Effect of the calcium:magnesium ratio in soil acidity correctives on the initial growth and mineral nutrition of coffee

Efecto de la relación calcio:magnesio de correctores de acidez del suelo en el crecimiento inicial y la nutrición mineral del café

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ABSTRACT

The Ca:Mg ratio of soil acidity correctives affects the availability of these nutrients and, consequently, coffee plant growth. In Colombia, available information on this subject is limited. The aim of this research was to study the effect of the calcium:magnesium ratio in soil acidity correctives on coffee growth and nutrition at the nursery stage. Three soil types (Andisol, Inceptisol, and Oxisol) were used, to which mixtures of calcite ($CaCO_3$) and magnesite ($MgCO_3$) were applied in six proportions, modifying to alter the Ca:Mg ratio (77:1, 6:1, 3:1, 1:1, 1:2, or 1:9). Six months after transplanting, soil pH, exchangeable cations in soil, plant dry biomass, growth variables, and nutrient concentration in plants were evaluated. The application of amendments raised the pH to values close to 5.5 and neutralized exchangeable Al^{3+} in all treatments. The Ca:Mg ratios significantly affected plant dry biomass, with the highest values observed at intermediate ratios (6:1 and 1:2), whereas extreme ratios, particularly with excess Mg (1:9), reduced growth in all three soils. In Andisol and Inceptisol, wider ratios (6:1 to 77:1) favored total biomass, while, in Oxisol, the best results were obtained with more balanced ratios (3:1 to 1:2). Foliar Ca concentrations decreased as this ratio was reduced, while Mg concentrations increased. The optimal exchangeable Ca^{2+}/Mg^{2+} ratio in soil for maximum biomass production was 5.0 in Andisol, ranging from 4.0 to 15.5 in Inceptisol and from 0.5 to 2.7 in Oxisol.

Keywords: amendments, Ca and Mg saturation, *Coffea arabica* L., nursery stage, exchangeable Ca:Mg ratio, Colombian coffee zone.

RESUMEN

La relación de Ca:Mg de los correctivos de la acidez del suelo afecta la disponibilidad de estos nutrientes y, en consecuencia, al crecimiento de las plantas de café. En Colombia, la información disponible sobre este tema es limitada. El objetivo de esta investigación fue estudiar el efecto de la relación calcio:magnesio en los correctivos de la acidez del suelo sobre el crecimiento y la nutrición del café en la etapa de almácigo. Se utilizaron tres tipos de suelo (Andisol, Inceptisol y Oxisol), a los que se aplicaron mezclas de calcita ($CaCO_3$) y magnesita ($MgCO_3$) en seis proporciones, modificándolas para alterar la relación Ca:Mg (77:1, 6:1, 3:1, 1:1, 1:2 o 1:9). Seis meses después del trasplante, se evaluaron el pH del suelo, los cationes intercambiables en el suelo, la biomasa seca de las plantas, las variables de crecimiento y la concentración de nutrientes en las plantas. La aplicación de enmiendas elevó el pH a valores cercanos a 5,5 y neutralizó el Al^{3+} intercambiable en todos los tratamientos. Las relaciones Ca:Mg afectaron significativamente a la biomasa seca de las plantas, observándose los valores más altos en relaciones Ca:Mg intermedias (entre 6:1 y 1:2), mientras que las relaciones extremas, en particular con exceso de Mg (1:9), redujeron el crecimiento en los tres suelos. En Andisol e Inceptisol, las relaciones más amplias (6:1 a 77:1) favorecieron la biomasa total, mientras que en Oxisol se obtuvieron los mejores resultados con relaciones más equilibradas (3:1 a 1:2). Las concentraciones foliares de Ca disminuyeron a medida que se reducía esta relación, mientras que las concentraciones de Mg aumentaron. La proporción óptima de Ca^{2+}/Mg^{2+} intercambiable en el suelo para la máxima producción de biomasa fue de 5,0 en el Andisol y osciló entre 4,0 y 15,5 en el Inceptisol y entre 0,5 y 2,7 en el Oxisol.

Palabras clave: enmiendas, saturación de Ca y Mg, *Coffea arabica* L., etapa de almácigo, relación Ca:Mg intercambiables, zona cafetera colombiana.

Introduction

Approximately 60% of the area with potential for cultivating coffee (*Coffea arabica* L.) in Colombia faces limitations due to soil acidity, a particularly critical issue in the departments of Antioquia, Bolívar, Boyacá, Meta, Caquetá, Casanare, and Santander. In these regions, the soil pH is below 5.0, with a predominance of exchangeable aluminum

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(Al^{3+}) over calcium (Ca^{2+}) and magnesium (Mg^{2+}) (Sadeghian Khalajabadi & Lince Salazar, 2024). Soil acidity (Al^{3+} toxicity and nutrient imbalance) affects coffee growth and yield, necessitating lime amendments to correct this condition (Pavan *et al*., 1982; Sadeghian Khalajabadi & Díaz Marín, 2020).

The corrective effect of lime amendments depends on various factors, including lime quality and rate, application method, soil buffering capacity, rainfall, and time elapsed since liming (Li *et al*., 2019; Moreira *et al*., 2023). Additionally, the efficiency and quality of these amendments vary with their chemical composition and reactivity, evaluated by chemical equivalence, particle-size efficiency, and neutralizing power (Athanase *et al*., 2013).

With respect to the quality of soil amendments, the Ca and Mg contents, and their relative proportion, deserve special attention. The use of Mg-rich amendments, such as dolomite, in soils deficient in this nutrient is a widely promoted strategy in soil acidity correction programs (Moreira *et al*., 2023; Olego *et al*., 2021), not only due to their lower cost compared to fertilizers but also because acidic soils often show a deficiency in this nutrient.

Several studies have explored the optimal Ca:Mg ratio in amendments to correct soil acidity across different crops and conditions. Oliveira and Parra (2003) conclude that in soils with adequate levels of exchangeable Ca^{2+} and Mg^{2+}, the Ca:Mg ratio in the amendment plays a secondary role in the development and yield of beans. Lange *et al*. (2021) indicate that for soybean and corn, ratios equal to or greater than 4:1 favor vegetative growth; nonetheless, the highest soybean yields are obtained with broader ratios (2:1, 1:1, and 5:1), while the optimal corn ratio is 6:1. In research conducted by Medeiros *et al*. (2008), increasing the Ca:Mg ratio raised Ca^{2+} concentrations in the exchange complex, which reduced Mg^{2+} and K^+ uptake, affecting early corn growth and development. This indicates that there is no clear consensus on the optimal Ca:Mg proportions in soil amendments, and that results may vary depending on the species and soil type.

In coffee cultivation, Malavolta (1993) emphasizes the importance of carefully considering both the quality and type of lime applied. Specifically, he recommends using liming materials with an effective calcium carbonate equivalent (ECCE) of at least 75% and selecting the appropriate lime type based on the soil Ca:Mg ratio: calcitic limestone when Ca:Mg $\leq$ 1.0, magnesian limestone when Ca:Mg ranges from 1.0 to 3.0, and dolomitic limestone when Ca:Mg > 3.0. According to Nogueira *et al*. (2012), a Ca:Mg ratio of 3:1 is ideal for mineral nutrition and development. A study by Díaz Poveda and Sadeghian Khalajabadi (2020) reveals differences in the quality of amendments used in Colombia's coffee-growing areas, particularly dolomites, which show variations in effective calcium carbonate equivalent (ECCE) Ca and Mg contents and ratios.

The previously described results corroborate that, in coffee cultivation, as in other crops, the optimal Ca:Mg ratio depends on amendment quality and local soil conditions.

After the reaction of lime amendments (such as $CaCO_3$ and $MgCO_3$), the availability of Ca^{2+} and Mg^{2+} to plants is determined by the ratio of exchangeable cations. An excessive concentration of one of these cations may antagonize the others, affecting their uptake (Jakobsen, 1992). For coffee, Oliveira *et al*. (1994) report increases in coffee seedling dry matter in response to higher Ca^{2+} saturation in the cation exchange capacity (CEC). In Colombia, characterized by a wide diversity of soils, available information on this subject is limited. Therefore, this study aimed to determine the influence of the Ca:Mg ratio of soil acidity correctives on the initial growth and nutrition of coffee plants at the seedling stage. This study hypothesized that coffee growth and nutritional responses to the calcium:magnesium ratio of soil acidity correctives differed across soil types.

Materials and methods

The study was conducted under controlled conditions, using three acidic soils representative of the Colombian coffee-growing region (588 municipalities across 23 of Colombia's 32 departments, covering almost the entire Andean region and the Sierra Nevada de Santa Marta). Coffee seedlings were established in plastic bags containing soils amended with various Ca:Mg proportions, applied through mixtures of calcite and magnesite. The corresponding methodological details are presented below.

The experiment was conducted at the National Center for Coffee Research (Cenicafé), located at an altitude of 1,310 m in the municipality of Manizales, department of Caldas, at 5°1' N and 75°35' W. During the experimental phase (March-August), the following climatic conditions were recorded: rainfall of 1,570 mm; minimum, maximum, and average air temperatures of 17.4°C, 26.7°C, and 21.4°C, respectively; and 720 h of sunshine duration.

Three soil types were used: an Andisol (Pachic Fulvudands), an Inceptisol (Typic Dystrudepts), and an Oxisol

(USDA Soil Taxonomy). Soil samples were collected from the topsoil (0-20 cm) of coffee crops located in the municipalities of Pereira (Risaralda department), Marsella (Risaralda department), and Cubarral (Meta department), respectively. The samples were then sieved to 6 mm, homogenized, and subjected to chemical and textural analysis (subsampling to <2 mm), following the methodology of the Agustín Codazzi Geographic Institute (IGAC, 2006) (Tab. 1).

TABLE 1. Initial chemical and granulometric properties of soils used in the experiment.

Property	Andisol (Pachic Fulvudands)	Inceptisol (Typic Dystropepts)	Oxisol
Soil pH	4.5	4.5	3.8
Organic carbon (%)	6.2	3.6	2.7
K ($cmol_c$ kg^{-1})	0.83	0.25	0.19
Ca ($cmol_c$ kg^{-1})	1.84	1.56	0.21
Mg ($cmol_c$ kg^{-1})	0.46	0.58	0.12
Na ($cmol_c$ kg^{-1})	0.01	0.03	0.01
Al ($cmol_c$ kg^{-1})	1.3	3.9	3.4
CEC ($cmol_c$ kg^{-1})	26	18	14
Al saturation (%)	29	62	86
Base saturation (%)	12	13	4
P (mg kg^{-1})	28.0	2.0	64.0
S (mg kg^{-1})	23.3	18.7	14.6
Fe (mg kg^{-1})	162	86	497
Mn (mg kg^{-1})	31	122	24
Zn (mg kg^{-1})	12.4	1.2	1.4
Cu (mg kg^{-1})	2.5	6.0	4.4
B (mg kg^{-1})	0.44	0.00	0.56
Clay (%)	25	55	33
Silt (%)	25	34	22
Sand (%)	50	11	45
Texture	Loam-Clay-Sandy	Clay	Loam clay

pH: soil:water ratio 1:1 (potentiometric); organic carbon: Walkley-Black (titration); P: Bray II; K, Ca, and Mg: ammonium acetate pH 7.0 (atomic absorption spectrophotometry – AAS); S: calcium phosphate monohydrate 0.008 M (turbidimetric); Al: 1.0 N KCl (AAS); Fe, Mn, Zn, and Cu: Modified Olsen (AAS); B: hot water (colorimetry); Texture: Bouyucos.

Treatments

The treatments consisted of six percentage ratios of a mixture between calcite ($CaCO_3$) (38.7% Ca, 0.5% Mg, ECCE = 99%) and magnesite ($MgCO_3$) (23% Mg, 2.6% Ca, ECCE = 100%), with the following percentage (w/w) combinations: 100:0, 80:20, 60:40, 40:60, 20:80, and 0:100. These percentage combinations allowed the Ca:Mg ratios of the acidity correctives to vary from 77:1 to 1:9 (Tab. 2). Source materials, of Colombian origin, and analyzed in the Cenicafé laboratories (Manizales, Colombia), were selected based on their high purity (low Mg content in calcite and low Ca content in magnesite) and comparable acid-neutralizing capacity. Given the lack of information on highly contrasting Ca:Mg ratios, this study included an extreme range of treatments (Ca:Mg ratios from 71:1 to 1:9) to evaluate their effects on coffee growth and nutrient status.

For each soil, the amendment rate was calculated to raise the soil pH to 5.5, a value recommended in Colombia for coffee growth at this stage (Sadeghian Khalajabadi & Díaz Marín, 2020). Thus, 4.44 g dm^{-3} (cubic decimeter, equivalent to 1,000 cm^3) were applied to both the Andisol and the Inceptisol, and 7.55 g dm^{-3} to the Oxisol.

TABLE 2. Treatments and the Ca:Mg ratios in the soil acidity correctives.

Treatment calcite:magnesite		Contents of		Ratio Ca:Mg
		Ca (CaO)	Mg (MgO)	
% (w/w)		g kg^{-1}		
100	0	387 (542)	5 (8)	77:1
80	20	315 (441)	50 (84)	6:1
60	40	243 (340)	95 (159)	3:1
40	60	170 (238)	140 (234)	1:1
20	80	98 (137)	185 (309)	1:2
0	100	26 (36)	230 (384)	1:9

Experimental design

The experimental unit consisted of a black low-density polyethylene bag containing 1.3 dm^3 of treated soil. It contained one coffee plant (*Coffea arabica* L.) of the var. Castillo. The amendments were incorporated into the soil 30 d before transplanting the seedlings, and the soil was incubated at room temperature (18-24°C) with soil moisture close to field capacity. The seedlings (locally known as *"chapola"*) were 60 d old. They had one pair of cotyledonary leaves when transplanted into bags.

In total, 90 experimental units per soil type were established, resulting from six treatments with 15 replicates each. The experimental design was completely randomized ($Yij = \mu + \tau i + \varepsilon ij$), and the plants were grown under shade netting. Phosphorus was applied at a rate of 1.0 g P_2O_5 per plant, one and three months after transplanting, using diammonium phosphate (18% N and 46% P_2O_5), following the recommendations of Sadeghian Khalajabadi and Ospina Penagos (2021) for the coffee seedling stage. Additionally, constant irrigation was provided to maintain field moisture capacity, and weed growth was controlled manually. Partial shading was removed 90 d after transplanting.

Evaluated variables

Six months after transplanting, the roots were extracted from the soil, and the plants were oven-dried at 65°C for 72 h to determine the dry matter weight of the shoots and roots.

For three replicates per treatment, soil pH and exchangeable concentrations of Ca^{2+}, Mg^{2+}, K^{+}, and Al^{3+} were measured. Additionally, for plants grown on the Oxisol, height from the root collar (ground level) to the shoot apex, and the number of stem nodes were evaluated. Likewise, the Ca and Mg contents in roots, stems, and leaves of entire plants were evaluated according to the methodology described by IGAC (2006). Given cost and operational constraints, chemical analyses were carried out on a randomly selected and representative subset of three of the 15 experimental replicates per treatment.

Data analysis

Before performing the analysis of variance (ANOVA), the assumptions of normality of residuals and homogeneity of variances were evaluated to ensure the validity of the statistical analysis. Subsequently, an analysis of variance (ANOVA; α = 0.05) was performed for each soil to determine the effect of the treatments on the dry weights of roots, shoots, and their sum. When significant differences were observed, Tukey's test was used to compare means. Regression models were also used to analyze the influence of the Ca:Mg amendments ratio on exchangeable Ca^{2+}/Mg^{2+}, and the effect of the Ca^{2+}/Mg^{2+} ratio on foliar concentrations of Ca and Mg. All analyses described were performed using RStudio version 17 (2017).

Results

Soil properties

Overall, the observed trends were consistent across the three evaluated soils. The initial soil pH increased to values near 5.5 in response to the application of amendments with various Ca:Mg ratios, without significant differences among treatments (Tab. 3). The average pH values were: Andisol 5.7, Inceptisol 5.4, and Oxisol 5.5. Another effect of liming was the neutralization of exchangeable Al^{3+} in all treatments, regardless of the Ca:Mg ratios. This result was inferred from descriptive comparisons with the soil's initial values.

Descriptively, exchangeable K^+ content showed a slight increase compared to the initial value in both the Inceptisol and the Oxisol after liming (Tab. 3). It was higher in the Ca:Mg ratio of 1:9 compared to 1:1, only for the Oxisol. Overall, exchangeable K^+ levels were higher in the Andisol (0.64 $cmol_c\ kg^{-1}$) than in the Inceptisol (0.36 $cmol_c\ kg^{-1}$) and Oxisol (0.37 $cmol_c\ kg^{-1}$).

The initial exchangeable Ca^{2+} content slightly increased in the treatment without calcite ($CaCO_3$) addition, and Mg^{2+} in the treatment without magnesite. Exchangeable Ca^{2+} content and Ca^{2+} saturation in the exchange complex (% CEC) increased significantly as the Ca:Mg ratio in the amendment decreased (Tab. 3), with changes fitting logarithmic equations (Tab. 4). Exchangeable Mg^{2+} levels and Mg^{2+} saturation decreased as the Ca:Mg ratio increased, showing an inverse pattern to Ca^{2+}.

The exchangeable Mg^{2+} level was very high in the 1:9 Ca:Mg treatment (>8.0 $cmol_c\ kg^{-1}$), with similar averages across the three soils. Although Mg^{2+} saturation was also high, contrasts were observed among soils, following the trend: Andisol <Inceptisol<Oxisol. Meanwhile, both exchangeable Ca^{2+} content and Ca^{2+} saturation reached maximum levels at the 77:1 ratio (>9.0 $cmol_c\ kg^{-1}$ and > 52.0%). Although the Andisol had the highest average Ca^{2+} content, the Oxisol had the highest Ca^{2+} saturation.

In the three soil types, the variations of the exchangeable Ca^{2+}/Mg^{2+} ratio as a function of the Ca:Mg ratio of the amendment material fit an exponential model (Fig. 1). In all three soils, the parameters of the equations were significant (α<0.05). The most marked differences between soils were observed at the widest Ca:Mg ratio (77:1), where the Oxisol had a significantly higher average than the Inceptisol and Andisol.

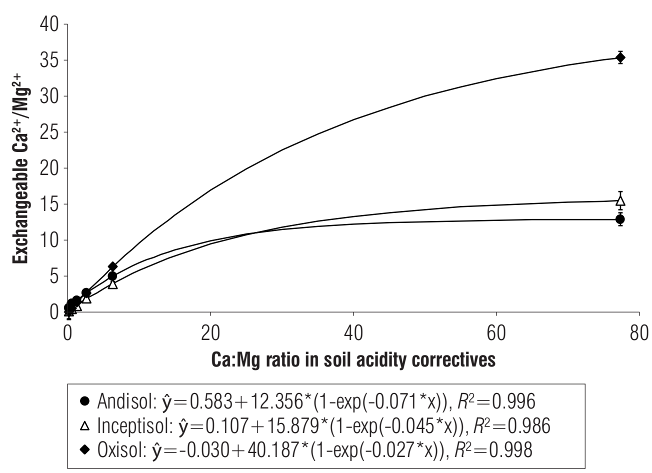

FIGURE 1. Soil Ca^{2+}/Mg^{2+} ratio as a function of the Ca:Mg ratio of the amendment material. Vertical bars indicate standard error. *Significant at P<0.05 according to Student's t-test.

TABLE 3. Average values of soil chemical variables in response to the Ca:Mg ratios in soil acidity correctives.

Property	Treatment (Ca:Mg ratio)					
	77:1	6:1	3:1	1:1	1:2	1:9
				Andisol		
pH	5.87a	5.73a	5.77a	5.63[a]	5.80a	5.47a
Ca^{2+} ($cmol_c\ kg^{-1}$)	16.93a	13.22b	11.68bc	9.87bc	9.49c	4.48d
Mg^{2+} ($cmol_c\ kg^{-1}$)	1.31e	2.64d	4.38c	6.21b	8.01a	8.40a
K^{+} ($cmol_c\ kg^{-1}$)	0.76a	0.58a	0.65a	0.60[a]	0.67a	0.59a
Al^{3+} ($cmol_c\ kg^{-1}$)	0.10a	0.10a	0.10a	0.10[a]	0.10a	0.10a
Ca^{2+}/Mg^{2+}	12.89a	4.99b	2.67c	1.59d	1.19de	0.53e
Ca^{2+}Sat. (%)	65.13a	50.85b	44.94bc	37.97bc	36.51c	17.22d
Mg^{2+}Sat. (%)	5.05e	10.17d	16.85c	23.87b	30.82a	32.32a
				Inceptisol		
pH	5.47a	5.53a	5.27a	5.35[a]	5.32a	5.43a
Ca^{2+} ($cmol_c\ kg^{-1}$)	9.50a	8.30b	6.33c	4.87d	3.17e	1.29e
Mg^{2+} ($cmol_c\ kg^{-1}$)	0.62 f	2.10e	3.34d	5.31c	6.49b	8.48a
K^{+} ($cmol_c\ kg^{-1}$)	0.35a	0.37a	0.33a	0.36[a]	0.37a	0.40a
Al^{3+} ($cmol_c\ kg^{-1}$)	0.13a	0.10a	0.13a	0.13[a]	0.07a	0.17a
Ca^{2+}/Mg^{2+}	15.48a	3.96b	1.90bc	0.92c	0.49c	0.15c
Ca^{2+}Sat. (%)	52.75a	46.11b	35.19c	27.07d	17.59e	7.15e
Mg^{2+}Sat. (%)	3.44 f	11.67e	18.56d	29.50c	36.04b	47.11a
				Oxisol		
pH	5.80a	5.67a	5.55a	5.45[a]	5.47a	5.63a
Ca^{2+} ($cmol_c\ kg^{-1}$)	10.35a	8.24b	4.95c	3.68d	2.57d	0.34e
Mg^{2+} ($cmol_c\ kg^{-1}$)	0.29 f	1.30e	1.83d	2.71c	4.88b	8.06a
K^{+} ($cmol_c\ kg^{-1}$)	0.36ab	0.36ab	0.36ab	0.32b	0.38ab	0.41a
Al^{3+} ($cmol_c\ kg^{-1}$)	0.10a	0.00a	0.03a	0.10[a]	0.17a	0.10a
Ca^{2+}/Mg^{2+}	35.32a	6.31b	2.71c	1.36cd	0.53d	0.04d
Ca^{2+}Sat. (%)	73.90a	58.83b	35.36c	26.31d	18.36d	2.43e
Mg^{2+}Sat. (%)	2.10f	9.31e	13.07d	19.33c	34.88b	57.55a

Means followed by different letters in the same column indicate statistical differences at the 5% level according to Tukey's test.

TABLE 4. Equations describing variations in the exchangeable Ca^{2+} and Mg^{2+} contents, in the values of Ca^{2+} saturation (Ca^{2+}Sat.) and Mg^{2+} saturation (Mg^{2+}Sat.) as a function of the Ca:Mg ratio of the liming material.

Property	Andisol	Inceptisol	Oxisol
Ca^{2+}	$y=9.57+1.829\ln(x)$ $R^2=0.965$	$y=4.57+1.341\ln(x)$ $R^2=0.936$	$y=3.80+1.621\ln(x)$ $R^2=0.960$
Mg^{2+}	$y=6.09-1.232\ln(x)$ $R^2=0.915$	$y=0.34-1.267\ln(x)$ $R^2=0.944$	$y=4.05-1.163\ln(x)$ $R^2=0.833$
Ca^{2+}Sat.	$y=36.81+7.036\ln(x)$ $R^2=0.965$	$y=25.37+7.451\ln(x)$ $R^2=0.936$	$y=27.16+11.578\ln(x)$ $R^2=0.960$
Mg^{2+}Sat.	$y=23.41-4.739\ln(x)$ $R^2=0.915$	$y=29.68-7.041\ln(x)$ $R^2=0.944$	$y=28.95-8.309\ln(x)$ $R^2=0.833$

Plant dry biomass

Analysis of variance showed treatment effects across the three soil types, with the following order of plant dry biomass: Inceptisol<Andisol<Oxisol. In all three soils, the treatments showed significant effects; however, the response to variations in the Ca:Mg ratio of the amendments differed among soils.

The lowest average aerial biomass of plants grown in the Andisol corresponded to the 1:9 Ca:Mg ratio, which differed statistically from the 6:1, 3:1, and 1:1 ratios (Tab. 5). For this soil, the treatments did not affect root growth, which was reflected in the total biomass, with differences detected between the 1:9 and 6:1 ratios.

In the Inceptisol, plant biomass, both root and shoot, decreased with increasing Mg content in the corrective, resulting in higher total biomass averages in the 77:1 and 6:1 ratios compared to 1:9.

In the Oxisol, the aerial biomass of plants grown at the 1:9 ratio was significantly lower than in the 3:1, 1:1, and 1:2 treatments. For roots, the lowest average values corresponded to the 77:1 and 1:9 ratios, with significant differences only compared to 1:1. This resulted in lower total dry biomass for the 1:9 ratio compared to 3:1, 1:1, and 1:2.

The optimal Ca^{2+}/Mg^{2+} ratios in soil, as indicated by the treatments with the highest dry biomass, were as follows. The highest dry biomass was obtained with the following Ca^{2+}/Mg^{2+} ratios: Andisol 5.0 (6:1 ratio), Inceptisol 4.0 to 15.5 (77:1 and 6:1 ratios), and Oxisol 0.5 to 2.7 (3:1, 1:1, and 1:2 ratios). Similarly, the optimal Ca^{2+} saturations in soil were: Andisol, 50.9%; Inceptisol, 46.1% to 52.8%; and Oxisol, 18.4% to 35.4%. The optimal Mg^{2+} saturations in soil were: Andisol, 10.2%; Inceptisol, 3.4% to 11.7%; and Oxisol, 13.1% to 34.9%.

Growth variables and nutrient concentration in leaves

The height of plants grown in the Oxisol showed the lowest average at the 1:9 ratio. Although a similar trend was observed for the number of stem nodes, significant differences were only detected in comparison to the 3:1 ratio; that is, 11 cm greater height and 1.1 stem nodes (Fig. 2).

TABLE 5. Dry biomass of roots, shoots, and total coffee plant biomass during the seedling stage in response to the Ca:Mg ratios in soil acidity correctives.

Dry biomass	Ca:Mg ratio in soil acidity corrective					
	77:1	6:1	3:1	1:1	1:2	1:9
			Andisol			
Roots (g)	0.53a	0.54a	0.53a	0.50a	0.48a	0.44a
Shoots (g)	1.38ab	1.68a	1.80a	1.62a	1.56ab	1.09b
Total (g)	1.91ab	2.22a	2.15ab	2.12ab	2.04ab	1.54b
			Inceptisol			
Roots (g)	0.16a	0.14a	0.15a	0.12ab	0.11ab	0.07b
Shoots (g)	0.35a	0.35a	0.28ab	0.27ab	0.24ab	0.06b
Total (g)	0.51a	0.49a	0.41ab	0.39ab	0.35ab	0.13b
			Oxisol			
Roots (g)	0.84b	1.06ab	1.14ab	1.23a	1.14ab	0.76b
Shoots (g)	3.87ab	4.5ab	5.04a	5.16a	5.00a	2.94b
Total (g)	4.71ab	5.56ab	6.18a	6.39a	6.14a	3.70b

Means followed by different letters on the same line indicate statistical differences at the 5% level according to Tukey's test. Shoots – aboveground part of each plant.

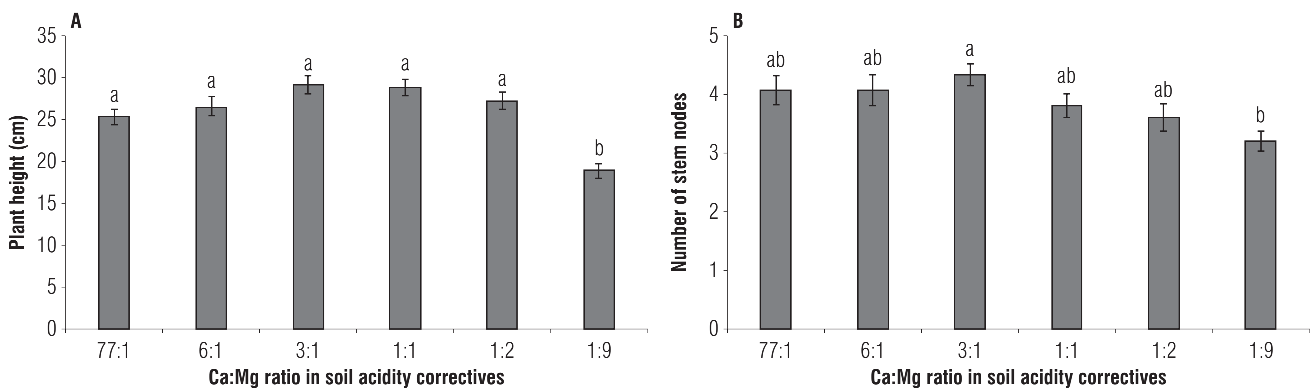

FIGURE 2. Average growth variables of coffee plants evaluated 180 d after transplanting in response to Ca:Mg ratios in soil acidity correctives: A) plant height, B) number of stem nodes. Vertical bars indicate standard error. Means followed by different letters within columns indicate significant differences according to Tukey's test ($P<0.05$). Data from plants grown in an Oxisol (n = 15).

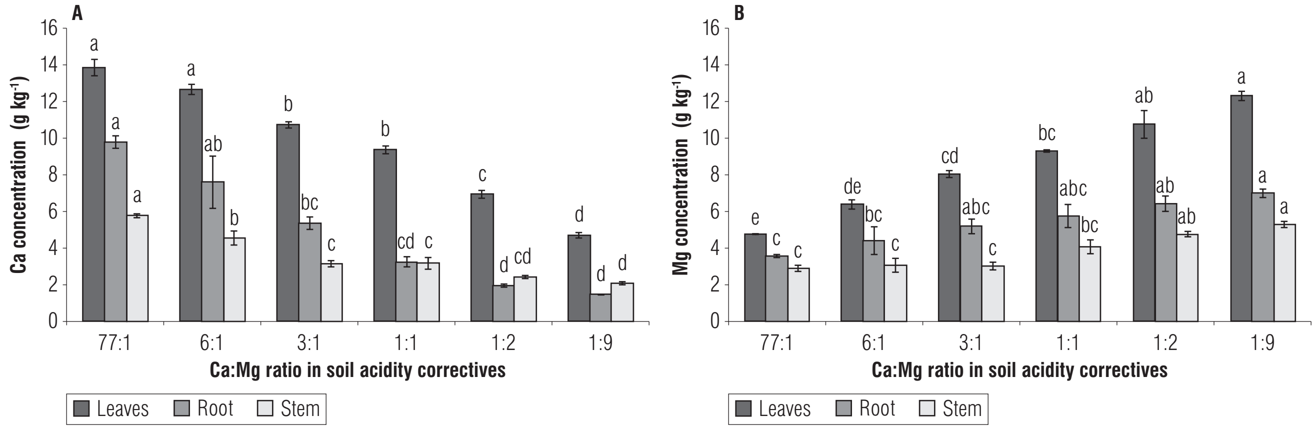

FIGURE 3. Average concentrations of Ca and Mg in in organs of coffee plants evaluated 180 d after transplanting in response to Ca:Mg ratios in soil acidity correctives. A) Ca concentration; B) Mg concentration. Vertical bars indicate standard error. Means followed by different letters within columns indicate significant differences according to Tukey's test (P<0.05). Data from plants grown in an Oxisol (n = 3).

The highest concentrations of Ca and Mg in the plants were found in the leaves, followed by the roots and then the stem, with slightly lower Mg averages compared to Ca (Fig. 3). As the Ca:Mg ratio of the corrective decreased, Ca contents in leaves, roots, and stem significantly declined. Mg levels showed the opposite trend, decreasing as the Ca:Mg ratio increased.

Foliar Ca concentrations decreased with the reduction of the exchangeable Ca^{2+}/Mg^{2+} ratio, while Mg exhibited the opposite trend. In both cases, the variations fit logarithmic equations (Fig. 4).

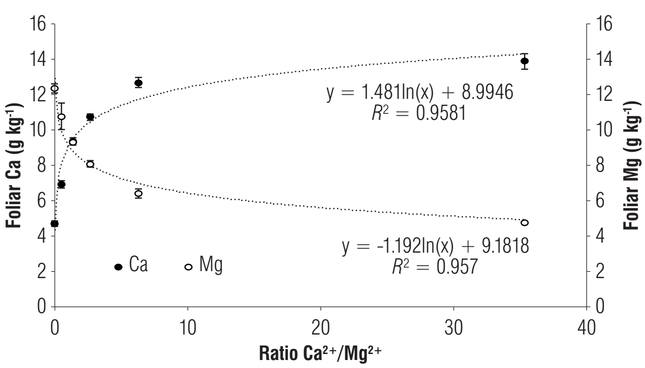

FIGURE 4. Foliar Ca and Mg concentrations in coffee plants 180 d after seedling transplanting as a function of the exchangeable Ca^{2+}/Mg^{2+} ratio in soil. Vertical bars indicate standard error. Data from plants grown in Oxisol (n=3).

Discussion

Soil properties

The application of acidity correctives increased the initial soil pH of the three evaluated soils, bringing them closer to the target value of 5.5, and neutralized exchangeable Al^{3+} (Tab. 3). Differences in the pH levels achieved among the soils can be attributed to soil properties that determine buffering capacity, such as texture, organic matter content, CEC, and iron and aluminum contents (Holland *et al*., 2018). Specifically, the greater pH increase observed in the Andisol compared to the Inceptisol (both with an initial pH of 4.5) could be related to its higher sand content and lower Al^{3+} content, rather than differences in organic matter or CEC. This interpretation aligns with the findings of Li *et al*. (2019), who, in a meta-analysis, find a higher liming efficiency in sandy soils. However, other studies, such as those by Sadeghian Khalajabadi and Díaz Marín (2020), report limited pH increases in sandy soils in the Colombian coffee region, attributed to possible leaching of the liming material and limited moisture retention, a key condition for the lime neutralization reaction.

Within each soil type, treatments showed no statistically significant differences in average pH or Al^{3+} concentrations, indicating equivalence in the neutralization power of the corrective treatments, results that are consistent with those reported by Medeiros *et al*. (2008) and Gomes *et al*. (2002). In contrast, Lange *et al*. (2021) report significant differences in soil pH depending on the Ca:Mg ratio of the correctives. However, these could be due to the ratios or sources used (calcite or dolomite). From the above, it can be concluded that the similarity in neutralizing capacity is associated with the quality and type of amendment used and should be consideredwhen combining different liming materials.

Increases in initial Ca^{2+} levels in the treatment without calcite and Mg^{2+} in the treatment without magnesite can be explained by the presence of these elements in the amendments used, since the commercial-grade materials containing minor Ca or Mg impurities were not completely pure. According to standards established for Colombia (Sadeghian, 2018), both the Oxisol and, to a lesser extent, the Inceptisol have unfavorable Ca^{2+} and Mg^{2+} levels for coffee growth. Additionally, the dynamics of Ca^{2+} and Mg^{2+} in the soil are influenced by the Ca:Mg ratio of the treatments, as documented in several studies (Guimarães *et al*., 2013; Lange *et al*., 2021; Loide *et al*., 2004; Medeiros *et al*., 2008; Oliveira & Parra, 2003).

Part of the Ca^{2+} and Mg^{2+} identified as exchangeable in laboratory analyses may correspond to residual amendment materials with low solubility. This hypothesis is supported by research conducted in Brazilian soils (Rheinheimer *et al*., 2018) and in Colombia's coffee region (Sadeghian Khalajabadi & Díaz Marín, 2020). This condition can also affect estimates of Ca^{2+} and Mg^{2+} saturation.

The logarithmic trends observed in the variation of Ca^{2+} and Mg^{2+} contents and their saturation percentages in relation to the Ca:Mg ratio of the amendments (Tab. 4) suggest that the adsorption and desorption of these cations in the soil exchange complex were not proportional to the amendment ratio. On the contrary, the increases tended to decline progressively. Non-linear responses are reported by Medeiros *et al*. (2008). As a result, the exchangeable Ca^{2+}/Mg^{2+} ratio also tended to decrease with increasing amendment Ca:Mg ratios (Fig. 1). However, the greater increase in this ratio in the Oxisol could be explained by its higher affinity for Ca^{2+}.

Plant dry biomass

This study evaluated the effect of the calcium:magnesium (Ca:Mg) ratio in soil acidity correctives on coffee growth and mineral nutrition in three acidic soils representative of the Colombian coffee-growing region.

The results support the hypothesis that coffee growth and nutritional responses to the Ca:Mg ratio in soil acidity correctives differed across soil types.

Overall, contrasting responses were observed among the evaluated soils, as observed by growth variables and Ca and Mg uptake, suggesting that the effect of this ratio depended on the specific edaphic properties of each soil.

Average total dry matter yields were higher in the Oxisol (5.45 g/plant), followed by the Andisol (2.03 g/plant), and the Inceptisol (0.38 g/plant). These differences exceeded those reported in other studies on acidity correction during the nursery stage conducted in Colombia and Brazil (Pavan *et al*., 1982; Sadeghian Khalajabadi & Díaz Marín, 2020) and could be attributed to the intrinsic properties of each soil.

The results are consistent with previous research that demonstrates the significant effect of the Ca:Mg ratio in amendments on crop yield (Gomes *et al*., 2002; Lange *et al*., 2021; Loide, 2004; Medeiros *et al*., 2008; Olego *et al*., 2021; Oliveira *et al*., 1994).

We know that after the reaction of lime amendments (such as $CaCO_3$ and $MgCO_3$), the availability of Ca^{2+} and Mg^{2+} to plants is determined by the ratio of exchangeable cations in soil. An excessive concentration of one of these cations may antagonize the others, affecting their uptake (Jakobsen, 1992). The above is attributable to competitive inhibition, whereby Ca and Mg compete for shared enzymatic binding sites. Accordingly, an excess of Ca may constrain Mg uptake, or vice versa, leading to disruptions in enzymatic activity and plant structural functions (Römheld, 2012). Therefore, achieving an appropriate balance among these cations in the soil through well-adjusted liming practices is critical to prevent nutrient imbalances and induced crop deficiencies (Faquin, 2005).

In contrast to our results, other authors such as Mello and Kaminski (1990) and Oliveira and Parra (2003) do not report significant effects of this ratio. Guimarães *et al*. (2013) report inconclusive results. Lack of response has been linked to factors such as the characteristics of the crop species (Oliveira & Parra, 2003), the soil's capacity to supply these nutrients (Mello & Kaminski, 1990; Oliveira & Parra, 2003), and the interaction between soil Ca:Mg ratio and pH (Takamoto *et al*., 2021).

The effect of the Ca:Mg ratio in amendments varied across soil types; furthermore, mean-comparison tests suggested that, within a single soil, there may be a range of suitable ratios rather than a single optimal one. Nevertheless, in all three soil types, the lowest yields were recorded in the treatment with the lowest Ca proportion (1:9 ratio), corresponding to the exclusive application of $MgCO_3$. This result highlighted the importance of Ca in coffee nutrition. In contrast, the 77:1 ratio treatment, which contained only $CaCO_3$ (no Mg), yielded results equal to or greater than the other treatments. This finding agreed with the results of Oliveira *et al*. (1994), who report reduced coffee seedling growth with increasing percentages of Mg^{2+} saturation in CEC; however, it partially diverges from most studies that emphasize the importance of Mg in amendments (Olego *et al*., 2021).

The fact that treatments significantly affected both soil properties and plant growth supported the hypothesis that the exchangeable Ca^{2+}/Mg^{2+} ratio and saturation percentages of these cations influenced coffee performance under the conditions of this study. This hypothesis is also confirmed in other crops (Oliveira, 1993; Oliveira & Parra, 2003). Moreover, our results suggested "optimal" values for the exchangeable Ca^{2+}/Mg^{2+} ratio and the saturations of Ca^{2+} and Mg^{2+} vary depending on soil type, with relatively wide ranges, differing from those that Graham (1959) reports. For coffee in the seedling stage in Colombia, ratios of 4.4:1 to 7.1:1 are reported (Sadeghian Khalajabadi & Díaz Marín, 2020). In contrast, this study recorded values ranging from 1.5 to 9.7.

Growth variables and nutrient concentration in plants

Variations in dry biomass in response to treatments directly reflected plant growth and development. This is shown by the lower height and number of stem nodes observed in the 9:1 Ca:Mg ratio, which may be explained by the antagonism between these nutrients; in particular, excess Mg can reduce Ca uptake. This phenomenon is demonstrated under conditions of high Mg content relative to Ca, as occurs in soils derived from serpentine rocks rich in Mg, where Ca uptake is limited, an effect confirmed in *Arabidopsis* (Bradshaw, 2005).

It should be noted that the occurrence of these soils in the Colombian coffee-growing region is very limited, if not virtually nonexistent.

The antagonism between Ca and Mg, as well as the impact of their ratios on the height of cultivated species, is also documented in Brazil in corn (Lange *et al*., 2021; Medeiros *et al*., 2008), forage crops (Guimarães *et al*., 2013), and soybean (Lange *et al*., 2021).

The accumulation of Ca and Mg in plant parts confirmed that the reactions required from the correctives to increase the availability of these nutrients in the soil occurred effectively, enabling root absorption. While higher Ca concentrations than Mg are expected in plants (Sadeghian Khalajabadi, 2022), the similar values found suggested greater bioavailability of Mg. This result could be related to the properties of the source used (magnesite), such as its reactivity and particle size.

Variations in Ca and Mg contents in leaves, stems, and roots followed the same trend as soil nutrient levels, supporting the findings of Oliveira *et al*. (1994) in coffee and those of Oliveira and Parra (2003) and Lange *et al*. (2021) in beans and soybeans. Furthermore, the logarithmic trends observed in foliar Ca and Mg concentrations in relation to the exchangeable Ca^{2+}/Mg^{2+} ratio (Fig. 4) reflected variations in Ca^{2+}, Mg^{2+}, and their respective saturations (Ca^{2+}Sat. and Mg^{2+}Sat.), associated with the Ca:Mg ratio of the amendments (Tab. 4). These patterns were consistent with those that Oliveira and Parra (2003) report in soybean studies.

Conclusions

The Ca:Mg ratio of soil acidity amendments significantly influenced soil properties (specifically exchangeable Ca and Mg contents, the Ca^{2+}/Mg^{2+} ratio, and their saturation relative to CEC) and, consequently, coffee growth and nutrition during the seedling stage; however, these effects varied across soil types. Moreover, the results indicated that, within a given soil, a range of suitable Ca^{2+}/Mg^{2+} ratios may exist rather than a single optimal value. In this respect, intermediate Ca:Mg ratios, especially between 6:1 and 1:2, favored plant dry biomass in all three evaluated soil types, while Andisol and Inceptisol showed the most notable effects. In the Oxisol, more balanced ratios (3:1 to 1:2) yielded better results. This finding has important practical implications, as it suggested greater flexibility in liming recommendations regarding Ca and Mg management in soil. The optimal exchangeable soil Ca^{2+}/Mg^{2+} ratio for maximum biomass production was 5.0 in the Andisol, ranged from 4.0 to 15.5 in the Inceptisol, and from 0.5 to 2.7 in the Oxisol. Correspondingly, optimal Ca^{2+} saturation levels were 51% in the Andisol, 46-53% in the Inceptisol, and 18-35% in the Oxisol, whereas optimal Mg^{2+} saturation levels were 10%, 3-12%, and 13-35%, respectively.

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Conflict of interest statement

The authors declare that there is no conflict of interest regarding the publication of this article.

Author's contributions

Conceptualization: SS; research: SS; methodology: SS and EFC; data analysis: SS and EFC; writing-original draft: SS; writing-review and editing: SS and EFC. All authors reviewed and approved the final version of the manuscript.

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