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AGRONOMIC AND PARTIAL ECONOMIC PERFORMANCE OF LIMESTONE AND AGRICULTURAL GYPSUM RATES IN NO-TILL MAIZE

DESEMPENHO AGRONÔMICO E ECONÔMICO PARCIAL DE DOSES DE CALCÁRIO E GESSO AGRÍCOLA NO MILHO EM PLANTIO DIRETO

DESEMPEÑO AGRONÓMICO Y ECONÓMICO PARCIAL DE DOSIS DE CALIZA Y YESO AGRÍCOLA EN MAÍZ BAJO SIEMBRA DIRECTA

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ABSTRACT

Soil acidity constrains maize production in tropical regions, and decisions regarding limestone and agricultural gypsum should consider both grain yield and the additional costs of these amendments. This study evaluated the agronomic response and partial economic performance of limestone and agricultural gypsum rates for no-tillage maize in Roraima, Brazil, using partial budgeting. The experiment was conducted in a randomized complete block design with a split-plot arrangement augmented by an additional control and four replications. Limestone rates corresponded to nominal base-saturation targets of 50, 60, 70, and 80%, and agricultural gypsum rates corresponded to 0, 50, 100, and 200% of the reference gypsum requirement. At the adopted maize price of R$ 66.00 per 60-kg bag, limestone applied alone at 0.55 t ha^{-1} (T1) provided the highest partial net benefit (R$ 6,123.61 ha^{-1}). The combination of 0.55 t ha^{-1} limestone and 1.20 t ha^{-1} agricultural gypsum (T3) produced the highest observed grain yield (12,437.50 kg ha^{-1}) but a lower partial net benefit (R$ 5,660.48 ha^{-1}). Switching-price analysis indicated that T1 was preferred from R$

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3.05 to R$ 127.52 per bag, whereas T3 became preferable only above R$ 127.52 per bag. Thus, the rate associated with the highest observed grain yield differed from the rate that maximized partial net benefit under the adopted prices. Because only amendment acquisition costs were deducted, the estimates represent partial net benefits rather than total farm profitability.

Keywords: Partial Budgeting. Soil Acidity. Liming. Agricultural Gypsum. Zea Mays L.

RESUMO

A acidez do solo limita a produção de milho em regiões tropicais, e as decisões sobre o uso de calcário e gesso agrícola devem considerar tanto a produtividade de grãos quanto os custos adicionais desses corretivos. Este estudo avaliou a resposta agronômica e o desempenho econômico parcial de doses de calcário e gesso agrícola no milho em plantio direto em Roraima, Brasil, por meio de orçamento parcial. O experimento foi conduzido em delineamento de blocos casualizados, em parcelas subdivididas, acrescido de uma testemunha adicional e com quatro repetições. As doses de calcário corresponderam a metas nominais de saturação por bases de 50, 60, 70 e 80%, e as doses de gesso agrícola corresponderam a 0, 50, 100 e 200% da necessidade de gesso de referência. Ao preço adotado de R$ 66,00 por saca de 60 kg de milho, a aplicação isolada de 0,55 t ha^{-1} de calcário (T1) proporcionou o maior benefício líquido parcial (R$ 6.123,61 ha^{-1}). A combinação de 0,55 t ha^{-1} de calcário e 1,20 t ha^{-1} de gesso agrícola (T3) apresentou a maior produtividade de grãos observada (12.437,50 kg ha^{-1}), porém menor benefício líquido parcial (R$ 5.660,48 ha^{-1}). A análise de preços de indiferença indicou que T1 foi preferível entre R$ 3,05 e R$ 127,52 por saca, enquanto T3 se tornou preferível apenas acima de R$ 127,52 por saca. Assim, a dose associada à maior produtividade de grãos observada diferiu daquela que maximizou o benefício líquido parcial nos preços adotados. Como foram deduzidos apenas os custos de aquisição dos corretivos, as estimativas representam benefícios líquidos parciais, e não a rentabilidade total da propriedade.

Palavras-chave: Orçamento Parcial. Acidez do Solo. Calagem. Gesso Agrícola. Zea Mays L.

RESUMEN

La acidez del suelo limita la producción de maíz en regiones tropicales, y las decisiones sobre el uso de caliza y yeso agrícola deben considerar tanto el rendimiento de grano como los costos adicionales de estas enmiendas. Este estudio evaluó la respuesta agronómica y el desempeño económico parcial de dosis de caliza y yeso agrícola en maíz bajo siembra directa en Roraima, Brasil, mediante un presupuesto parcial. El experimento se realizó en un diseño de bloques completos al azar, con parcelas divididas, un testigo adicional y cuatro repeticiones. Las dosis de caliza correspondieron a metas nominales de saturación de bases del 50, 60, 70 y 80%, y las dosis de yeso agrícola correspondieron al 0, 50, 100 y 200% del requerimiento de yeso de referencia. Al precio adoptado de R$ 66,00 por saco de 60 kg de maíz, la aplicación de caliza sola a 0,55 t ha^{-1} (T1) proporcionó el mayor beneficio neto parcial (R$ 6.123,61 ha^{-1}). La combinación de 0,55 t ha^{-1} de caliza y 1,20 t ha^{-1} de yeso agrícola (T3) presentó el mayor rendimiento de grano observado (12.437,50 kg ha^{-1}), pero un beneficio neto parcial menor (R$ 5.660,48 ha^{-1}). El análisis de precios de indiferencia indicó que T1 fue preferible entre R$ 3,05 y R$ 127,52 por saco, mientras que T3 pasó a ser preferible solo por encima de R$ 127,52 por saco. Por lo tanto, la dosis asociada al mayor rendimiento de grano observado difirió de la que maximizó el beneficio neto parcial con los

precios adoptados. Dado que solo se descontaron los costos de adquisición de las enmiendas, las estimaciones representan beneficios netos parciales y no la rentabilidad total de la explotación.

Palabras clave: Presupuesto Parcial. Acidez del Suelo. Encalado. Yeso Agrícola. Zea Mays L.

1 INTRODUCTION

Soil-amendment decisions should account for the additional revenue generated by yield gains and the additional costs required to obtain them. This distinction is especially important when inputs differ markedly in price or when the treatment that maximizes grain yield is not the one that maximizes economic benefit. Partial budgeting is appropriate for such decisions because it isolates the revenues and costs that change among alternatives and supports transparent farm-level comparison of incremental management choices (Kelton *et al.*, 2025).

Maize (*Zea mays* L.) is highly responsive to soil-fertility management, but its productivity in acidic tropical soils can be limited by aluminum toxicity, low base saturation, and restricted nutrient availability. Field studies have shown that properly selected lime rates and application methods can improve soil chemical properties, maize yield, and economic return, although responses remain strongly site-specific (Alemu *et al.*, 2022; Kibet *et al.*, 2023).

In highly weathered tropical soils, maize growth can be constrained by low pH, aluminum toxicity, and limited availability of calcium, magnesium, and phosphorus. Liming neutralizes soil acidity, increases base saturation, and can improve nutrient availability and crop yield, although the magnitude of the response varies with crop and soil conditions (Enesi *et al.*, 2023). Accurate rate selection is therefore important because lime requirement depends on soil buffering capacity and the diagnostic method used (Merlos *et al.*, 2023). However, because limestone has low mobility when surface-applied under no-tillage, its short-term effects are concentrated mainly in the upper soil layers (Fontoura *et al.*, 2019; Minato *et al.*, 2023).

Agricultural gypsum is more mobile in the soil profile and can complement surface liming by supplying calcium and sulfur and by improving chemical conditions in acidic subsoil. Crop responses nevertheless vary with soil properties, water availability, application rate, and time after application. A meta-analysis of no-tillage acid soils showed that positive grain-yield responses to gypsum were most likely when subsoil aluminum saturation was high (Pias *et al.*, 2020), whereas long-term field experiments have also demonstrated that residual responses depend on amendment rate and soil conditions (Caires *et al.*, 2011).

Although the agronomic effects of limestone and agricultural gypsum are well documented, fewer studies have examined whether the additional grain produced offsets the additional amendment cost under local market conditions. This economic distinction is

relevant because the highest-yielding combination may require an expenditure that is not recovered at the prevailing crop price. Evidence from smallholder and value-chain studies likewise shows that profitability depends on amendment price, complementary inputs, transport, and market conditions (Hijbeek *et al.*, 2021; Oumer *et al.*, 2023). Furthermore, conclusions based on a partial budget must be distinguished from total profitability because freight, field application, and production costs common to all treatments may not be included.

Therefore, this study aimed to evaluate maize grain yield and the partial economic performance of limestone and agricultural gypsum rates under no-tillage conditions in Roraima, Brazil, and to identify economically efficient strategies across a range of maize prices.

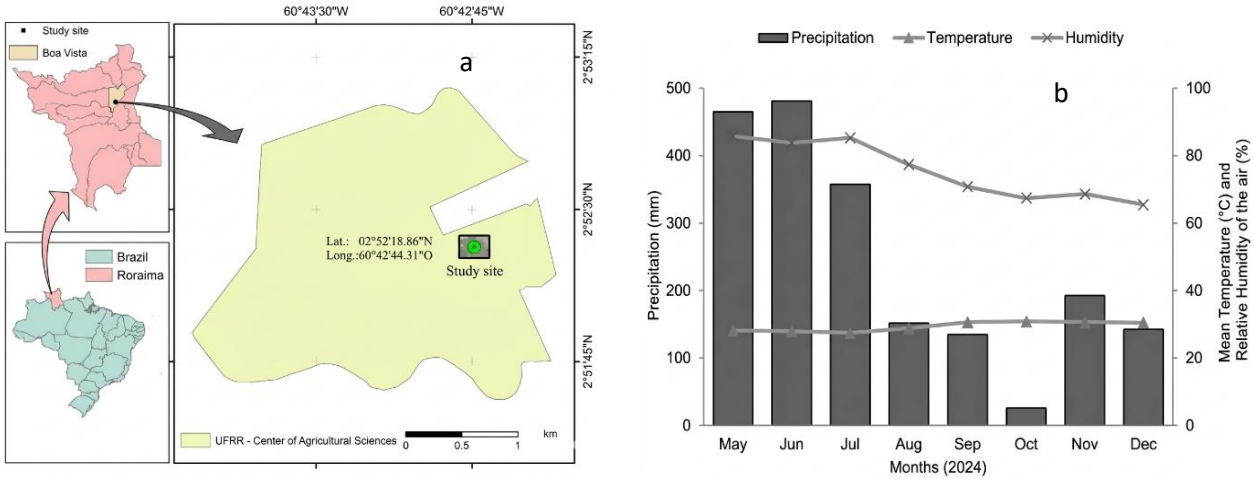
2 METHODOLOGY

2.1 CHARACTERIZATION OF THE EXPERIMENTAL AREA

The field experiment was established in May 2024 at the Center for Agricultural Sciences of the Federal University of Roraima (CCA/UFRR), in Boa Vista, Roraima, Brazil (2°52′18.86″ N, 60°42′44.31″ W; 85 m above sea level) (Figure 1a). Maize was harvested in August 2024. The location map was adapted from Benedetti *et al.* (2011). The site lies within the tropical monsoon (Am) domain represented in the 1991–2020 high-resolution Köppen–Geiger climate classification (Beck *et al.*, 2023). For broader seasonal characterization, monthly precipitation, mean air temperature, and mean relative humidity for May–December 2024 were obtained from the Boa Vista automatic weather station (A135) of the Brazilian National Institute of Meteorology (INMET, 2024) and are shown in Figure 1b.

Figure 1

Study location in Boa Vista, Roraima, Brazil (a), and monthly climate during May–December 2024 (b)



(a) Location map adapted from Benedetti *et al.* (2011); (b) precipitation, mean air temperature and mean relative humidity from INMET station A135 (INMET, 2024).
Source: Benedetti *et al.* (2011); INMET (2024).

The soil was classified as a Typic Dystrophic Yellow Latosol according to the Brazilian Soil Classification System (Santos *et al.*, 2013). Before the experiment, the area was covered by native savanna vegetation and had no recorded land use during the preceding 10 years. A composite soil sample was prepared from 20 subsamples collected across the experimental area. Soil chemical analyses were performed according to Teixeira *et al.* (2017). In the 0.00–0.20 m layer, the soil had pH 5.0; soil organic matter, 16.7 g dm^{-3}; P (Mehlich-1), 19.30 mg dm^{-3}; exchangeable K, Ca, Mg, Na, and Al of 0.19, 1.01, 0.46, trace, and 0.16 cmolc dm^{-3}, respectively; H+Al, 2.79 cmolc dm^{-3}; sum of bases, 1.67 cmolc dm^{-3}; effective cation-exchange capacity (CEC), 1.83 cmolc dm^{-3}; total CEC, 4.46 cmolc dm^{-3}; base saturation, 37.50%; and aluminum saturation, 8.73%. Clay contents at 0.00–0.10, 0.10–0.20, 0.20–0.40, and 0.40–0.60 m were 170, 220, 250, and 277 g kg^{-1}, respectively.

2.2 EXPERIMENTAL DESIGN AND SOIL AMENDMENTS

The experiment followed a randomized complete block design in a split-plot arrangement augmented with an additional control, with four replications. Limestone requirements were estimated using the base-saturation method for nominal targets of 50, 60, 70, and 80%. The corresponding rates of 0.55, 1.00, 1.45, and 1.90 t ha^{-1}, respectively, were assigned to the main plots. Within each limestone main plot, agricultural gypsum rates of 0,

0.60, 1.20, and 2.40 t ha^{-1} were assigned to the subplots and corresponded to 0, 50, 100, and 200%, respectively, of the 1.20 t ha^{-1} reference gypsum requirement adopted for the experiment. This reference requirement was established from the clay content of the 0.20–0.40 m layer following the regional recommendation framework of Sousa and Lobato (2004). Treatment combinations are presented in Table 1.

Table 1

Limestone and agricultural gypsum application rates for treatments defined by nominal base-saturation targets and the reference gypsum requirement

Trt.	Code	Limestone rate (t ha^{-1})	Agricultural gypsum rate (t ha^{-1})
T0	C0 G0	0.00	0.00
T1	C50% G0	0.55	0.00
T2	C50% G50%	0.55	0.60
T3	C50% G100%	0.55	1.20
T4	C50% G200%	0.55	2.40
T5	C60% G0	1.00	0.00
T6	C60% G50%	1.00	0.60
T7	C60% G100%	1.00	1.20
T8	C60% G200%	1.00	2.40
T9	C70% G0	1.45	0.00
T10	C70% G50%	1.45	0.60
T11	C70% G100%	1.45	1.20
T12	C70% G200%	1.45	2.40
T13	C80% G0	1.90	0.00
T14	C80% G50%	1.90	0.60
T15	C80% G100%	1.90	1.20
T16	C80% G200%	1.90	2.40

C0 denotes no limestone; C50%, C60%, C70%, and C80% denote limestone rates targeting base saturations of 50%, 60%, 70%, and 80%, respectively. G0, G50%, G100%, and G200% denote 0%, 50%, 100%, and 200% of the reference agricultural gypsum requirement, respectively. Source: Prepared by the authors.
Source: Prepared by the authors.

The additional absolute control received neither limestone nor agricultural gypsum and was evaluated as an unsplit main plot in each block.

Each main plot measured 9 × 16 m (144 m²) and was divided into four 9 × 4 m subplots (36 m²). Each subplot comprised five 9-m-long maize rows spaced 0.8 m apart, with hills spaced 0.5 m apart and three plants maintained per hill. Grain yield was determined in a 5 m² harvest area located in the central rows after exclusion of border plants. The target population was 75,000 plants ha^{-1}.

The dolomitic limestone had relative total neutralizing power of 95%, neutralizing power of 98.05%, 32.64% CaO, 14.95% MgO, 23.34% Ca, and 9.01% Mg. Agricultural gypsum contained 18.74% total Ca, 26.27% CaO, and 14.63% total S. The amendments were manually surface-applied without incorporation 30 days before sowing.

Fertilization was standardized across treatments and followed recommendations for high maize yield; therefore, fertilizer costs were common to all treatments and were not included in the partial budget.

2.3 CROP ESTABLISHMENT AND MANAGEMENT

The FS564PWU Agrisure Viptera maize hybrid was used. The hybrid is tolerant to postemergence glyphosate application and contains insect-resistance traits targeting Lepidoptera. It has an early cycle.

Maize was grown under no-tillage, with planting rows opened manually. Ten days before sowing, 300 kg ha^{-1} of a 04-14-08 N–P–K fertilizer and 50 kg ha^{-1} of FTE BR20 were broadcast according to the fertilization program adopted for the experiment (Comissão de Fertilidade do Solo do Estado de Minas Gerais, 1999). At sowing, 20 kg ha^{-1} N, 45 kg ha^{-1} K_2O, and 80 kg ha^{-1} P_2O_5 were applied as urea, potassium chloride, and triple superphosphate, respectively. Topdressing was performed at 20 days after sowing (DAS; V4) with 50 kg ha^{-1} N as ammonium sulfate and 50 kg ha^{-1} K_2O as potassium chloride; at 30 DAS (V7) with 50 kg ha^{-1} N as urea and 50 kg ha^{-1} K_2O as potassium chloride; and at 40 DAS (V10) with 50 kg ha^{-1} N as urea and 50 kg ha^{-1} K_2O as potassium chloride.

Glyphosate (480 g L^{-1} active ingredient) was applied postemergence at V4 at 1,200 g a.i. ha^{-1}. Pest management was performed as needed throughout the crop cycle.

2.4 MEASUREMENTS AND ECONOMIC ANALYSIS

For grain-yield determination, all ears from the 5 m² harvest area of each experimental unit were collected and mechanically threshed. Grain mass was measured, adjusted to 13% moisture, and expressed as kg ha^{-1}.

Economic performance was evaluated using an incremental partial-budget framework, which compares only the revenues and costs that change among management alternatives (Kelton *et al.*, 2025). The components included were additional maize revenue and the acquisition costs of limestone and agricultural gypsum. Freight, field-application costs, financing, and production costs common to all treatments were excluded. Therefore, the resulting partial net benefit is an incremental economic indicator rather than whole-farm profit.

For treatment i, additional grain yield was calculated relative to the absolute control (T0) and converted to 60-kg bags. Additional revenue was obtained by multiplying the additional number of bags by the adopted maize price. Partial net benefit was calculated as additional revenue minus the limestone and agricultural gypsum acquisition costs.

The partial-budget scenario adopted a maize price of R$ 66.00 per 60-kg bag, a dolomitic limestone price of R$ 540.00 t^{-1}, and an agricultural gypsum price of R$ 800.00 t^{-1}. These fixed prices were applied uniformly to all treatment means.

Economic dominance and switching-price analyses were used to assess whether the treatment ranking changed with maize price. A treatment was strictly dominated when another treatment had an equal or lower amendment cost and an equal or higher grain yield, with at least one strict inequality. After treatments were ordered by amendment cost, extended dominance was identified when an intermediate strategy had a higher incremental switching price than the subsequent strategy and therefore did not lie on the economic efficiency frontier. For adjacent strategies i and j on the frontier, the switching price was calculated as $Pij = (Cj - Ci)/[(Yj - Yi)/60]$, where C is amendment cost (R$ ha^{-1}) and Y is grain yield (kg ha^{-1}).

2.5 STATISTICAL ANALYSIS

Grain-yield data were subjected to analysis of variance (ANOVA) using R software (R Core Team, 2024), with the statistical model accounting for the split-plot structure and the additional absolute control. Normality and homogeneity of variance were evaluated using the Shapiro-Wilk and Levene tests, respectively. When treatment effects were significant ($p \leq 0.05$), Tukey's test was used to compare agricultural gypsum means within each limestone

level, and Dunnett's test was used to compare amended treatments with the absolute control (T0).

The economic analysis was descriptive and based on treatment mean yields; therefore, no inferential comparison was assigned to partial net benefits. Interpretation focused on partial net benefit, strict and extended dominance, and switching prices.

3 RESULTS AND DISCUSSION

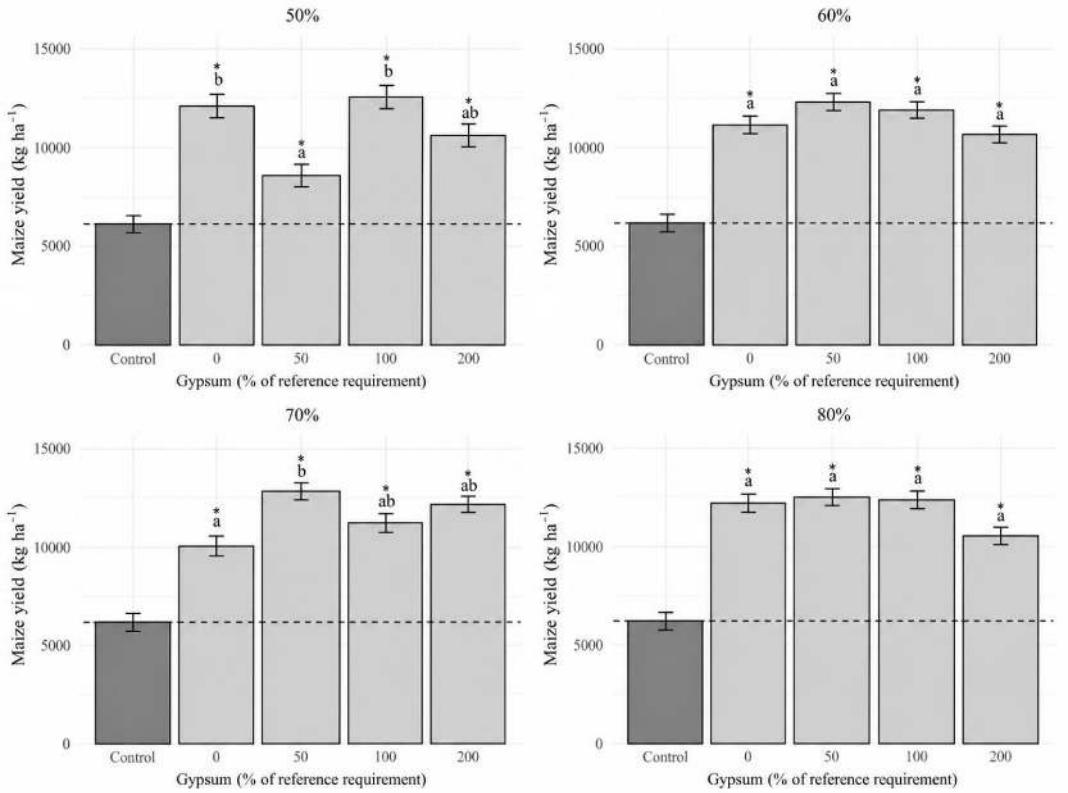
ANOVA indicated a significant interaction between limestone and agricultural gypsum rates ($p \leq 0.05$). Therefore, agricultural gypsum rates were compared separately within each limestone level (Figure 2). Different letters indicate differences by Tukey's test within a limestone level, and asterisks indicate differences from the absolute control by Dunnett's test ($p \leq 0.05$).

Liming without agricultural gypsum increased grain yield relative to the absolute control at all nominal base-saturation targets. The response to gypsum depended on the limestone rate. In the treatment targeting 50% base saturation, 100% of the reference gypsum requirement produced the highest observed mean yield (12,437.50 kg ha^{-1}). In contrast, in the treatments targeting 60, 70, and 80% base saturation, the highest observed mean yields occurred with 50% of the gypsum requirement: 12,021.70, 12,173.10, and 11,685.00 kg ha^{-1}, respectively.

The 200% gypsum rate did not produce the highest observed mean yield at any limestone level and generally produced less grain than one or more lower gypsum rates. Thus, the rate associated with the highest observed yield varied with the limestone treatment, and increasing gypsum beyond a moderate rate did not provide a consistent yield advantage.

Figure 2

Maize grain yield (kg ha⁻¹) in response to agricultural gypsum rates of 0, 50, 100, and 200% of the reference requirement under limestone rates corresponding to nominal base-saturation targets of 50, 60, 70, and 80%



Bars represent treatment means, and error bars indicate standard errors of the means. Within each limestone level, different letters indicate differences among agricultural gypsum rates by Tukey's test ($p \leq 0.05$). Asterisks indicate differences from the absolute control by Dunnett's test ($p \leq 0.05$).
Source: Prepared by the authors.

The marked response to limestone is compatible with the initial soil conditions, particularly pH 5.0 and base saturation of 37.5%. Field evidence shows that liming acidic soils can increase pH, exchangeable bases, nutrient availability, and maize yield, but that response magnitude varies with lime formulation, application method, site, and accompanying fertilization (Alemu *et al.*, 2022; Kibet *et al.*, 2023). Broad evidence likewise indicates that effect sizes depend on initial soil conditions and management (Enesi *et al.*, 2023). Nevertheless, because soil chemical properties and root growth were not measured after amendment application, the mechanisms responsible for the yield responses in this experiment should be interpreted from the literature rather than as directly observed effects.

The interaction also produced contrasting economic outcomes because amendment cost increased independently of whether yield increased proportionally. The partial budget

therefore complements the agronomic analysis by distinguishing the highest-yielding treatment from the treatment that generated the greatest partial net benefit.

Limestone and agricultural gypsum acquisition costs increased directly with application rate (Table 2). T0 had no amendment cost, whereas the total cost ranged from R$ 297.00 ha^{-1} for T1 to R$ 2,946.00 ha^{-1} for T16. At a fixed limestone rate, moving from no gypsum to 200% of the reference requirement added R$ 1,920.00 ha^{-1}.

These values include only amendment acquisition. They do not represent total implementation cost because freight and field application were excluded, as were costs common to all treatments. The economic results should therefore be interpreted as comparative partial net benefits under the adopted prices.

Table 2

Estimated limestone and agricultural gypsum acquisition costs for each soil-amendment treatment based on prices adopted in the study

Trt.	Code	Limestone cost (R$ ha⁻¹)	Agricultural gypsum cost (R$ ha⁻¹)	Total amendment cost (R$ ha⁻¹)
T0	C0 G0	0.00	0.00	0.00
T1	C50% G0	297.00	0.00	297.00
T2	C50% G50%	297.00	480.00	777.00
T3	C50% G100%	297.00	960.00	1,257.00
T4	C50% G200%	297.00	1,920.00	2,217.00
T5	C60% G0	540.00	0.00	540.00
T6	C60% G50%	540.00	480.00	1,020.00
T7	C60% G100%	540.00	960.00	1,500.00
T8	C60% G200%	540.00	1,920.00	2,460.00
T9	C70% G0	783.00	0.00	783.00
T10	C70% G50%	783.00	480.00	1,263.00
T11	C70% G100%	783.00	960.00	1,743.00
T12	C70% G200%	783.00	1,920.00	2,703.00
T13	C80% G0	1,026.00	0.00	1,026.00
T14	C80% G50%	1,026.00	480.00	1,506.00
T15	C80% G100%	1,026.00	960.00	1,986.00
T16	C80% G200%	1,026.00	1,920.00	2,946.00

Costs were calculated using R$ 540.00 t⁻¹ for limestone and R$ 800.00 t⁻¹ for agricultural gypsum. Only amendment acquisition costs were included; freight, field application, and production costs common to all treatments were excluded. Source: Authors' calculations.
Source: Autores' calculations.

The R$ 2,946.00 ha⁻¹ difference between T16 and T0 illustrates the increasing financial exposure associated with high amendment rates. Whether this additional expenditure is justified depends on the corresponding yield gain and the maize price, not on amendment rate alone.

Accordingly, the treatment with the lowest acquisition cost is not automatically the best option, nor is the treatment with the highest yield necessarily the most economically efficient.

The relevant comparison is the additional revenue generated per unit of additional amendment cost.

The partial budget (Table 3) used T0, with a yield of 6,148.88 kg ha^{-1}, as the baseline. Every limed treatment had a positive partial net benefit at R$ 66.00 per bag, but the magnitude varied substantially because yield gains did not increase proportionally with amendment cost.

Table 3

Maize grain yield, amendment costs, additional grain yield, additional revenue, and partial net benefit for soil-amendment treatments relative to the absolute control

Trt.	Code	Grain yield (kg ha⁻¹)	Amendment cost (R$ ha⁻¹)	Additional grain yield (kg ha⁻¹)	Additional grain yield (60-kg bags ha⁻¹)	Additional revenue (R$ ha⁻¹)	Partial net benefit (R$ ha⁻¹)
T0	C0 G0	6,148.88	0.00	0.00	0.00	0.00	0.00
T1	C50% G0	11,985.80	297.00	5,836.92	97.28	6,420.61	6,123.61
T2	C50% G50%	8,604.17	777.00	2,455.29	40.92	2,700.82	1,923.82
T3	C50% G100%	12,437.50	1,257.00	6,288.62	104.81	6,917.48	5,660.48
T4	C50% G200%	10,530.00	2,217.00	4,381.12	73.02	4,819.23	2,602.23
T5	C60% G0	10,983.30	540.00	4,834.42	80.57	5,317.86	4,777.86
T6	C60% G50%	12,021.70	1,020.00	5,872.82	97.88	6,460.10	5,440.10
T7	C60% G100%	11,786.70	1,500.00	5,637.82	93.96	6,201.60	4,701.60
T8	C60% G200%	10,595.80	2,460.00	4,446.92	74.12	4,891.61	2,431.61
T9	C70% G0	10,010.00	783.00	3,861.12	64.35	4,247.23	3,464.23
T10	C70% G50%	12,173.10	1,263.00	6,024.22	100.40	6,626.64	5,363.64
T11	C70% G100%	10,675.00	1,743.00	4,526.12	75.44	4,978.73	3,235.73
T12	C70% G200%	11,415.00	2,703.00	5,266.12	87.77	5,792.73	3,089.73
T13	C80% G0	11,424.40	1,026.00	5,275.52	87.93	5,803.07	4,777.07
T14	C80% G50%	11,685.00	1,506.00	5,536.12	92.27	6,089.73	4,583.73
T15	C80% G100%	11,575.00	1,986.00	5,426.12	90.44	5,968.73	3,982.73
T16	C80% G200%	10,395.00	2,946.00	4,246.12	70.77	4,670.73	1,724.73

Additional values were calculated relative to the absolute control (T0). Additional revenue was calculated using R$ 66.00 per 60-kg bag. Partial net benefit equals additional revenue minus limestone and agricultural gypsum acquisition costs; freight, field application, and production costs common to all treatments were excluded. Values are based on treatment means and do not represent inferential economic comparisons.
Source: Authors' calculations.
Source: Authors' calculations.

Among the limestone-only treatments (T1, T5, T9, and T13), T1 (C50%G0) had the highest yield, 11,985.80 kg ha⁻¹, corresponding to an increase of 5,836.92 kg ha⁻¹ (97.28 bags ha⁻¹; 94.9%) over T0. Because its amendment cost was only R$ 297.00 ha⁻¹, T1

generated the highest partial net benefit in the study, R$ 6,123.61 ha^{-1}, at the adopted maize price.

The strong response to the lowest limestone rate is agronomically plausible in an acidic, low-base-saturation soil. Recent field studies indicate that relatively small or micro-dosed lime applications can improve crop performance and soil chemical properties when rates are matched to local acidity and management conditions (Dugalić *et al.*, 2024; Yenesew *et al.*, 2024), while broader evidence shows that yield responses may plateau as lime rates increase (Enesi *et al.*, 2023). These results reinforce the need for soil-specific lime recommendations rather than uniform rates (Merlos *et al.*, 2023). However, the present data do not demonstrate which chemical or biological process was responsible, because post-treatment soil properties, nutrient uptake, and root attributes were not evaluated.

The economic advantage of T1 resulted from the combination of a large yield gain and the lowest amendment cost among the limed treatments. Higher limestone rates without gypsum did not produce proportional additional yield, so their partial net benefits were lower. This result supports a rate-specific economic interpretation rather than the assumption that progressively higher base-saturation targets necessarily increase economic performance.

T3 (C50%G100%) produced the highest observed grain yield, 12,437.50 kg ha^{-1}, an increase of 6,288.62 kg ha^{-1} (104.81 bags ha^{-1}; 102.3%) over T0. Its total amendment cost was R$ 1,257.00 ha^{-1}, resulting in a partial net benefit of R$ 5,660.48 ha^{-1}, the second highest in the study. Thus, T3 had the highest observed physical output but did not maximize partial net benefit at R$ 66.00 per bag.

Agricultural gypsum can improve subsoil chemical conditions because of its mobility and its supply of calcium and sulfur. In four no-tillage Oxisol experiments encompassing 17 harvests, Dalla Nora *et al.* (2017) observed yield increases from gypsum and lime in 82% of the harvests and reported that combined application was especially beneficial where acidity or an abrupt decline in chemical quality constrained a thicker root zone. More recent evidence from a double-cropped system showed that lime and gypsum can jointly improve soil fertility, soil physical conditions, and crop yields while modifying fertilizer requirements (de Oliveira Andrade *et al.*, 2025). This evidence is consistent with the complementary response of T3, but it does not establish the underlying mechanism in the present experiment because post-treatment soil chemistry and root growth were not measured.

The interaction pattern shows that the gypsum rate associated with the highest observed mean yield depended on limestone rate. The highest observed yield occurred at

100% of the reference gypsum requirement under the nominal 50% base-saturation target, whereas it occurred at 50% of the reference requirement under the 60, 70, and 80% targets. Contrasting field evidence reinforces this conditional response: Dalla Nora *et al.* (2017) reported lime–gypsum synergy under restrictive root-zone conditions, whereas Fontoura *et al.* (2019) found no interaction in a moderately acidic clayey Oxisol and only a 4% mean yield gain from gypsum in three of 22 crop seasons. Long-term evidence also indicates that crop response depends on amendment reactivity, residual acidity dynamics, and time after application (Alves *et al.*, 2025). Thus, initial subsoil acidity and the existing calcium and sulfur status, rather than gypsum dose alone, are central to determining whether a yield response occurs (Pias *et al.*, 2020). Because gypsum-only treatments were not included, the present results apply to gypsum used with limestone and do not quantify its response in unlimed soil.

At all limestone levels, 200% of the gypsum requirement failed to produce the highest observed mean yield. Evidence from a coarse-textured Ultisol with low cation-exchange capacity showed that gypsum reduced maize yield in the first harvest by 0.20 Mg ha^{-1} for each Mg ha^{-1} applied, while later maize and soybean harvests did not respond (Alves *et al.*, 2021). In a very clayey Oxisol with low initial acidity, Minato *et al.* (2023) likewise observed declining soil magnesium with increasing gypsum rates and no effect of limestone or gypsum on cumulative soybean-maize yield. These comparisons make nutrient imbalance a plausible explanation to test, especially given the low total CEC of the soil in the present study, but the lower yields at high gypsum rates cannot be attributed to magnesium loss because post-treatment soil and plant measurements were not performed.

T16 (C80%G200%) combined the highest amendment cost (R$ 2,946.00 ha^{-1}) with a partial net benefit of only R$ 1,724.73 ha^{-1}, the lowest among amended treatments. The additional expenditure was therefore not offset by a proportional yield gain under the adopted price conditions.

Moderate gypsum use produced comparatively high partial net benefits in T6 and T10, R$ 5,440.10 and R$ 5,363.64 ha^{-1}, respectively. Nevertheless, neither treatment remained on the economic efficiency frontier: T10 was strictly dominated by T3, and T6 was removed through extended dominance. Positive partial net benefit alone is therefore insufficient to identify the economically preferred strategy when a more efficient alternative is available.

Taken together, these field studies and the meta-analyses of Pias *et al.* (2020) and Enesi *et al.* (2023) show that limestone and agricultural gypsum can improve crop performance in acidic soils, but the magnitude and economic value of the response depend

on initial soil conditions, amendment rate, and input prices. In the present study, this conditionality was expressed by the lack of a monotonic yield response to either progressively higher nominal base-saturation targets or gypsum rates.

The partial-budget scope is an important limitation. In Rwanda, Jaleta *et al.* (2024) estimated substantial maize yield gains from liming, but the first-season financial margin was narrow at the unsubsidized lime price and became clearly positive with a 50% subsidy; the authors also noted that excluding transport and labor costs overestimates returns. Studies in Kenya and Ethiopia similarly show that short-term profitability is sensitive to complementary fertilizer use, amendment supply chains, transport, and residual benefits (Hijbeek *et al.*, 2021; Oumer *et al.*, 2023). Although those production and market conditions differ from Roraima, they reinforce that an agronomic response does not by itself establish profitability. In the present analysis, including freight, field application, financing, or other treatment-specific operational costs would reduce partial net benefits and could increase the maize-price threshold required to justify gypsum. Conversely, a one-season budget does not capture possible residual benefits that may distribute amendment costs across later harvests (Fontoura *et al.*, 2019). Future budgets should therefore retain transparent incremental-cost definitions and test locally relevant price scenarios (Kelton *et al.*, 2025).

At R$ 66.00 per bag, T1 was the preferred strategy in the partial-budget comparison, whereas T3 was the highest-yielding alternative. These treatments represent different management objectives: minimizing amendment expenditure while retaining most of the attainable yield response versus accepting a higher cost to obtain the maximum observed yield.

To determine whether this ranking persisted at other maize prices, strict dominance, extended dominance, and switching-price analyses were applied (Table 4). After strictly dominated treatments and T6 through extended dominance were removed, only T0, T1, and T3 remained on the economic efficiency frontier.

Table 4

Partial net benefits, economic dominance, and maize-price thresholds for economically relevant soil-amendment strategies

Trt.	Amendment cost (R$ ha⁻¹)	Grain yield (kg ha⁻¹)	Partial net benefit (R$ ha⁻¹)	Switching price (R$ per 60-kg bag)	Preferred maize-price interval	Decision status
T0	0.00	6,148.88	0.00	—	Below R$ 3.05	Baseline (no amendment)
T1	297.00	11,985.80	6,123.61	3.05	R$ 3.05 to R$ 127.52	Preferred at the adopted price
T3	1,257.00	12,437.50	5,660.48	127.52	Above R$ 127.52	Highest-yield alternative

Switching prices identify the maize price at which the partial net benefit of the next strategy on the economic efficiency frontier exceeds that of the preceding strategy. At the adopted price of R$ 66.00 per 60-kg bag, T1 provides the highest partial net benefit. T2, T4, T5, T7, T8, T9, and T11–T16 were strictly dominated by T1; T10 was strictly dominated by T3; and T6 was excluded by extended dominance. Partial net benefit is relative to T0 and deducts only limestone and agricultural gypsum acquisition costs. Values are based on treatment means and do not represent inferential economic comparisons. Source: Authors' calculations.
Source: Authors' calculations.

The switching-price analysis indicated that T0 would be preferred only below R$ 3.05 per 60-kg bag. T1 maximized partial net benefit from R$ 3.05 to R$ 127.52 per bag and, at the adopted price of R$ 66.00, produced a partial net benefit of R$ 6,123.61 ha⁻¹ compared with R$ 5,660.48 ha⁻¹ for T3. The additional yield of T3 relative to T1 would offset its additional amendment cost only above R$ 127.52 per bag. T1 was therefore preferred in the partial-budget comparison across a broad price interval, while T3 became preferable only under substantially higher maize prices.

4 CONCLUSIONS

At the adopted maize price of R$ 66.00 per 60-kg bag, limestone applied alone at 0.55 t ha⁻¹, corresponding to the nominal 50% base-saturation target (T1), produced the highest partial net benefit, R$ 6,123.61 ha⁻¹.

The combination of 0.55 t ha⁻¹ limestone and 1.20 t ha⁻¹ agricultural gypsum (T3) produced the highest observed grain yield, 12,437.50 kg ha⁻¹, but a lower partial net benefit, R$ 5,660.48 ha⁻¹. T3 became economically preferred to T1 only when the maize price exceeded R$ 127.52 per bag.

Applying 200% of the reference gypsum requirement did not produce the highest observed mean yield at any limestone level and reduced economic efficiency because amendment costs increased without proportional yield gains.

These conclusions are conditional on the adopted grain and amendment prices and on the exclusion of freight and field-application costs. Future studies should evaluate residual responses across cropping seasons and conduct sensitivity analyses that jointly vary maize price, amendment price, transport cost, and application cost.

COMPETING INTERESTS

The authors declare no competing interests.

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