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# CORN RESPONSE TO PHOSPHOGYPSUM, BASE SATURATION AND LIME APPLICATION METHOD

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**ABSTRACT -** the lime (L) and phosphogypsum (G) promote changes in the chemical attributes of the soil that can alter the development of corn. The objective was to evaluate morphological and yield components of corn after liming and G and to correlate them with yield. The treatments consisted of a 2 x 4 + 3 factorial, with two methods of application of L: surface (SL) and incorporated (IL) to obtain different levels of base saturation (BS): 44, 60, 70 and 90%. Three additional treatments were evaluated involving the use of L and G applied on the surface, being: BS 60% + 3.71 Mg ha$^{-1}$ of G (60G50); BS 70% + 3.71 Mg ha$^{-1}$ of G (70G50) and BS 70% + 7.42 Mg ha$^{-1}$ of G (70G100). Plant height (PH), ear insertion height (EIH) and stem diameter (SD) were not influenced by the treatments. The SL increased the length of the ear (LE), number of grains per row (NGR) and mass of a thousand grains (TMG) up to BS of 72, 80 and 72%, respectively. Thus, there were no advantages of higher base saturation (BS 90%). The combination of L and G promoted improvements in ear diameter (ED), NGF, LE, TMG. The yield in IL was 445 kg ha$^{-1}$ higher than SL, however when combining G and L the production increased 6 to 12% in relation to BS 44% SL. BS% levels in IL did not influence any response variable. Grain yield was positively correlated to ED, TMG, LE and PH.

**Keywords**: *Zea mays* L., yield components, soil acidity, correlation.

# *RESPOSTA DO MILHO AO GESSO AGRÍCOLA, SATURAÇÃO POR BASES E MODO DE APLICAÇÃO DE CALCÁRIO*

**RESUMO -** o calcário (C) e gesso agrícola (G) promovem alterações nos atributos químicos do solo que podem alterar o desenvolvimento do milho. O objetivo foi avaliar componentes morfológicos e de produtividade de milho após calagem e gessagem e correlacioná-los com a produtividade. Os tratamentos consistiram num fatorial 2 x 4 + 3, sendo duas formas de aplicação de C: superficial (CS) e incorporado (CI) para obter diferentes níveis de saturação por bases (V%): 44, 60, 70 e 90. Três tratamentos adicionais envolvendo uso de C e G aplicados em superfície foram avaliados, sendo: V 60% + 3,71 Mg ha$^{-1}$ de G (60G50); V 70% + 3,71 Mg ha$^{-1}$ de G (70G50) e V 70% + 7,42 Mg ha$^{-1}$ de G (70G100). Altura de planta (AP), altura de inserção da espiga (AIE) e diâmetro do colmo (DC) não foram influenciadas pelos tratamentos. A CS aumentou o comprimento da espiga (CE), número de grãos por fileira (GF) e massa de mil grãos (MMG) até V de 72, 80 e 72%, respectivamente. Assim, não houve vantagens de saturação por bases mais elevadas (V 90%). A combinação de C e G promoveram incrementos no diâmetro da espiga (DE), GF, CE, MMG. A produtividade em CI foi 445 kg ha$^{-1}$ maior que CS, porém ao combinar G e C a produção aumentou 6 a 12% em relação a V 44% em CS. Os níveis de V% em CI não influenciaram nenhuma variável resposta. A produtividade de grãos se correlacionou positivamente com DE, MMG, CE e AP.

**Palavras-chave**: *Zea mays* L., componentes de rendimento, acidez do solo, correlação.

## INTRODUCTION

Corn is the second culture of greater agricultural importance in Brazil, being overcome only by soybeans that leads grain production. Although the country stands out globally as an agricultural power, only 7.8% of the territorial area is cultivated with crops (MIRANDA, 2018). Of this amount, 4,104 and 12,878 million hectares were allocated to the cultivation of growing season and second growing season corn, respectively (CONAB, 2020).

In addition to the use in human food and growing use in the production of ethanol, corn is the basis for pig and poultry feeding in Brazil. However, when considering the total corn production, there is a great variation between the producing regions, with the national average of only 5,599 kg ha$^{-1}$ (CONAB, 2020). Therefore, the adoption of systems that present greater production efficiency is essential to increase the competitiveness of the culture and consequently the profitability to the producer (BESEN et al., 2020).

The achievement of higher yield has been limited by the occurrence of climatic adversities. In this sense, soil management must be strategic to enable conditions favorable to the development of corn. However, about

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70% of all agricultural land in Brazil is naturally acidic (CRUSCIOL et al., 2017), limiting root growth and consequently water and nutrient absorption (NEPAR/SBCS, 2019), making plants more vulnerable to biotic and abiotic factors limiting plant growth.

Acid soils have low levels of calcium ($Ca^{2+}$) and magnesium ($Mg^{2+}$) and high levels of exchangeable aluminum ($Al^{3+}$), which is toxic to plants. The most common solution used to correct soil acidity in Brazil is the use of lime, due to its low cost (CASTRO et al., 2016) and wide availability. The increase in pH, and in the levels of $Ca^{2+}$ and $Mg^{2+}$, provided by liming together with the neutralization of toxic $Al^{3+}$, provide adequate conditions for plant development (CASSOL et al., 2019). Although limestone consumption grew 16% between 2017 and 2018, its use is still low and should be double the current (ABRACAL, 2019).

With the strong advance of no-till from the '90s, the application of lime began to be carried out superficially without incorporation. However, lime is poorly soluble and its dissociated components have limited mobility, therefore, liming effects are generally restricted to the soil surface (CAIRES et al., 2006; SORATTO; CRUSCIOL, 2008).

In order to improve chemical conditions in the subsurface, phosphogypsum ($CaSO_4.2H_2O$) appears as an alternative in areas managed under no-tillage. Phosphogypsum is a by-product of phosphoric acid production; it is a source of Ca and sulfur (S) and about 200 times more soluble in water than lime (CABRERA, 2009). Its greater solubility favors the movement of $Ca^{2+}$ and the displacement of $S\text{-}SO_4^{2-}$ along the soil profile (PAULETTI et al., 2014). Caires et al. (1998) observed that the application of phosphogypsum caused a reduction in the levels of exchangeable aluminum and increased the levels of calcium throughout the soil profile.

Recently it has been realized that modern hybrids are more responsive to lime and less tolerant to aluminum than traditional ones (DALLA NORA et al., 2017). Therefore, high doses of lime and consequently higher levels of base saturation (BS%) can be advantageous, however they lack information. Also, according to Dalla Nora et al. (2017) the positive effect of phosphogypsum is increased when combined with lime.

Most studies involving the application of soil conditioners and concealers emphasize only the yield and/or production of dry matter, associated with nutritional status, and other components of the plant have not been properly evaluated, restricting important information on the development of corn. Consequently, little is known about which of the production components is positively influenced by liming and phosphogypsum application and explain the increase in grain yields. Grain yield is a complex character resulting from the expression and association of different components, and is therefore affected by almost all other characters of the plant (SOUZA et al., 2014).

Souza et al. (2014) studying the relationship between yield components and corn morphological characteristics observed that the weight of 100 grains was the yield component that had the greatest direct effect on grain production and among the morphological components, the ear height was the most influential in the variation of yield, being, therefore, the secondary component of greater relevance. Besen et al. (2019) observed that corn yield was not only associated with yield components, but also with the height of the ear insertion and stem diameter.

There is little information on the effect of liming and phosphogypsum application on the yield and biometric components of corn and its relationship with yield in Brazilian subtropical conditions. Thus, the hypothesis of this work is that the way of applying lime; level of base saturation and the use of phosphogypsum alter the biometric and yield components of corn, and these are associated with grain yield. The objective of the present work was to evaluate the influence of levels of base saturation through liming in different methods of application associated with the use of phosphogypsum, as well as the correlation between the variables in a Red Latosol under subtropical climate conditions.

## MATERIAL AND METHODS

The experiment was installed in 2012 at the experimental farm of the Cooperativa Agroindustrial Mourãoense (COAMO), located in Campo Mourão (PR), under geographical coordinates of 24º05'28" S, 52º21'31" W. According to Köppen's classification, the climate in this region it is classified as Cfa, humid temperate with hot summer, presenting average annual temperature of 20 to 2°C, with annual precipitation varying from 1600 to 1800 mm.

The precipitation data during the experiment are shown in Figure 1. The climatic conditions were favorable to the development of corn with accumulated precipitation of 853 mm and well distributed, where 650 mm already meet the water requirement of the medium cycle hybrids (BERGAMASCHI et al., 2001). The soil of the area was classified as dystrophic Red Latosol (SANTOS et al., 2018), with a very clayey texture (740 g $kg^{-1}$ of clay). The chemical characterization revealed the attributes at the depth of 0.00-0.20 m and 0.20-0.40 m, respectively: pH $CaCl_2$ = 5.25 and 4.96; P (mg $dm^{-3}$) = 20.7 and 6.50; $K^+$ ($cmol_c$ $dm^{-3}$) = 0.50 and 0.37; $Ca^{2+}$ ($cmol_c$ $dm^{-3}$) = 3.82 and 2.37; $Mg^{2+}$ ($cmol_c$ $dm^{-3}$) = 0.81 and 0.54; H + Al ($cmol_c$ $dm^{-3}$) = 5.28 and 5.61; $Al^{3+}$ ($cmol_c$ $dm^{-3}$) = 0.0 and 0.0; base saturation (BS%) = 50 and 37 and organic carbon (g $dm^{-3}$) = 25.05 and 21.51.

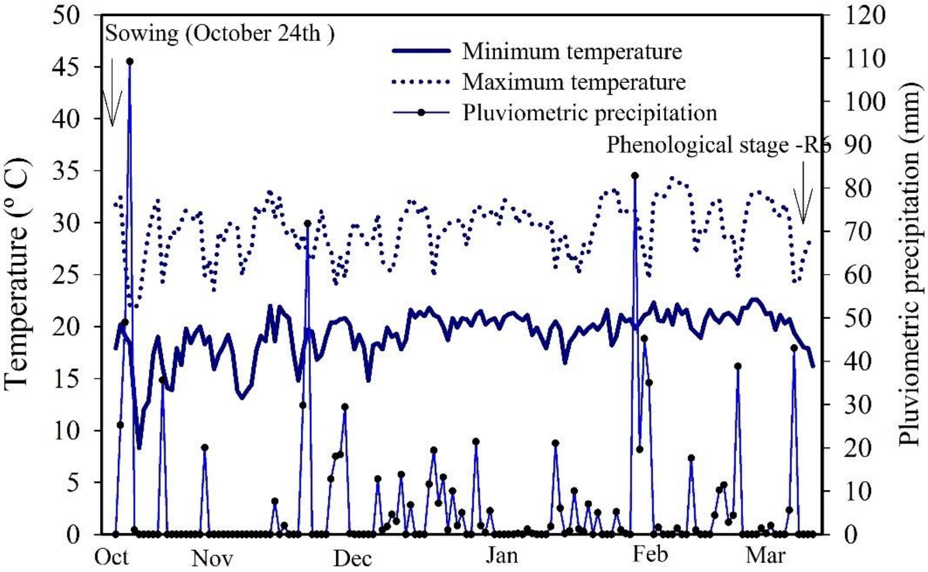

**FIGURE 1** - Maximum temperature, minimum temperature and precipitation data for the period from October 2016 to March 2017, referring to the experiment carried out in Campo Mourão - PR.

The experimental design used was complete blocks, with randomized treatments, in a factorial scheme 2 x 4 + 3 with 2 forms of application of lime, being: superficial (SL) and incorporated (IL) x 4 desired levels of base saturation (BS%), corresponding to 44 (natural), 60, 70 and 90%. Three additional treatments were evaluated involving the use of lime and phosphogypsum (G) applied on the surface, being: V 60% + 3.71 Mg ha$^{-1}$ of G (60G50); V 70% + 3.71 Mg ha$^{-1}$ of G (70G50) and V 70% + 7.42 Mg ha$^{-1}$ of G (70G100)], containing 4 repetitions. The dose of phosphogypsum (NG) of 3.71 Mg ha$^{-1}$ was calculated according to the clay content, according to the formula: NG = 50 x clay (%), proposed by Souza et al. (2005). The highest dose of phosphogypsum of evaluating twice the recommended dose: NG = 100 x clay (%).

The first application of lime and phosphogypsum was carried out in May 2012 and reapplied in June 2016. The doses of phosphogypsum and lime applied in each year and treatment can be seen in detail in Table 1. Between the years 2012 to 2016, 4 soybean crops were grown in the spring/summer season and 4 wheat crops in the autumn/winter season, under no-tillage system. For the reapplication of treatments in June 2016, samples of soil were made in order to determine the doses of lime and phosphogypsum to be applied in each treatment. In lime reapplication in 2016, dolomitic lime with 80% relative power total neutralization (RPTN) was used.

The definition of lime doses on both occasions followed the method based on the elevation of base saturation, which has as a principle the relationship between pH and soil base saturation (NEPAR/SBCS, 2019). To define the liming requirement (LN) by the proposed method, it was necessary to determine the potential acidity (H+Al), calculus of the sum of bases (SB = $Ca^{2+}$ + $Mg^{2+}$ + $K^{+}$), from CEC to $pH_7$ of the soil (CEC = BS + H+Al) and base saturation (BS% = SB x CEC/100).

With this information, the LN was determined by the formula:

$$\frac{\mathrm{LN}\ (\mathrm{Mg\ ha^{-1}}) = [(BS_2 - BS_1) \times \mathrm{CEC}]}{RPTN}$$

On what:
BS1 = saturation by initial soil base,
BS2 = saturation by desired base (60, 70 and 90%),
CEC = cation exchange capacity at pH = 7 and
RPTN = relative power of total neutralization

The lime incorporation on both occasions was carried out by means of a double-sided moldboard plow with an effective depth of incorporation of 0.00-0.20 m, followed by a disc harrow containing 20 discs of 28” and subsequently a light harrow with grid containing 20” discs in order to level the soil. For superficial liming treatments, lime was applied manually to the soil surface, without incorporation. Each experimental unit was 12 m long and 7 m wide, with a total of 84 m² experimental units.

The hybrid corn 30F53VYHR was sown on October 24, 2016 (134 days after application of lime and phosphogypsum) in succession to the wheat, with seeding fertilization of 300 kg ha$^{-1}$ of the formulated NPK 12-18-12. Nitrogen cover fertilization was carried out between the V4 stages of the crop, applying 180 kg ha$^{-1}$, using urea with urease inhibitor (NBPT) as a source of N (Super N®). Cultural treatments followed technical recommendations for the region.

The morphological components of corn plants were evaluated at the phenological stage of grain meal (R5), as presented by Besen et al. (2019), in 10 plants in the useful area of the plot, in which the plant height (PH), stem diameter (SD) and insertion height of the main ear (IHE) were determined. The production components were evaluated at the physiological maturation stage of the plants (R6), in which the ear length (EL), number of rows per ear (NRE), number of grains per row (NGR) were determined. The ear diameter (ED) was measured in the middle of the ear, with the aid of a digital caliper. For these estimates, 10 ears of corn collected at random in the useful area of the plot were used. Also, at the stage of physiological maturation (R6), the mass of a thousand grains (TGM) and the yield, which had the humidity corrected at 13%, were evaluated.

**TABLE 1 -** Chemical characterization of 2016 (4 years after the first application of lime and phosphogypsum) used to define the reapplication doses.

| Treatments | Depth (cm) | pH ($CaCl_2$) | ---------------cmol$_c$ dm$^{-3}$--------------- | | | | | ---mg dm$^{-3}$--- | | Doses of Lime (Mg ha$^{-1}$) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | $Al^{3+}$ | $Ca^{2+}$ | $Mg^{2+}$ | $K^+$ | CEC | $SO_4^{2-}$ | P | 2012 | 2016 | Total |
| BS 44% IL | 0.00-0.20 | 4.97 | 0.08 | 2.86 | 0.58 | 0.39 | 9.18 | 4.87 | 22.81 | - | - | - |
| | 0.20-0.40 | 4.75 | 0.14 | 2.04 | 0.39 | 0.28 | 8.67 | 4.95 | 7.91 | | | |
| BS 60% IL | 0.00-0.20 | 4.79 | 0.15 | 2.73 | 0.63 | 0.23 | 9.14 | 4.96 | 23.55 | 1.50 | 2.30 | 3.80 |
| | 0.20-0.40 | 4.82 | 0.12 | 2.14 | 0.51 | 0.20 | 8.00 | 4.68 | 7.14 | | | |
| BS 70% LI | 0.00-0.20 | 5.08 | 0.00 | 3.24 | 0.88 | 0.29 | 9.02 | 4.95 | 21.37 | 2.90 | 2.30 | 5.20 |
| | 0.20-0.40 | 5.23 | 0.00 | 2.78 | 0.70 | 0.25 | 8.17 | 3.97 | 10.26 | | | |
| BS 90% IL | 0.00-0.20 | 5.07 | 0.00 | 3.03 | 0.99 | 0.30 | 9.87 | 4.91 | 20.88 | 5.50 | 5.60 | 11.10 |
| | 0.20-0.40 | 4.84 | 0.10 | 2.30 | 0.74 | 0.25 | 8.25 | 5.39 | 7.80 | | | |
| BS 44% SL | 0.00-0.20 | 5.00 | 0.04 | 3.52 | 0.74 | 0.26 | 9.67 | 5.10 | 21.38 | - | - | - |
| | 0.20-0.40 | 4.74 | 0.19 | 2.12 | 0.41 | 0.20 | 7.88 | 5.13 | 5.08 | | | |
| BS 60% SL | 0.00-0.20 | 5.16 | 0.00 | 3.47 | 0.90 | 0.26 | 9.59 | 5.07 | 30.06 | 1.50 | 1.40 | 2.90 |
| | 0.20-0.40 | 4.92 | 0.08 | 2.14 | 0.56 | 0.19 | 7.67 | 4.53 | 8.02 | | | |
| BS 70% SL | 0.00-0.20 | 5.24 | 0.00 | 3.11 | 1.00 | 0.24 | 8.63 | 5.05 | 13.73 | 2.90 | 2.10 | 5.00 |
| | 0.20-0.40 | 5.14 | 0.00 | 2.55 | 0.77 | 0.22 | 7.98 | 4.59 | 6.12 | | | |
| BS 90% SL | 0.00-0.20 | 5.41 | 0.00 | 3.57 | 1.46 | 0.21 | 9.52 | 4.79 | 22.44 | 5.50 | 4.10 | 9.60 |
| | 0.20-0.40 | 4.80 | 0.15 | 2.04 | 0.73 | 0.18 | 8.10 | 7.29 | 8.67 | | | |
| BS 60% + G50 | 0.00-0.20 | 5.29 | 0.00 | 4.11 | 0.86 | 0.26 | 9.51 | 5.39 | 23.18 | 1.50 | 0.60 | 2.10 |
| | 0.20-0.40 | 4.97 | 0.03 | 2.40 | 0.45 | 0.20 | 7.66 | 5.23 | 5.68 | | | |
| BS 70% + G50 | 0.00-0.20 | 5.00 | 0.03 | 3.09 | 0.70 | 0.19 | 8.59 | 4.87 | 26.74 | 2.90 | 2.50 | 5.40 |
| | 0.20-0.40 | 4.60 | 0.30 | 1.71 | 0.34 | 0.15 | 7.55 | 6.40 | 5.39 | | | |
| BS 70% + G100 | 0.00-0.20 | 5.06 | 0.00 | 3.16 | 0.65 | 0.19 | 8.96 | 5.98 | 34.34 | 5.50 | 2.80 | 5.70 |
| | 0.20-0.40 | 4.75 | 0.22 | 2.01 | 0.31 | 0.14 | 7.81 | 5.76 | 7.14 | | | |

IL = incorporated liming, SL = surface liming, G = phosphogypsum, CEC = cation exchange capacity at $pH_7$, D. = depth, G50 and G100 = dose of phosphogypsum of 3.71 and 7.42 Mg ha$^{-1}$, respectively.

The data were submitted to homogeneity of variance (Bartlett) and error normality (Shapiro Wilk) tests, thus meeting the basic assumptions of analysis of variance (ANOVA). Subsequently, they were subjected to anova by the Snedecor F test at 5% probability. Regardless of the significance of the F test in the interactions, partitioning was performed. The average of additional treatments (lime + phosphogypsum) was compared using the Tukey test, with at 5% probability of error. For the comparison between factorial treatments (2 x 4, lime application mode and BS%) with the additional treatments, the Dunnett test was used, with at 5% probability of error. The analyses were performed in the Sisvar statistical program (FERREIRA, 2011). Among the biometric, yield and yield components, Pearson's correlation analysis was performed using the software R 3.6.3 (R Development Core Team).

## RESULTS AND DISCUSSION

The treatments did not influence the morphological components SD, PH and EIH, presenting average values of 23.17 mm, 251.17 cm and 139.19 cm, respectively (Table 2). However, yield and production components were influenced by the application of lime and phosphogypsum (Figures 2 and 3), except for the number of RE (Table 2).

The results obtained differ from Caires et al. (2002), who observed that the PH of corn increased in a quadratic way, with the application of doses of dolomitic lime, the highest values being found in the dose of 3.5 Mg ha$^{-1}$. In a study by Andreotti et al. (2001), with three levels of base saturation (15.50 and 70%), associated with Zn doses, an increase in PH was also observed with the application of lime in three evaluated crops. In both cases, the acidity was higher than in the present study.

**TABLE 2 -** Plant height (PH), ear insertion height (EIH), stem diameter (SD) and number of rows per ear (NRE), depending on different levels of base saturation (BS%) by liming on the surface (SL) and incorporated (IL).

| Treatments | PH | EIH | SD | NRE |
|---|---|---|---|---|
| | -------cm-------- | | ---mm--- | |
| BS 44% SL | $249.27^{ns*}$ | $139.18^{ns}$ | $23.17^{ns}$ | $15.80^{ns}$ |
| BS 60% SL | 252.08 | 140.67 | 22.90 | 15.50 |
| BS 70% SL | 250.75 | 137.43 | 23.06 | 16.30 |
| BS 90% SL | 251.23 | 139.62 | 22.96 | 15.70 |
| BS 44% IL | 251.72 | 139.84 | 22.59 | 16.20 |
| BS 60% IL | 250.15 | 138.09 | 23.25 | 15.50 |
| BS 70% IL | 251.22 | 139.73 | 23.98 | 15.70 |
| BS 90% IL | 250.46 | 138.16 | 23.40 | 15.50 |
| 60 G50 | 253.64 | 140.22 | 23.41 | 15.70 |
| 70 G50 | 252.14 | 140.35 | 23.12 | 16.50 |
| 70 G100 | 250.48 | 139.87 | 23.08 | 16.10 |
| Media | 251.17 | 139.19 | 23.17 | 16.31 |
| CV (%) | 1.30 | 1.49 | 3.18 | 18.74 |

*ns = not significant by the F test at 5% probability. CV = Variation coefficient, G50 and G100 indicate a phosphogypsum dose of 3.71 and 7.42 Mg $ha^{-1}$, respectively.

In a study carried out in the state of Mato Grosso, Amaral et al. (2017) observed a positive effect of phosphogypsum on SD, indicating that the higher concentration of Ca2+ in the soil may have contributed to the formation of structural cell walls. The critical level of Ca2+ in the soil is 2 cmolc $dm^{-3}$ (NEPAR/SBCS, 2019) and all treatments showed higher levels even before lime reapplication (Table 1), which may explain the lack of liming and phosphogypsum application effects.

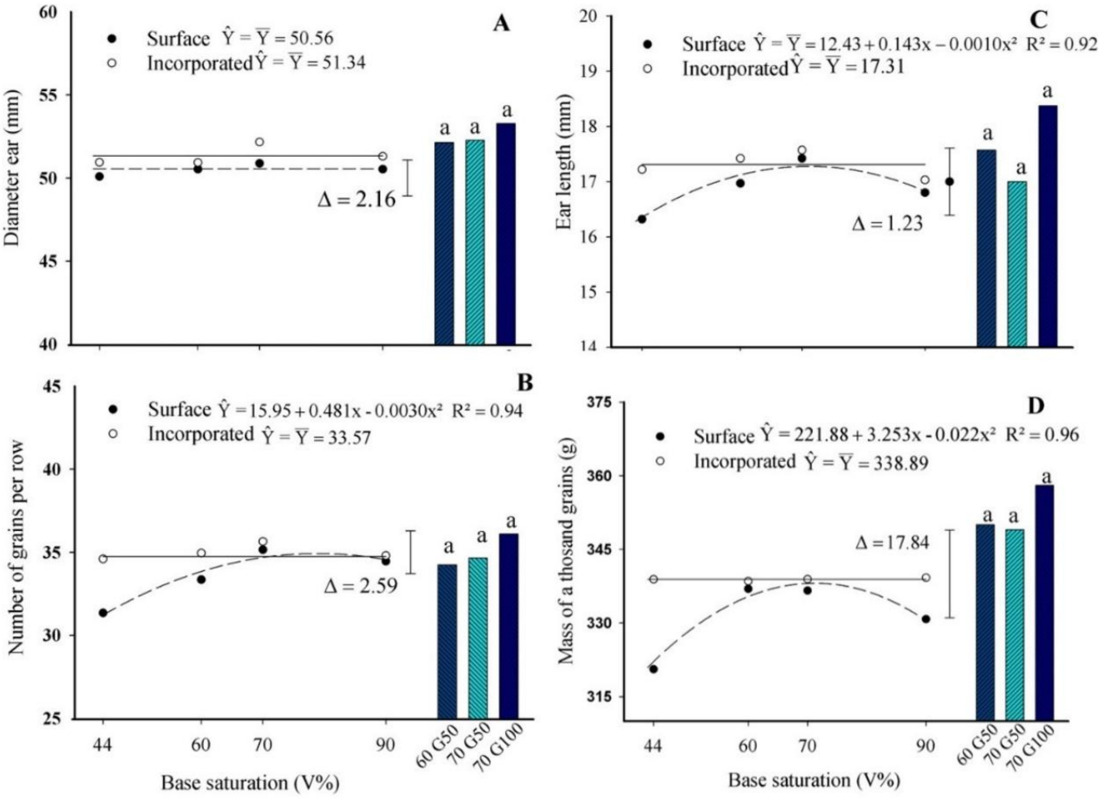

**FIGURE 2** - Ear diameter (A), number of grains per row (B), ear length (C) and mass of a thousand grains (D) of corn, after application of lime and doses of phosphogypsum. Different letters in the bars indicate a significant difference between treatments with phosphogypsum (*p* <0.05). Vertical bar indicates the DMS between each additional x factorial treatment (lime + phosphogypsum), by Dunnet's test (*p* <0.5).

The results obtained differ from Caires et al. (2002), who observed that the PH of corn increased in a quadratic way, with the application of doses of dolomitic lime, the highest values being found in the dose of 3.5 Mg ha$^{-1}$. In a study by Andreotti et al. (2001), with three levels of base saturation (15, 50 and 70%), associated with Zn doses, an increase in PH was also observed with the application of lime in three evaluated crops. In both cases, the acidity was higher than in the present study.

Among the ear variables, only the NRE was not influenced by the treatments (Table 2). The potential NRE is determined between the V10-V12 stages of the scale proposed by Ritchie et al. (1993), being greatly influenced by the hybrid's genetic characteristics (SANGOI et al., 2010) and to a lesser extent by the environment. There was an effect of treatments for ED, where 70G100 exceeded all levels of BS of SL (44, 60, 70 and 90%) and BS 44 and 60% of LI. Superiority of 70G50 was also verified in relation to the control without tilling (BS 44%) (Figure 2A).

Other studies have observed an increase in ED, after nitrogen fertilization (FERNANDES et al., 2017) and inoculation with rhizobacteria (OLIVEIRA et al., 2012). The events that determine the ED coincide with the second week after the plant emergence, the phase in which the formation of the early ear begins (OLIVEIRA et al., 2012), therefore the improvements imposed by phosphogypsum application associated with liming on the chemical attributes of the soil and consequently in the nutritional status may have been determinant for the observed results. Although ED is a poorly evaluated variable in phytotechnic studies, it was positively associated with yield (Figure 4).

The NGR was influenced by the superficial liming, with adjustment of the quadratic model with maximum point in the BS 80% (Figure 2B). The phosphogypsum treatments did not differ from each other, but all of them increased the number of NGR in relation to the BS by 44% in IL, in addition to the superiority of 70G100 in relation to the BS of 60% in SL. Dalla Nora et al. (2014) also observed that the combined use of lime and phosphogypsum increased the NGR in relation to the control treatment. According to the authors, phosphogypsum maximized the effect of lime treatments, positively affecting the development of the culture. Between the V12-V18 stages on the scale of Ritchie et al. (1993), there is a longitudinal expansion of the future corn ear, when the potential number of ovules is defined (SANGOI et al., 2010), so the improvements in chemical attributes imposed by surface liming were favorable to the development of the NGR.

The superficial liming increased the LE, with adjustment of the quadratic model, with a maximum point in the BS of 72% (Figure 2C). In the comparison between factorial vs. additional, there was a superiority of 60G50 in relation to the control without incorporation (BS 44%) and superiority of 70G100 in relation to the levels of BS 70 and 90% (regardless of the mode of lime application), in addition to increments in relation to BS 44 and 60% in SL (Figure 2A). Sbardelotto and Ottoni (2020) also observed positive effect of lime and phosphogypsum on LE. According to the authors, the phosphogypsum dose for maximum technical efficiency was 2.9 Mg ha$^{-1}$.

TGM was influenced by BS% only in SL, adjusting the quadratic model with the maximum point in BS 72% (Figure 2D). The phosphogypsum treatments did not differ, however, they increased TGM in relation to BS 44 and 90% in SL; it was also observed that the 70G100 surpassed all other factorials (Figure 2D). Tiritan et al. (2016) reported a positive effect of liming on TGM, regardless of the mode of lime application. In a study conducted on a dystrophic Red Latosol, Parente et al. (2014) observed a linear increase in grain mass with the increase of superficial lime doses.

TGM is mainly affected by the characteristics of the genotype that express the cavity of the endosperm (MAGALHAES; JONES, 1990), however it is influenced by the edaphic and climatic conditions that occurred during growth (TIRITAN et al., 2016). Other studies have also observed that TGM can vary with experimental conditions, especially those of an edaphoclimatic nature (CAIRES; MILLA, 2016; BESEN et al., 2019).

Factors that limit the photosynthetic activity of the corn plant and its ability to remobilize the photoassimilates to the grains, reduce TGM. At 15 days after fertilization, the development of corn grains begins a phase in which there is a rapid and constant accumulation of dry matter in the grains, a process that lasts about 30 days (approximately 80% of the dry weight of the grains is accumulated in this phase) (SANGOI et al., 2010). Nutritional restrictions or limiting factors of a biotic or abiotic order in this phase will reduce TGM, therefore the improvements imposed by superficial liming favored the increase of TGM even in a year without water restrictions.

The results demonstrate that the levels of BS% of the incorporated liming did not influence the response variables, unlike the superficial liming (Figure 2). This may be due to the soil tilling in the act of lime incorporation, promoting changes in soil attributes (physical/chemical and microbiological) so pronounced as to minimize the effects of the addition of lime itself, decreasing possible responses to BS%.

Grain yield was not influenced by BS% levels in IL and SL, however, it was 445 kg ha$^{-1}$ higher when tilling the soil. However, by associating phosphogypsum and lime on the surface, the best results were obtained, with increments of 6 to 12% compared to BS 44% SL (Figure 3). Thus, it is preferable to apply phosphogypsum associated with liming than to incorporate lime. The highest dose of phosphogypsum (7.42 Mg ha$^{-1}$) did not promote gains in relation to the 3.71 Mg ha$^{-1}$ dose.

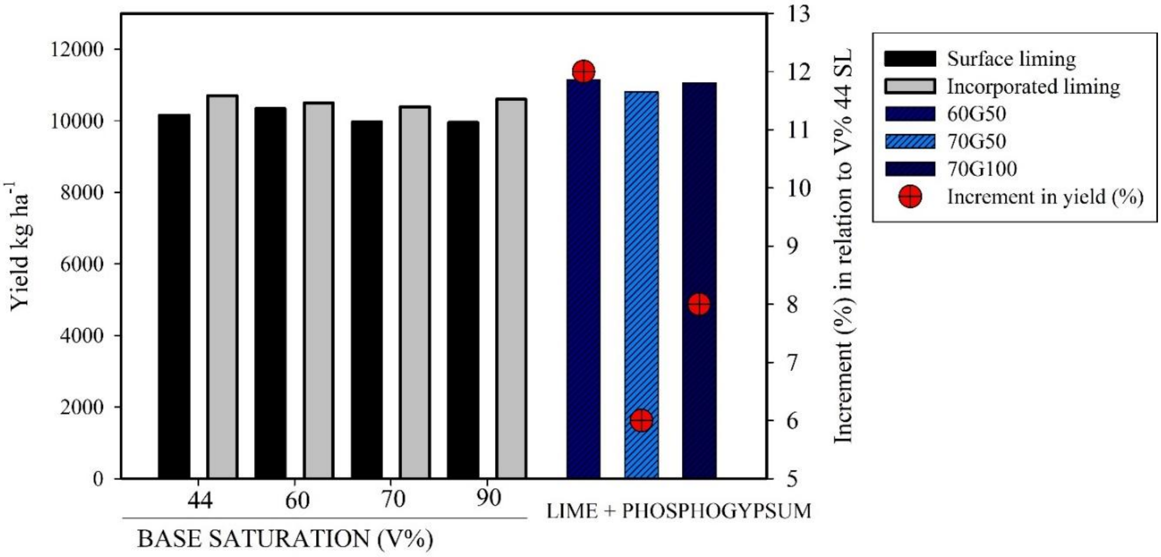

**FIGURE 3 -** Corn yield as a function of base saturation (BS%), by means of surface and incorporated liming and use of phosphogypsum (G) associated with surface liming: BS 60% + 3.71 Mg of G ha$^{-1}$ (60G50), BS 70% + 7.42 Mg ha$^{-1}$ of (70G50) and BS 70% + 7.42 Mg ha$^{-1}$ of (70G100).

Currently the Manual of Fertilization and Liming for the state of Paraná, recommends BS 70% for corn (NEPAR/SBCS, 2019), meeting the maximum technical efficiency of grain per row and ear length found in this study (BS 72%). Although Prado (2001) observed that base saturation of 65% presented a greater contribution to the increases in the yield components. The results of research obtained in different places and conditions of soil and climate, show that in areas where no-tillage is consolidated, liming carried out on the surface is effective for maintaining acidity at adequate levels considering 20 cm of the soil surface, and lime can be applied on the surface (NEPAR/SBCS, 2019).

Also, the combination of phosphogypsum and lime promoted improvements (Figures 2 and 3), which tend to be more expressive in years of water deficit, since phosphogypsum promotes favorable conditions for root development. According to Tiecher et al. (2018) the critical soil levels used for the recommendation of phosphogypsum in tropical soils are not the same as those observed in subtropical soils under no-tillage. For grasses grown in a subtropical Latosol under no-tillage, the use of 10% $Al^{3+}$ saturation and/or 3.0 $cmol_c$ $dm^{-3}$ of $Ca^{2+}$ in the subsurface layer of the soil (0.20-0.40 m) is more appropriate than the current recommendation ($Al^{3+}$ saturation> 20% and/or $Ca^{2+}$content> 0.5 $cmol_c$ $dm^{-3}$ Ca) for tropical soils. In a meta-analysis study evaluating the responses of cultures to phosphogypsum in South America, Pias et al. (2020) observed that for cereals, the application of phosphogypsum is advisable in soils with $Al^{3+}$ saturation> 5% in the layer of 0.20-0.40m. Both studies show that positive responses to plaster are more frequent than expected according to old recommendations.

Pearson's correlation analysis shows that TGM, which is an important yield component, correlated with PH, ED, NGR, GE and LE (Figure 4), with the highest correlation coefficient (0.89) for TGM x ED. Among the characters of the ear, significant correlations were observed for the variable ED with other components that define the crop yield, showing the importance of measuring this response variable.

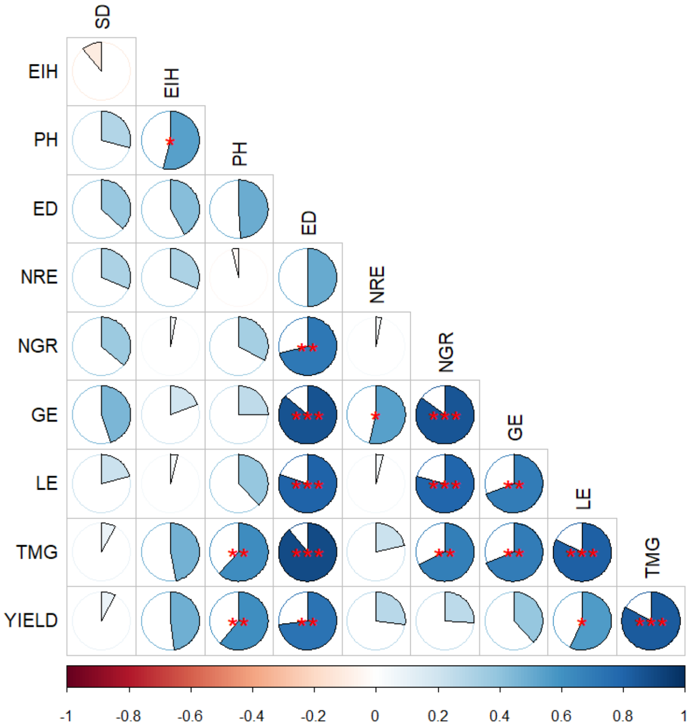

**FIGURE 4** - Simple linear correlation matrix between corn morphological and yield components: stem diameter (SD), ear insertion height (EIH), plant height (PH), ear diameter (ED), number of rows per ear (NRE), number of grains per row (NGR), grains per ear (GE), length of ear (LE), mass of a thousand grains (TGM) and yield (YIELD). *significant at 10%, **significant at 5%, ***significant at 1%.

Among the variables of the corn ear, yield correlated with TGM, ED and LE. According to Kappes et al. (2009), the LE is one of the characteristics that can directly interfere in the number of NGR and consequently in the yield of the corn crop. Other studies have also observed a positive correlation between LE and yield (BESEN et al., 2019; BESEN et al., 2020). However, according to Lopes et al. (2007) the relationships between the characteristics of ears are dependent on the genotypes. Souza et al. (2014) studying five corn hybrids, observed that TGM was the yield component that had the greatest direct effect on grain production and that the ear height was the most influential in the yield variation, being the secondary component of greatest relevance to yield.

Locatelli et al. (2019) also observed a positive association of yield with PH, in addition to the SD. According to the authors, corn plants with greater structural capacity have greater capacity for photosynthetic assimilation, reflecting in grain yield. The positive effects of superficial liming were observed, with the best responses obtained between the BS of 72 to 80%. However, advantages were observed when associating BS 70% in surface with phosphogypsum, however the dose of phosphogypsum of 7.42 Mg ha$^{-1}$ does not promote benefits in relation to the dose of 3.71 Mg ha$^{-1}$ of phosphogypsum. No advantage was observed in increasing the BS to 90%. High doses of lime can be harmful due to the interaction between Ca, Mg and K, and the excess of the first two can result in K$^+$ deficiency.

The application of lime and phosphogypsum is more advantageous than the incorporation of lime. Future studies should evaluate the effect of soil concealers and conditioners on the primary and secondary yield components in other crops, as well as maximize the amount of information in corn, such as leaf area and carbon partition, seeking to correlate them with grain yield.

## CONCLUSIONS

The surface liming increased the LE, TMG, NGR, with the maximum responses obtained in the BS of 72, 72 and 80%, respectively.

The use of phosphogypsum associated with lime provides improvements in corn ear variables, except for NRE, which was not influenced by treatments. Therefore, it is preferable to use 3.71 Mg ha$^{-1}$ associated with BS 70%.

The applied and incorporated lime doses did not alter any response variable.

Corn yield was positively associated with ED, PH, LE and TGM. Also, by combining lime and phosphogypsum, both on the surface, production increased by 6 to 12% compared to treatment without lime and without tilling.

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