\text{Mg ha}^{-1}$  for DL, respectively; 7.13, 10.58 and 14.03  $\text{Mg ha}^{-1}$  for GMC, respectively; 6.82, 10.12 and 13.42  $\text{Mg ha}^{-1}$  for GMD, respectively; and 8.91, 13.22 and 17.54  $\text{Mg ha}^{-1}$  for CS, respectively.

The liming materials were duly homogenized with the soil and incubated for 0, 7, 15, 30, 45, 60, 75 and 90 days. Constant temperature of  $23 \pm 2^\circ\text{C}$  and soil humidity of 60% soil water retention capacity, were maintained 339.0 and 224.0  $\text{mL kg}^{-1}$  deionized water with an average electrical conductivity of 0.5  $\mu\text{S cm}^{-1}$  were added to Typic Distrudept and Rhodic Hapludox, respectively.

At the end of each incubation period (0, 7, 15, 30, 45, 60, 75 and 90 days), the experimental units of both soils were removed from the incubation room and taken to the laboratory, dried in oven at  $40^\circ\text{C}$  with forced air circulation, ground and sieved in a 2.0 mm mesh sieve. Then, the attributes exchangeable  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$  and  $\text{K}^+$ , and available P were determined with the methods suggest by Pavan et al. (1992).

The data was submitted to statistical analysis employing the computer program SAS Version 9.1.2 (SAS 2004). The program suggested transformations of exchangeable Mg and available P

**Table 1.** Interactions significant effects (F values) ( $p < 0.0001$ ) between liming materials (dolomitic limestone, granulated micronized calcite, granulated micronized dolomite and carbonated suspension) after application of 50, 70 and 90% dose to increase soil base saturation and a control treatment, for eight incubation periods (0, 7, 15, 30, 45, 60, 75 and 90 days) on exchangeable calcium (Ca), magnesium (Mg) and potassium (K), and available phosphorus (P) in two different soils (Typic Distrudept and Rhodic Hapludox).

Soils	Ca	Mg	K	P
<b>Typic Distrudept</b>				
Liming material x Dose applied	121.73	333.69	397.95	245.45
Liming material x Incubation period	33.52	41.64	74.50	185.32
Dose applied x Incubation period	25.95	120.33	126.04	105.23
Liming material x Dose applied x Incubation period	14.75	39.89	48.63	59.03
<b>Rhodic Hapludox</b>				
Liming material x Dose applied	551.59	809.31	4.07	17.68
Liming material x Incubation period	89.92	219.94	32.59	46.30
Dose applied x Incubation period	53.18	247.75	6.99	115.00
Liming material x Dose applied x Incubation period	42.22	142.79	10.50	49.27

concentrations of both soils into square root. Three factors were considered in the statistical model: (i) four liming materials (DL, GMC, GMD and CS), (ii) four doses (a control treatment, V to 50, 70 and 90%) and (iii) eight incubation periods (0, 7, 15, 30, 45, 60, 75 and 90 days). The effect of predictive variables (dose of liming materials) was adjusted to the response variables (soil attributes) for each incubation period, using the regression models (linear or quadratic). The profile analysis was also used to compare the effects of each dose of liming material used during the periods of incubation.

## RESULTS

### Typic Distrudept

This study was conducted to observe the efficiency of liming materials in the variation of exchangeable Ca, Mg and K, and available P concentrations. Significant effects ( $p < 0.0001$ ) were observed in Typic Distrudept on Ca, Mg, K and P content from the interactions between the liming materials, doses applied and incubation periods (Table 1).

All liming materials increased exchangeable Ca concentration in soil (Figure 1). The DL, GMC, GMD and CS increased from 30.8  $\text{mmol}_c \text{dm}^{-3}$  (soil initial condition) to 66.5, 81.7, 71.0 and 103.0  $\text{mmol}_c \text{dm}^{-3}$  in the dose to increased V (DIV) to 90%, respectively. The CS in DIV to 70 and 90% resulted in higher exchangeable Ca concentration in soil than the others (liming materials and doses) at the end of 90 days incubation period (Figure 1). However, between 7 and 60 days of incubation, the CS with the DIV of 90% presented higher exchangeable Ca concentration than the other liming materials (Figure 3).

During the incubation period, the DL provided the highest exchangeable Mg concentration in all the doses

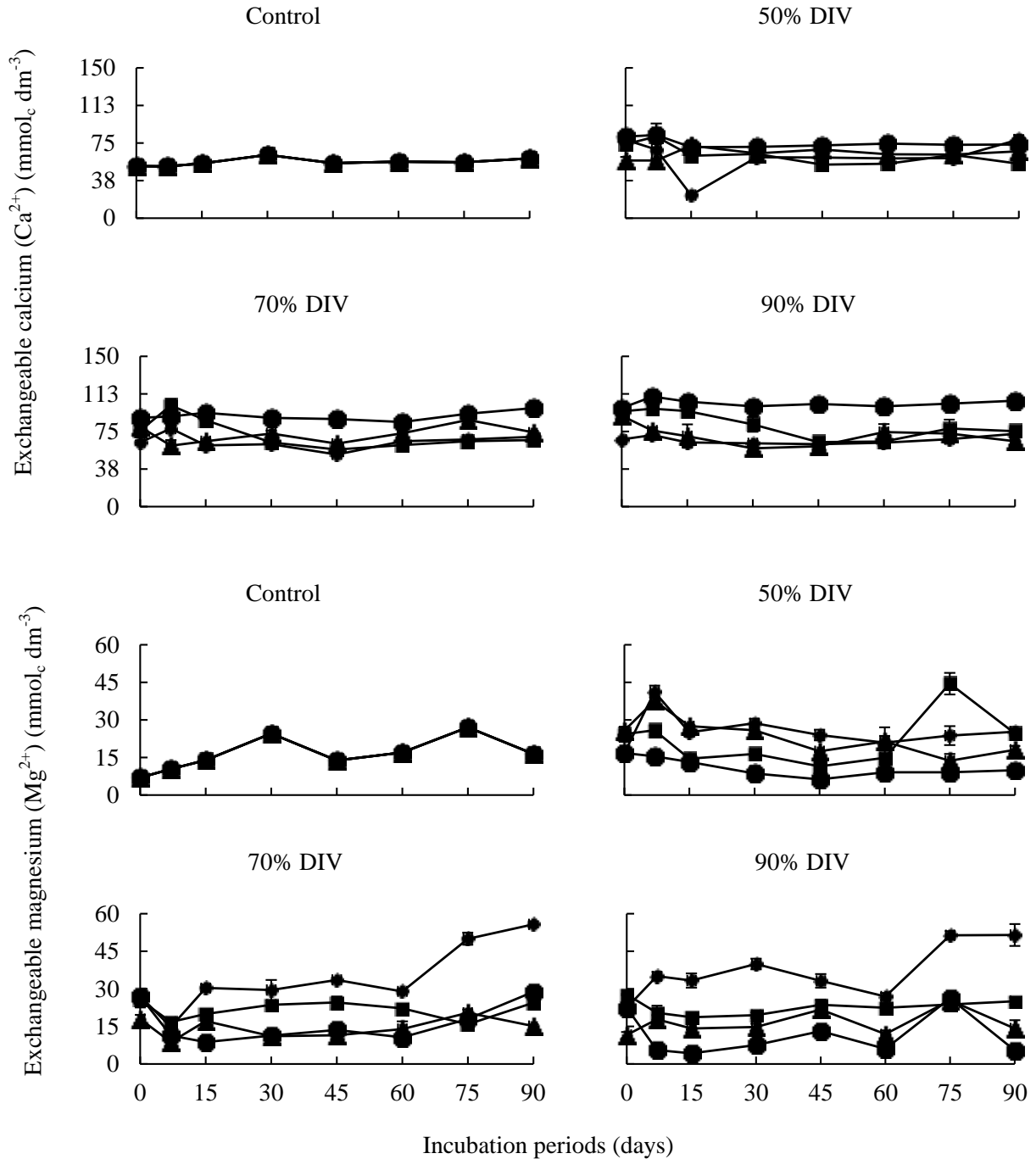
(Figure 1). Also, DL, applied with the DIV of 70 and 90%, efficiently increased Mg in DIV to 70 and 90%, more clearly at 90 days of incubation (Figure 4).

The exchangeable K concentrations after DL application were changed along the time (Figure 2). The doses of CS applied at 50 and 70% DIV resulted in higher exchangeable K concentrations in all the incubation periods (Figures 2 and 5). This increase was also observed with GMD (applied at 90% DIV). For GMC dose of 70% DIV, this special liming material increased exchangeable K concentration at the end of the incubation period of 90 days.

The available P concentrations were highly increased by special liming materials (GMC, GMD and CS) than DL (Figure 2). This increase was more evident with the application of GMC at 90% DIV, between 75 and 90 days (Figure 6).

### Study in Rhodic Hapludox

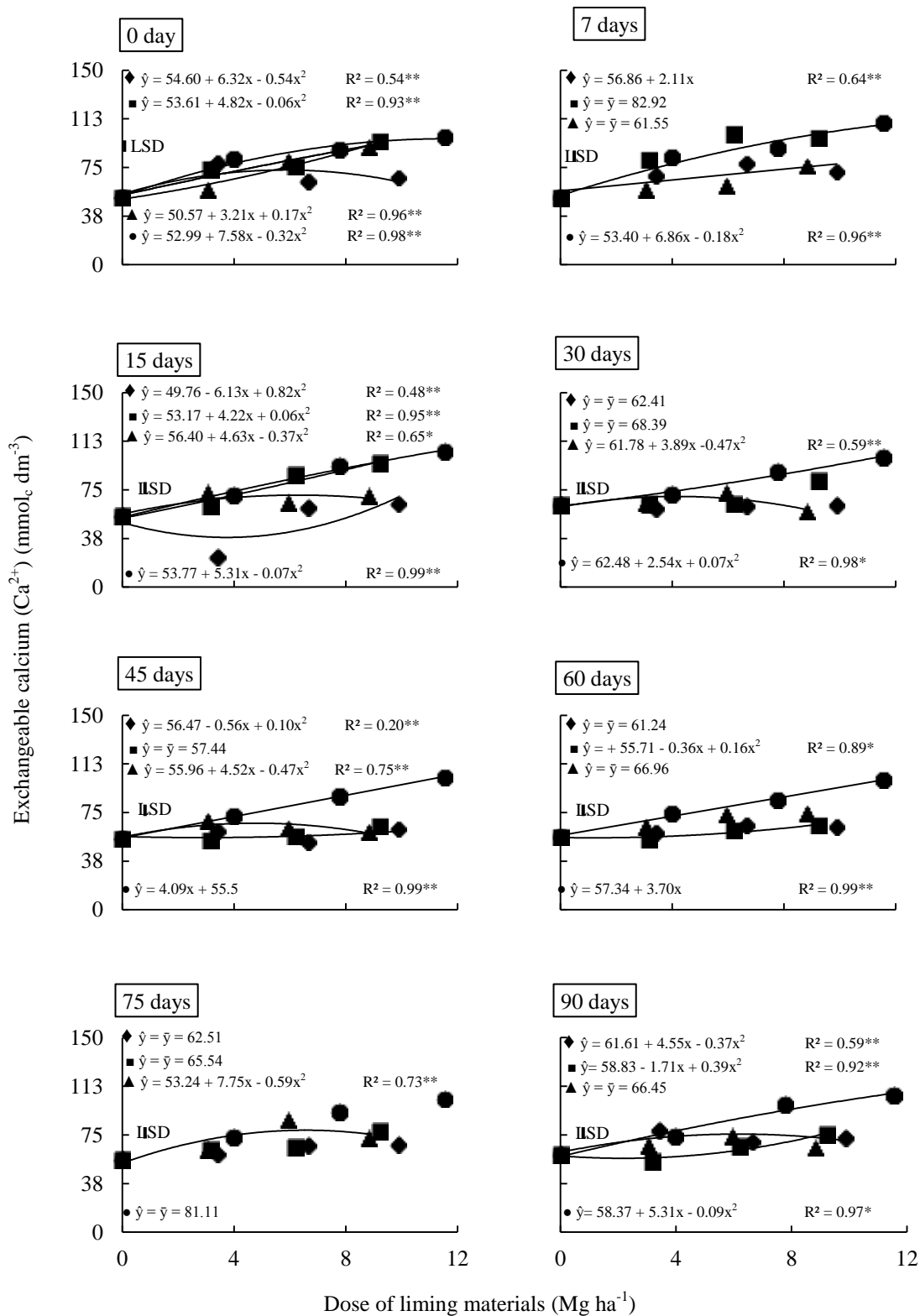
Significant effects ( $p < 0.0001$ ) were observed in Rhodic Hapludox from the interactions between the liming materials, doses applied and incubation periods (Table 1). GMC and CS were more efficient in increasing exchangeable Ca concentrations than DL and GMD. After application of GMC at 70 and 90% DIV, the exchangeable Ca concentrations increased to 66.4 and 76.0  $\text{mmol}_c \text{dm}^{-3}$ , respectively (Figure 7). When CS was applied at 70 and 90% DIV, the exchangeable Ca concentrations increased to 75.5 and 85.6  $\text{mmol}_c \text{dm}^{-3}$ , respectively (Figure 7). Moreover, these increases of the exchangeable Ca concentrations in CS treatment soil were more evident after 75 days of incubation (Figure 9).



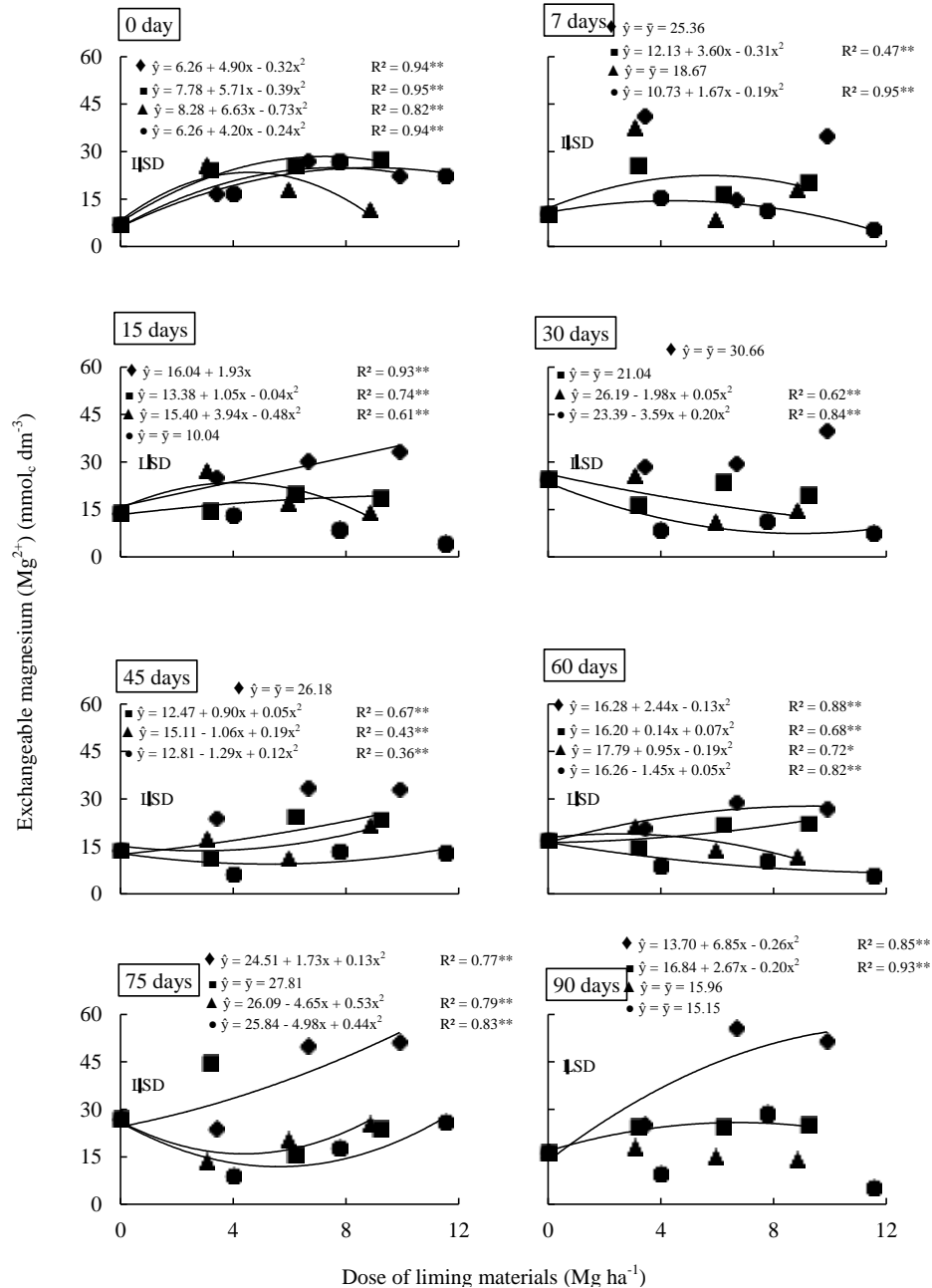
**Figure 1.** Liming materials effects on exchangeable calcium (Ca<sup>2+</sup>) and magnesium (Mg<sup>2+</sup>) concentrations in Typic Distrudept (n = 4 ± standard deviation) at different periods of incubation (90 days) for the control treatment and after application of 50, 70 and 90% dose to increase soil base saturation (DIV). (◆) Dolomitic limestone. (■) Granulated micronized calcite. (▲) Granulated micronized dolomite. (●) Carbonated suspension. Coefficient of variation: 5.2 and 4.5% to Ca and Mg, respectively.

All liming materials (DL, CMG, DMG and SC) increased the exchangeable Mg concentration in soil (Figure 7). However, DL doses of 70 and 90% DIV were more efficient than others in increasing and maintaining

exchangeable Mg concentrations all the time (Figure 10). All liming materials and doses application, generally, resulted in slight increase of exchangeable K and their concentrations were maintained in all the times (Figures



**Figure 3.** Response of Typic Distrudept ( $n = 4$ ) to different doses of liming materials (control treatment and after application of 50, 70 and 90% dose to increase soil base saturation (DIV)) through exchangeable calcium ( $\text{Ca}^{2+}$ ) concentrations at different periods of incubation (days). (◆) Dolomitic limestone. (■) Granulated micronized calcite. (▲) Granulated micronized dolomite. (●) Carbonated suspension. Vertical bars indicate the least significant difference (LSD). \*:  $P < 0.05$ . \*\*:  $P < 0.01$ .



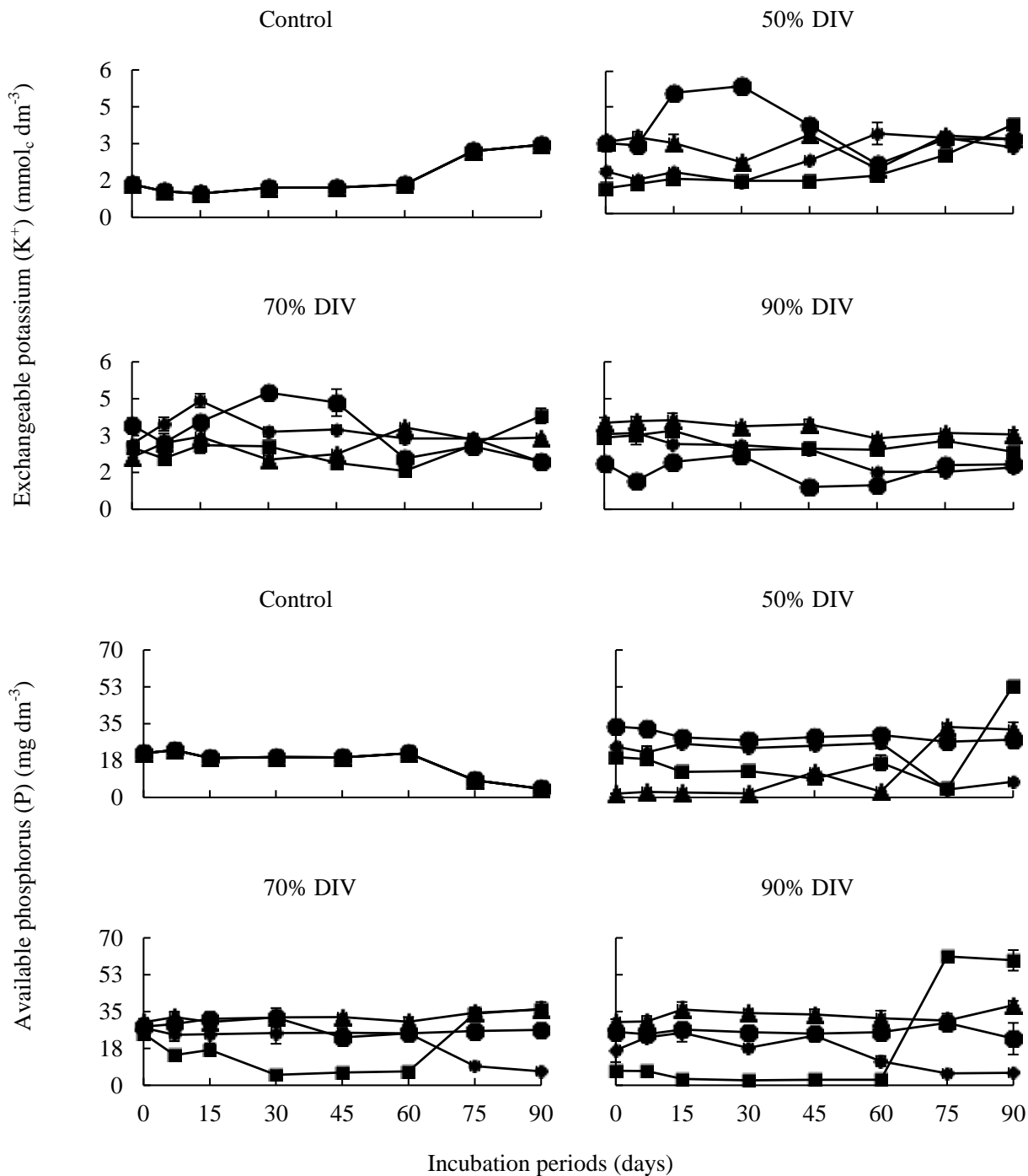
**Figure 4.** Response of Typic Distrudept ( $n = 4$ ) to different doses of liming materials (control treatment and after application of 50, 70 and 90 % dose to increase soil base saturation (DIV)) through exchangeable magnesium ( $Mg^{2+}$ ) concentrations at different periods of incubation (days). (◆) Dolomitic limestone. (■) Granulated micronized calcite. (▲) Granulated micronized dolomite. (●) Carbonated suspension. Vertical bars indicate the least significant difference (LSD). \*:  $P < 0.05$ . \*\*:  $P < 0.01$ .

8 and 11). However, CS at 90% DIV led to little increase of exchangeable K concentrations until 45 days of incubation (Figure 11). Available P concentrations were increased highly by GMC, GMD and CS (in all doses) than DL (Figure 8), mainly after 15 days (Figure 12).

## DISCUSSION

### Liming in Typic Distrudept

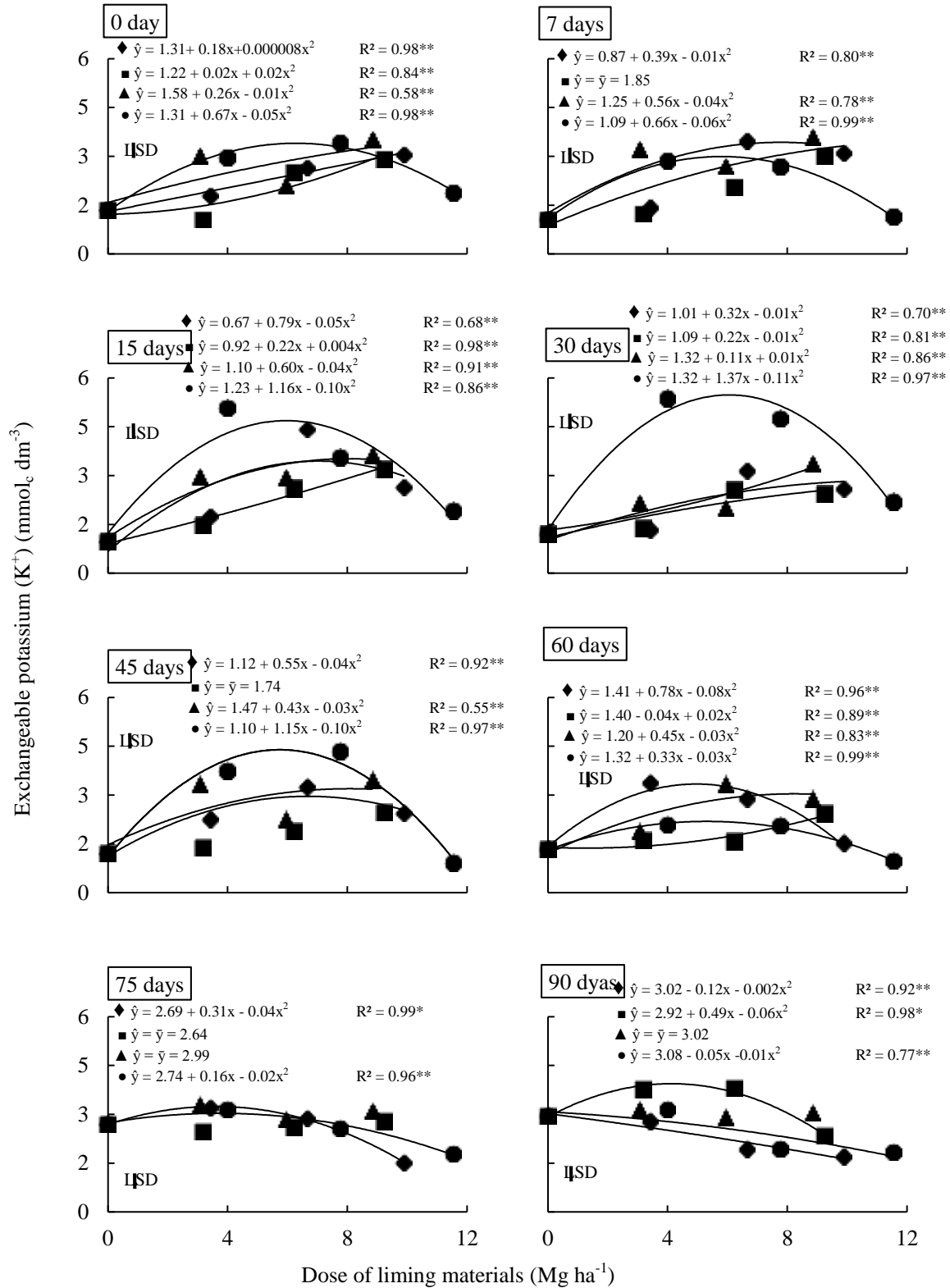
All liming materials increased exchangeable Ca



**Figure 2.** Liming materials effects on exchangeable potassium ( $K^+$ ) and available phosphorus (P) concentrations on a Typic Distrudept ( $n = 4 \pm$  standard deviation) at different periods of incubation (90 days) for the control treatment and after application of 50, 70 and 90% dose to increase soil base saturation (DIV). (♦) Dolomitic limestone. (■) Granulated micronized calcite. (▲) Granulated micronized dolomite. (●) Carbonated suspension. Coefficient of variation: 4.5 and 5.2% to K and P, respectively.

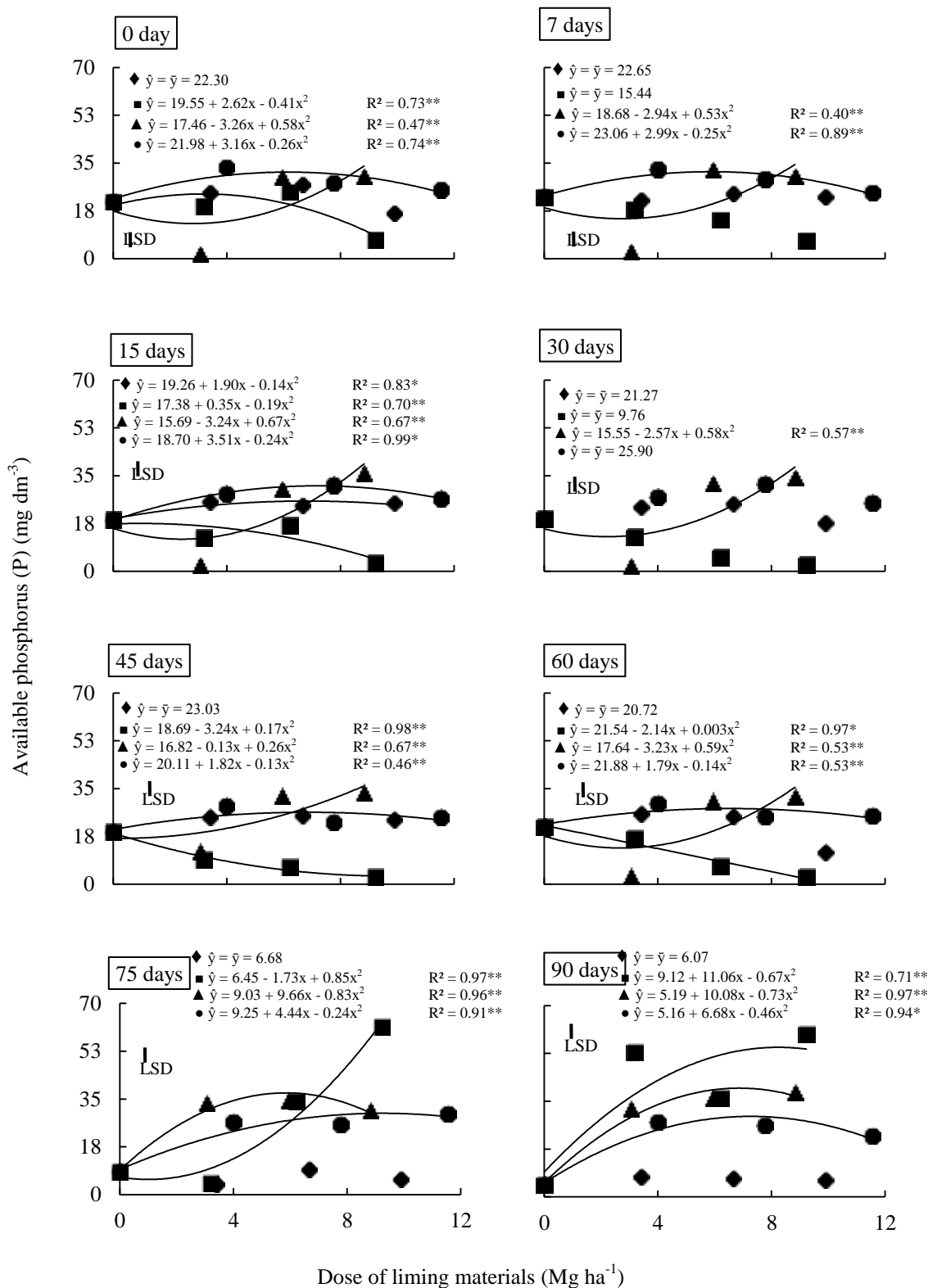
concentration in soil. Oleynik et al. (1998) considered concentrations of Ca above  $40.0 \text{ mmol}_c \text{ dm}^{-3}$  as high level. At the end of 90 days incubation, CS applied at 70

and 90% DIV resulted in higher exchangeable Ca concentration in soil than the others (liming materials and doses). Then, the CS efficiency regarding fast and major

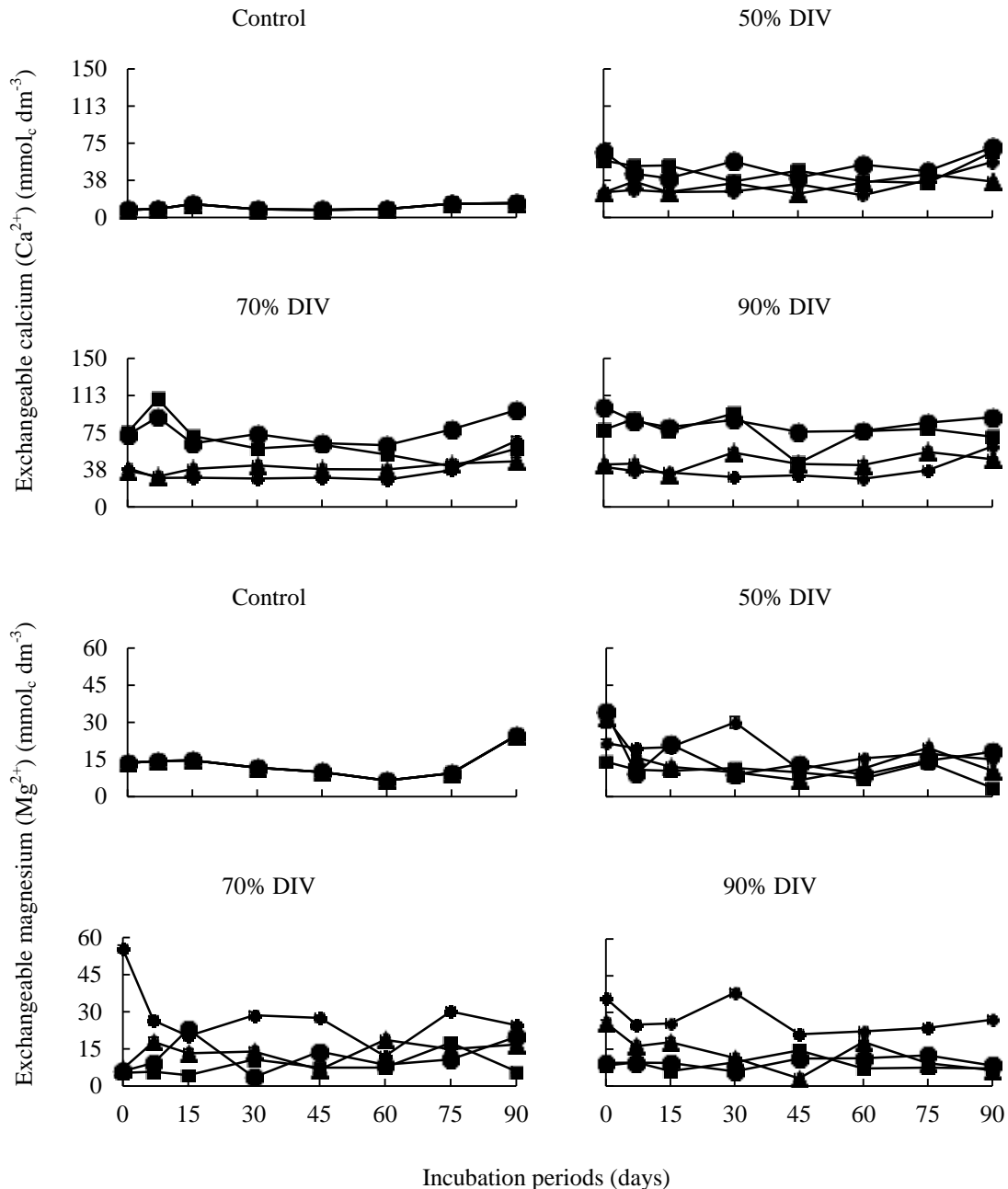


**Figure 5.** Response of Typic Distrudept ( $n = 4$ ) to different doses of liming materials (control treatment and after application of 50, 70 and 90% dose to increase soil base saturation (DIV)) through exchangeable potassium ( $K^+$ ) concentrations at different periods of incubation (days). ( $\blacklozenge$ ) Dolomitic limestone. ( $\blacksquare$ ) Granulated micronized calcite. ( $\blacktriangle$ ) Granulated micronized dolomite. ( $\bullet$ ) Carbonated suspension. Vertical bars indicate the least significant difference (LSD). \*:  $P < 0.05$ . \*\*:  $P < 0.01$ .





**Figure 6.** Response of Typic Distrudept ( $n = 4$ ) to different doses of liming materials (control treatment and after application of 50, 70 and 90% dose to increase soil base saturation (DIV)) through available phosphorus (P) concentrations at different periods of incubation (days). (◆) Dolomitic limestone. (■) Granulated micronized calcite. (▲) Granulated micronized dolomite. (●) Carbonated suspension. Vertical bars indicate the least significant difference (LSD). \*:  $P < 0.05$ . \*\*:  $P < 0.01$ .

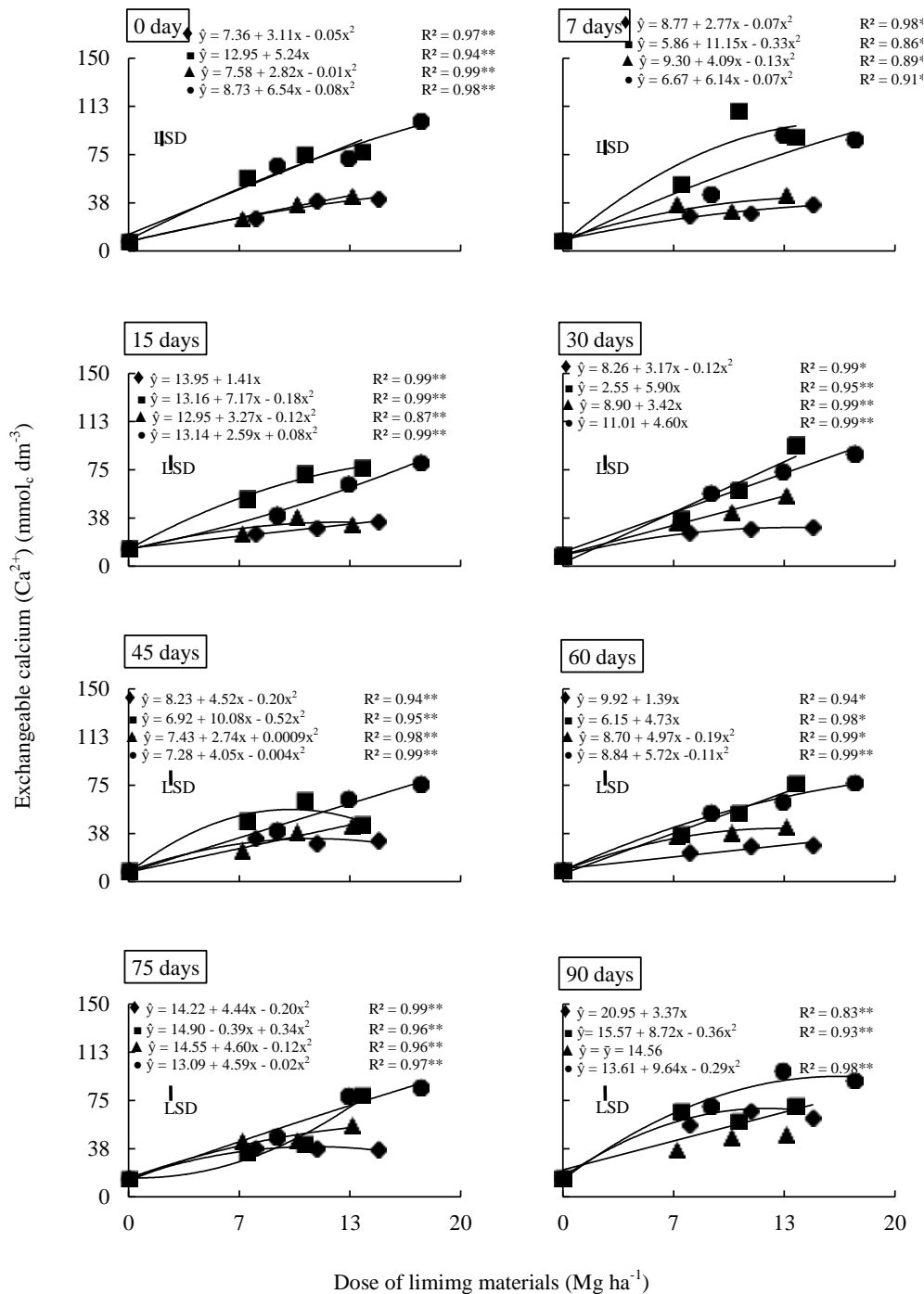


**Figure 7.** Liming materials effects on exchangeable calcium (Ca<sup>2+</sup>) and magnesium (Mg<sup>2+</sup>) concentrations in Rhodic Hapludox ( $n = 4 \pm$  standard deviation) at different periods of incubation (90 days) for the control treatment and after application of 50, 70 and 90 % dose to increase soil base saturation (DIV). (◆) Dolomitic limestone. (■) Granulated micronized calcite. (▲) Granulated micronized dolomite. (●) Carbonated suspension. Coefficient of variation: 6.0 and 2.9% to Ca and Mg, respectively.

soil Ca availability can be due to the following factors: finer particle size (in order  $< 7.0 \mu\text{m}$ ), higher SSA ( $1559.0 \text{ m}^2 \text{ kg}^{-1}$ ) and higher CaO content ( $361.1 \text{ g kg}^{-1}$  of CaO).

DL applied at 90% DIV increased the exchangeable Mg concentration from 9.3 (soil initial condition) to  $36.7 \text{ mmol}_c \text{ dm}^{-3}$  (at the end of the experimental period of 90

days). The high efficiency of DL in MgO concentration increase could be due to its higher content of MgO ( $257.6 \text{ g kg}^{-1}$ ) than other liming materials. In fact, Mg could have been released from DL during the incubation period (Alcarde, 2005). However, these increases had few practical implications because exchangeable Mg

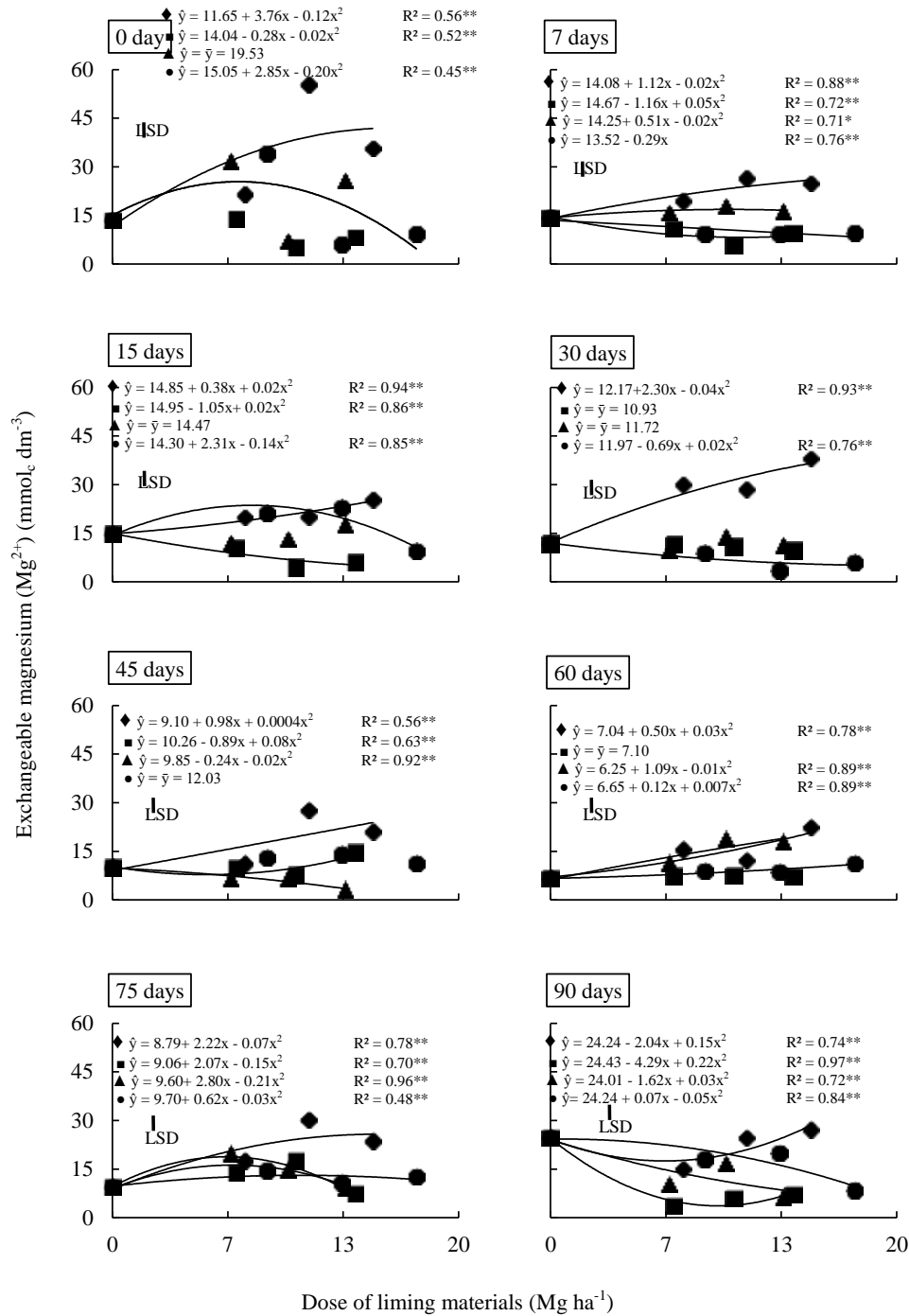


**Figure 9.** Response of Rhodic Hapludox ( $n = 4$ ) to different doses of liming materials (control treatment and after application of 50, 70 and 90% dose to increase soil base saturation (DIV)) through exchangeable calcium ( $\text{Ca}^{2+}$ ) concentrations at different periods of incubation (days). (◆) Dolomitic limestone. (■) Granulated micronized calcite. (▲) Granulated micronized dolomite. (●) Carbonated suspension. Vertical bars indicate the least significant difference (LSD). \*:  $P < 0.05$ . \*\*:  $P < 0.01$ .

concentrations higher than  $8.0 \text{ mmol}_c \text{dm}^{-3}$  has been considered to be sufficiently high level (Oleynik et al.,

1998).

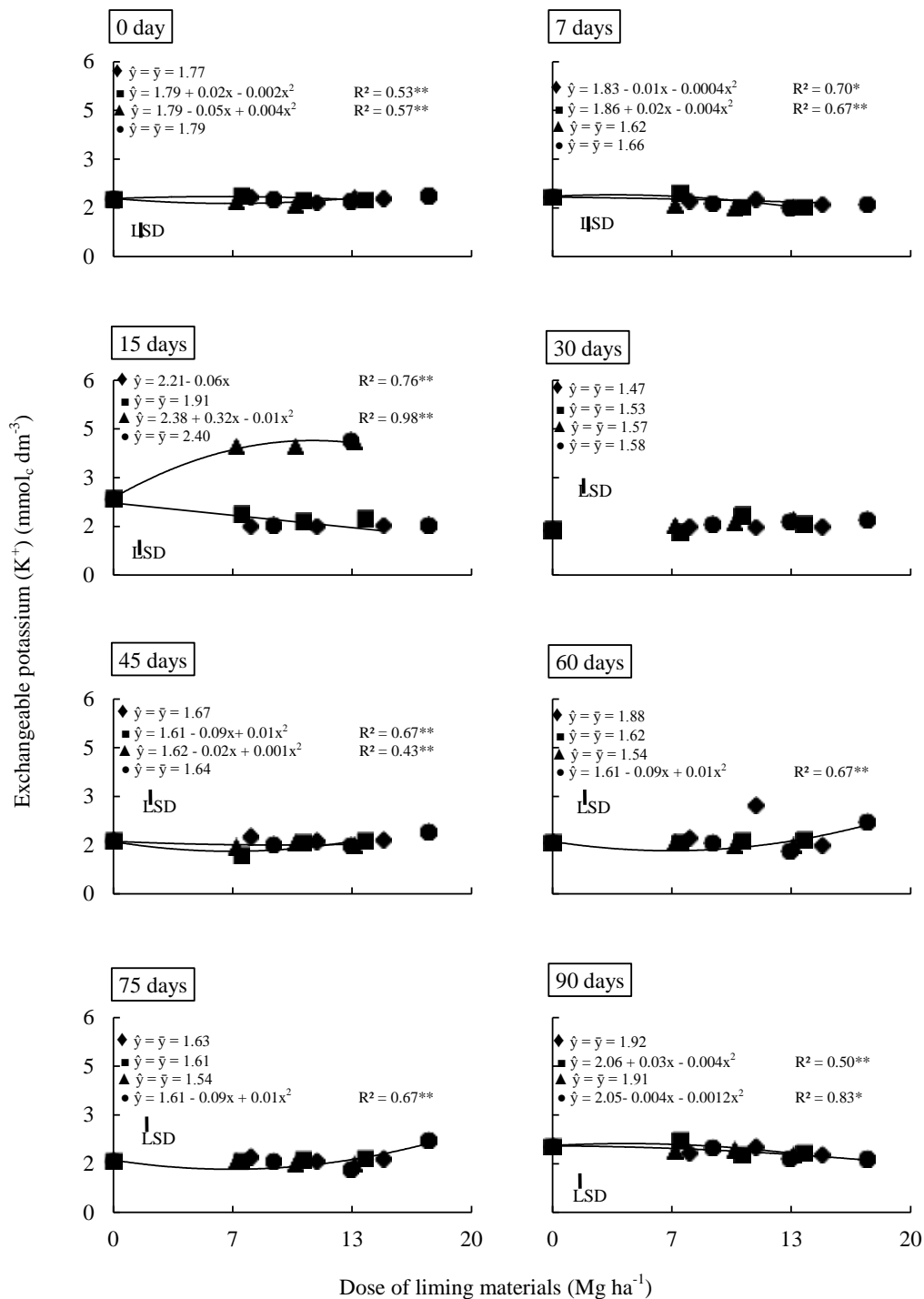
The exchangeable K concentrations after liming



**Figure 101.** Response of Rhodic Hapludox ( $n = 4$ ) to different doses of liming materials (control treatment and after application of 50, 70 and 90% dose to increase soil base saturation (DIV)) through exchangeable magnesium ( $Mg^{2+}$ ) concentrations at different periods of incubation (days). (◆) Dolomitic limestone. (■) Granulated micronized calcite. (▲) Granulated micronized dolomite. (●) Carbonated suspension. Vertical bars indicate the least significant difference (LSD). \*:  $P < 0.05$ . \*\*:  $P < 0.01$ .

material application had few changes together with time. These changes in exchangeable K concentrations can be

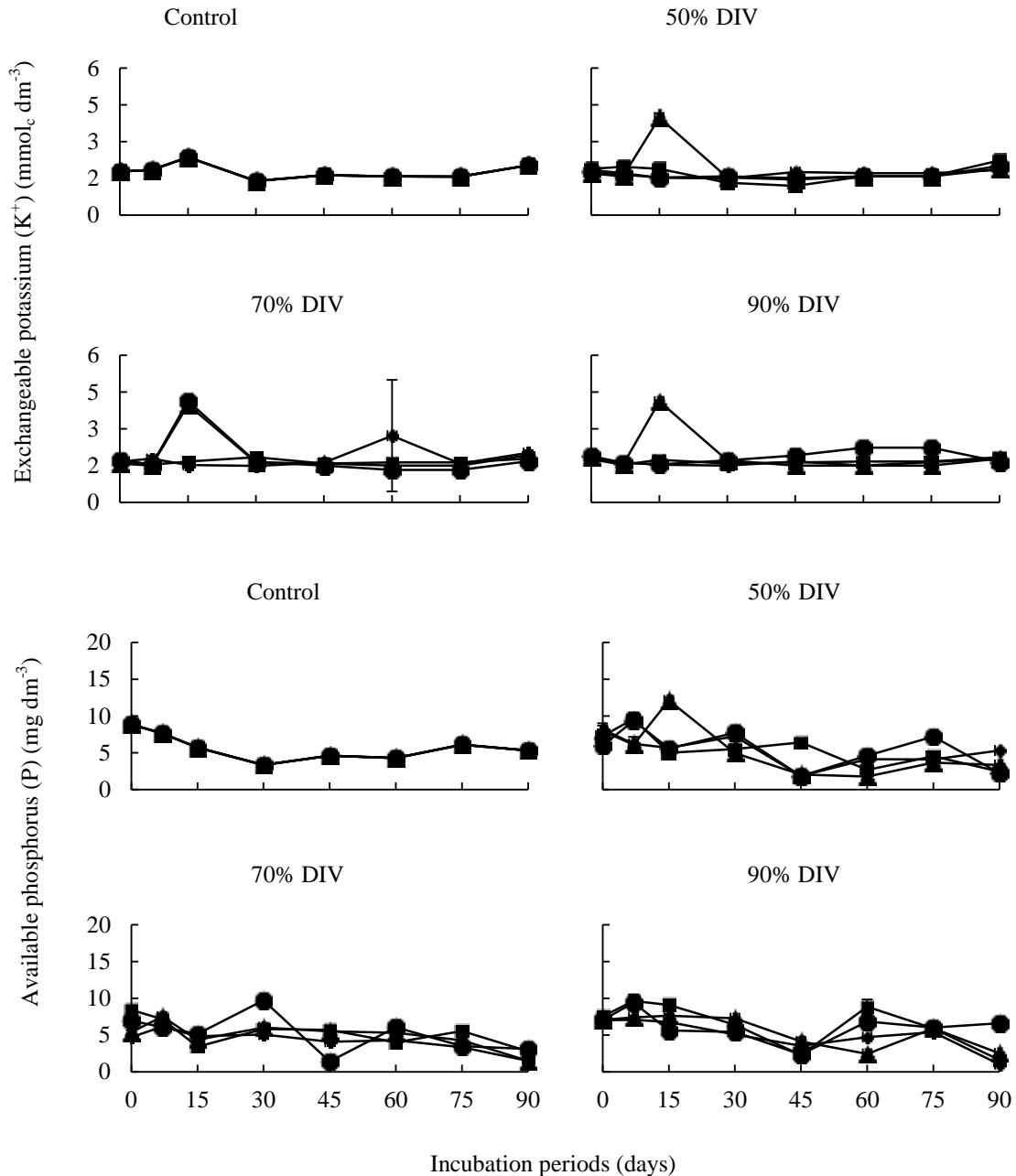
ascribed to soil pH increase (Malavolta, 2006). Besides, the high Ca and Mg concentrations in soil can increase



**Figure 11.** Response of Rhodic Hapludox ( $n = 4$ ) to different doses of liming materials (control treatment and after application of 50, 70 and 90 % dose to increase soil base saturation (DIV)) through exchangeable potassium ( $K^+$ ) concentrations at different periods of incubation (days). (◆) Dolomitic limestone. (■) Granulated micronized calcite. (▲) Granulated micronized dolomite. (●) Carbonated suspension. Vertical bars indicate the least significant difference (LSD). \*:  $P < 0.05$ . \*\*:  $P < 0.01$ .

desorption and availability of soil K (Havlin et al., 2014).

However, these exchangeable K concentrations normally

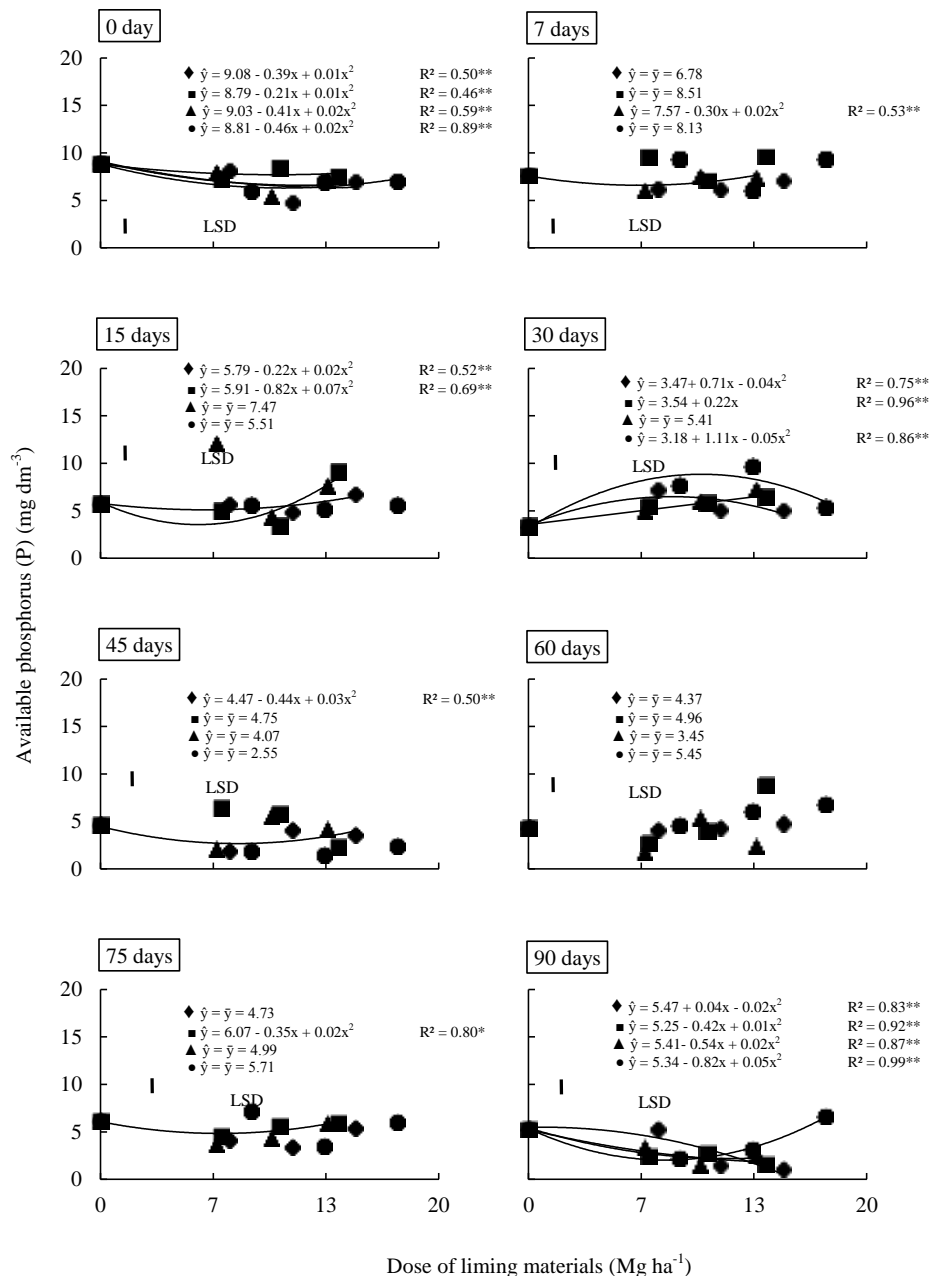


**Figure 8.** Liming materials effects on exchangeable potassium ( $K^+$ ) and available phosphorus (P) concentrations in Rhodic Hapludox ( $n = 4 \pm$  standard deviation) at different periods of incubation (90 days) for the control treatment and after application of 50, 70 and 90% dose to increase soil base saturation (DIV). (◆) Dolomitic limestone. (■) Granulated micronized calcite. (▲) Granulated micronized dolomite. (●) Carbonated suspension. Coefficient of variation: 12.6 and 3.7% to K and P, respectively.

vary in the medium sufficient levels (between 1.1 and 3.0 mmol<sub>c</sub> dm<sup>-3</sup>) required for grain (maize) crops (Oliveira, 2003).

Changes in available P concentrations were also consequence of soil pH increase due to special liming materials application. The special liming materials

increased pH values in short-term (up to 90 days). That could have resulted in the release of adsorbed phosphates and increased this availability (Barrow, 1985). However, these available P concentrations changed in the high sufficient level (between 9.1 and 36.0 mg dm<sup>-3</sup>) required for grain (maize) cropped in soils with



**Figure 12.** Response of Rhodic Hapludox ( $n = 4$ ) to different doses of liming materials (control treatment and after application of 50, 70 and 90 % dose to increase soil base saturation (DIV)) through available phosphorus (P) concentrations at different periods of incubation (days). (◆) Dolomitic limestone. (▲) Granulated micronized calcite. (■) Granulated micronized dolomite. (●) Carbonated suspension. Vertical bars indicate the least significant difference (LSD). \*:  $P < 0.05$ . \*\*:  $P < 0.01$ .

clay concentrations below 360 g kg<sup>-1</sup> (Oliveira, 2003).

### Liming in Rhodic Hapludox

At the beginning of the experiment, the exchangeable Ca

concentration was 6.0 mmol<sub>c</sub> dm<sup>-3</sup> as considered by Oleynik et al. (1998) to be low sufficient level (< 20.0 mmol<sub>c</sub> dm<sup>-3</sup>). At the end of the experiment, soil samples treated with liming material (DL, CMG, DMG and CS), increased the exchangeable Ca concentrations in the soil (Figure 7) to high sufficient level (> 40.0 mmol<sub>c</sub> dm<sup>-3</sup>)

(Oleynik et al., 1998) varying from 24.03 to 109.00 mmol<sub>c</sub> dm<sup>-3</sup>. However, the CS can be an important source of Ca for production systems and makes them similar (Fraser and Scott, 2011; Oliveira et al., 2014) or superior (as observed in this study) to commercial limestone used for liming purposes.

Particularly, exchangeable Mg concentrations were increased from medium sufficient level (7.0 mmol<sub>c</sub> dm<sup>-3</sup>) to high sufficient level (> 8.0 mmol<sub>c</sub> dm<sup>-3</sup>) according to the scale of Oleynik et al. (1998). DL was reported to be effective material to increase exchangeable Mg concentrations (Hou et al., 2012) because of its higher higher MgO concentration of 257.6 g kg<sup>-1</sup>.

The changes in exchangeable K concentrations can be ascribed to the increases of the pH, Ca and Mg concentrations that favored the soil K solubility (Malavolta, 2006) and release (Havlin et al., 2014). Exchangeable K concentrations [between 1.1 and 3.0 mmol<sub>c</sub> dm<sup>-3</sup> required for grain (maize) crops (Oliveira, 2003)] were in the medium sufficient level and good as per grain (maize) crops (Oliveira, 2003).

The soil pH increased (from around 4.0 to 6.5) in short period of 90 days because of the treatments. That can have resulted in more P desorption (Silva et al., 2000; Motta et al., 2002) and/or labile-P (Calegari et al., 2013) concentrations, widely seen in others clayed soils (Raij, 2011). In addition, the available P concentrations were along the time increased from low of 1.6 mg dm<sup>-3</sup> to high sufficient levels varying from 4.6 to 11.0 mg dm<sup>-3</sup>. Thus, through the available P increase, liming could contribute efficiently to the cultivation of cereals crop (maize) in soils with clay concentrations above 360 g kg<sup>-1</sup> (Oliveira, 2003).

Therefore, it can be concluded that all the liming materials increased exchangeable Ca and Mg, and available P concentrations in soils with variable charges (Typic Distrudept and Rhodic Hapludox). The application of liming materials (except GMD) at the dose of 70% DIV was efficient to promote this increase of available nutrients. The DL was efficient to improve exchangeable Ca and Mg concentrations in soils with variable charge. However, CS followed by GMC were more efficient than DL regarding exchangeable Ca increases in both soils.

### Conflict of Interests

The authors have not declared any conflict of interests.

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