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Nitrogen management in second-crop maize in Southwestern Goiás

Manejo de nitrogênio no milho cultivado em segunda safra no sudoeste Goiano

Alice Maria Albert[1*], Gustavo Castoldi[1], Carlos Ribeiro Rodrigues[1], Thomas Jefferson Cavalcante[1], Matheus Martins Nogueira[1], Amanda Oliveira Fonseca[1]

[1]Instituto Federal Goiano, Campus Rio Verde. Rio Verde, GO, Brasil
[*]Corresponding authors: aliceberft@hotmail.com
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ABSTRACT
Nitrogen (N) fertilizer management is a key factor in the success of maize crops. The objective of this work was to evaluate the response of second-crop maize to N applied exclusively as topdressing or at planting + topdressing. Five experiments were conducted in areas in southwestern Goiás in 2019 and 2020 to evaluate N application rates of 0 and 30 kg ha^{-1} at planting, combined with five N rates applied as topdressing at the maize V3 stage over a total of 0, 75, 150, 225, and 300 kg ha^{-1}. Dry matter production in the V6 or V9 stage and yield parameters at harvest were evaluated. N application did not affect the number of grain rows per ear but increased the number of grains per row and, particularly, grain weight. The crop responded positively to increases in the total N rate in 4 of the 5 experiments: in 1 of these experiments, N fertilizer application at planting contributed to an increase in the efficiency of topdressing fertilization, resulting in a higher maize yield with a lower total N rate; in the other 3, a positive maize response to N occurred when total N was applied as topdressing at V3. However, the highest mean maize grain yield (8,233 kg ha^{-1}) was found in the trial that showed no response to N fertilizer application – probably due to the better chemical fertility conditions of the area combined with an adequate distribution of rainfall, considering the multiple factors involved in N application recommendations.

Index terms: *Zea mays* L.; N fertilizer application; grain yield.

RESUMO
O manejo de nitrogênio (N) na cultura do milho é fator chave para o sucesso de seu cultivo, de modo que se objetivou com esse estudo avaliar a resposta da cultura, em segunda safra, à doses de N aplicadas exclusivamente em cobertura ou na adubação de base (semeadura) complementada com a adubação de cobertura. Para tal, em 2019 e 2020 foram realizados cinco experimentos em áreas da região Sudoeste do Estado de Goiás, testando 0 e 30 kg ha^{-1} de N aplicados na base combinados com cinco doses totais de N (0, 75, 150, 225 e 300 kg ha^{-1}) completadas em cobertura, quando as plantas estavam em estádio V3. Avaliou-se a produção de massa seca na fase vegetativa V6 ou V9, e, por ocasião da colheita, os parâmetros produtivos. Verificou que a aplicação de N não interfere no número de fileiras de grãos, mas aumenta o número de grãos por fileira e, principalmente, o peso de grãos. Em 4 dos 5 ensaios, a cultura respondeu positivamente ao incremento da dose total de N; em 1 desses, a adubação de base contribuiu para aumento da eficiência da adubação de cobertura, de modo que a produtividade do milho foi maior e atingida com uma dose total de N menor. Nos outros 3, respostas positivas foram observadas quando da aplicação total do N em cobertura e em dose única. A maior produtividade média de grãos de milho (8.233 kg ha^{-1}), no entanto, ocorreu justamente no ensaio com ausência de resposta à adubação nitrogenada – provavelmente devido às melhores condições de fertilidade química da área aliada à adequada distribuição das chuvas, considerando assim múltiplos fatores para N recomendações de aplicação.

Termos para indexação: *Zea mays* L.; adubação nitrogenada; produtividade de grãos.

INTRODUCTION

Adequate availability of nutrients, particularly nitrogen (N), for plants throughout the vegetative and reproductive stages is one of the most important factors in obtaining a high grain yield in maize (*Zea mays* L.) crops (Von Pinho et al., 2009). Increases in world food production have involved the expansion of maize crops and, consequently, increases in the consumption of N fertilizers due to the high N demand of these plants (Pires et al., 2015; Sui et al., 2015; Jankowski et al., 2018; Shen et al., 2018)

In plants, N is a constituent of chlorophylls, proteins, enzymes, DNA, and RNA and is important for metabolic, biochemical, and physiological processes; thus, it is the most highly accumulated nutrient in most cultivated plants (Marschner; Kirkby; Cakmak, 1996; Hawkesford et al., 2012; Elazab et al., 2016; Gabriel et al., 2017). N deficiency in maize reduces plant height, the leaf area index, shoot and root growth, biomass production, and the number of ears per plant and consequently reduces grain yield (Li et al., 2009; Wang; Xing, 2017; Qi; Hu; Xue, 2020).

Nitrogen use efficiency in plants is relatively low due to the combination of climate conditions and N transformation processes in the soil, which are mediated by microorganisms, resulting in N losses by volatilization and leaching (Cantarella; Duarte, 2004; Afshar et al., 2018; Panday et al., 2020). This dynamic makes the management and recommendation of N application complicated. The correct use of N fertilizers at optimal rates results in increases in the production parameters of maize crops and decreases in N losses, reducing production costs and potential environmental damage. The main N source used in Brazil is urea, mainly because of its high N concentration (45% to 46%), which results in a lower price per unit of nutrient applied (Empresa Brasileira de Pesquisa Agropecuária - Embrapa, 2018; Internation Fertilizer Association-IFA, 2022).

Nitrogen fertilizer application in maize crops is carried out at planting and as topdressing until the V4 to V6 stages. The results have shown that N fertilizer application at planting can be a determining factor for better initial growth of maize crops, increasing the production potential and even the topdressing efficiency (Simão et al., 2021). Studies conducted on second-crop maize in the states of Mato Grosso and São Paulo, Brazil, compared the application of 0 or 39 kg ha^{-1} of N at planting and found grain yield increases only when N was applied at planting (Duarte; Cantarella; Kappes, 2017).

In maize crops grown in the Central-West region of Brazil under rainfed conditions, N is commonly applied as topdressing when the plants have up to 6 fully expanded leaves (V6 stage), with a single application in some cases. In addition to being operationally interesting, the results of this strategy have shown that maize can positively respond to high N rates (> 180 kg ha^{-1}) applied in a single application in early stages (V3–V4) (Lyra et al., 2014). Maize crop responses to N fertilizer application are variable and depend on several factors, such as the management system adopted (conventional, no-tillage, and crop rotation), the previous crop, the use of hybrids, the region (climate, soil, and altitude) and the planting season. The literature shows different results, with the highest maize yields obtained under N rates of 20 to 90 kg ha^{-1} (Simão et al., 2021), 60 to 120 kg ha^{-1} (Amado et al., 2017), 0 to 180 kg ha^{-1} (Ahmad et al., 2020) or even 250 kg ha^{-1} (Lyra et al., 2014) applied as topdressing.

Therefore, determining the optimal N rate for maize crops is a complicated task, as there are different variables that should be taken into consideration. In this context, the objective of this work was to evaluate N management strategies for second-crop maize based on the application of N (or lack thereof) at planting and the application of different N rates as topdressing in different agricultural areas in southwestern Goiás.

MATERIAL AND METHODS

The study comprised five field experiments carried out in grain-producing areas in the southwest region of the state of Goiás (municipalities of Jataí, Rio Verde, and Montividiu), Brazil. According to the Köppen (1931) international climate classification, the climate of the region is Aw, tropical with a dry winter; the regions presented cumulative rainfall of approximately 359 to 595 mm during the experiments (Table 1) (Alvares et al., 2013).

The experiments were conducted in two years (2019 and 2020) in the second crop seasons, and the experimental areas were designated A1 to A5 for ease of reference: A1, municipality of Jataí, Rio Verdinho 3 Barras Farm (2019); A2 and A3, municipality of Rio Verde, research station of the Group Terra Forte (2019); A4, municipality of Jataí, Rio Verdinho 3 Barras Farm (2020); and A5, municipality of Montividiu, Goiás State Agriculture Institute (2020).

The soils of the areas were sampled for the characterization of fertility and granulometry before the implementation of the experiments (Table 2).

The soils of all study areas were prepared under a no-tillage system, with planting on the straw of the preceding crops. In A1 and A4, the preceding crop was maize, and in the other areas (A2, A3, and A5), the preceding crop was soybean.

A randomized block experimental design in a 5×2 factorial arrangement with four replications was used for each experiment, where the factors consisted of rates of 0 and 30 kg ha^{-1} of N at planting, combined with five N rates as topdressing at the maize V3 stage over a total of 0, 75, 150, 225, and 300 kg ha^{-1}. Each plot was 6 m long and 4 m wide (8 rows of planting), totalling 24 m^2, with 12 m^2 of useful area.

Table 1: Planting dates, mean minimum and maximum temperatures, and cumulative rainfall during the experiments (Instituto Nacional de Meterologia - INMET, 2022).

	Municipality	Mean Maximum Temperature (°C)	Mean Minimum Temperature (°C)	Cumulative rainfall (mm)	Planting date
Area 1	Jataí	23.30	21.80	595.20	February 02, 2019
Areas 2 and 3	Rio Verde	23.50	22.00	388.84	February 19, 2019
Area 4	Jataí	23.40	21.90	359.60	February 13, 2020
Area 5	Montividiu	28.70	26.70	487.30	February 21, 2020

Table 2: Soil granulometry and chemical attributes of the 0–0.2 m layer.

Area	pH	P	K^+	Ca^{2+}	Mg^{2+}	Al^{3+}	H+Al	SB	OM	Sand	Silt	Clay
		mg dm^{-3}	-------------------------			$cmol_c$ dm^{-3}		-------------------------	g dm^{-3}		g kg^{-1}	
1	5.35	7.92	0.22	2.16	0.58	0.02	1.63	2.96	40.4	420	140	440
2	5.75	5.32	0.31	1.98	0.80	0.02	1.06	3.09	29.4	460	120	420
3	5.45	2.26	0.11	0.99	0.59	0.03	1.06	1.69	28.2	640	120	240
4	5.32	7.90	0.22	2.02	0.51	0.02	1.63	2.75	40.4	420	140	440
5	5.70	6.60	0.30	3.76	1.21	0.01	1.60	5.27	42.2	340	160	500

pH determined in calcium chloride ($CaCl_2$); P determined in Mehlich 1; K^+, Ca^{2+}, Mg^{2+} and Al^{3+} extracted with potassium chloride solution at 1 mol L^{-1}; H+Al determined in SMP buffer solution at pH 7.5.

The hybrid Dekalb DKB390 was used in all experiments; the seeds were sown mechanically, with a spacing of 0.5 m between rows for a population of 60,000 plants ha^{-1}; 30 kg ha^{-1} of N was applied on the same day as planting for the treatments with fertilizer application at planting; the fertilizer was applied manually alongside each planting row. Topdressing was carried out only once and was applied at the maize V3 stage; the fertilizer was manually broadcast over the total plot area to reach the total rates specified for each treatment. Urea (45% of N) treated with N-butyl thiophosphoric triamide (NBPT), which is a urease-inhibiting compound, was used as a source of N in the application of fertilizer at planting and as topdressing.

Five plants from each plot were sampled at the maize V6 (A1, A2, A3, and A4) or V9 (A5) stage; they were cut at ground level, taken to a laboratory, and dried in a forced air circulation oven at 65 °C until constant weight. Then, the entire aerial part of the plant was weighed on a precision balance to determine the dry weight.

Ears within two metres of the four central rows of each plot were collected at harvest. Ten ears per plot were used to determine the number of grain rows and number of grains per row. The ears were mechanically threshed, and the grains were evaluated for moisture content and weighed to calculate the yield corrected to 13% moisture. One-thousand grain weight was determined by weighing 8 subsamples of 100 grains per plot.

The collected data were subjected to analysis of variance and Tukey's test at a 5% probability to compare the treatments with N fertilizer application at planting and the fit to polynomial linear or quadratic models as a function of N topdressing rates. The analyses were carried out in the Sisvar program (Ferreira, 2011).

RESULTS AND DISCUSSION

The number of grain rows per ear was the only variable not affected by N management in the evaluated areas (Table 3). This result occurred because this production component variable is more closely related to genetic potential than fertilizer application (Bertheloot; Martre; Andrieu, 2008; Valderrama et al., 2011).

The interaction between N fertilizer application at planting and as topdressing was significant only for dry weight at the maize V6 stage in areas A3 and A4 and for grain yield in area A2 (Table 3). It is important to mention that the magnitude of the response to N fertilizer is closely related to the response capacity of the genotype. In this context, the DKB390 hybrid seems to show a reasonable ability to recover N from fertilizer and use it efficiently (Carvalho; Von Pinho; Davide, 2011).

Table 3: Analysis of variance for dry weight (V6 or V9 stage), number of grain rows per ear, number of grains per row, one-thousand grain weight, and grain yield of second-crop maize as a function of nitrogen (N) rates applied at planting (0 and 30 kg ha^{-1}) and complemented by N as topdressing in five areas in southwestern Goiás.

Variable	Planting (P)	Topdressing (T)	P*T	CV (%)	$\hat{x}$
Jataí – GO 2019 second crop (A1)					
Dry weight V6	0.702^{ns}	3.557**	1.200^{ns}	25.3	20.14 kg ha^{-1}
One-thousand grain weight	5.852^{ns}	15.790**	0.850^{ns}	4.93	341.44 g
Number of grain rows	0.859^{ns}	1.765^{ns}	0.143^{ns}	6.00	17.05
Number of grains per row	0.368^{ns}	10.203**	0.312^{ns}	5.65	32.28
Grain yield	0.150^{ns}	19.058**	0.853^{ns}	10.2	5,451.80 kg ha^{-1}
Rio Verde – GO 2019 second crop (A2)					
Dry weight V6	22.622^{ns}	5.483**	1.314^{ns}	19.9	17.01 kg ha^{-1}
One-thousand grain weight	0.001^{ns}	5.139**	0.530^{ns}	4.79	315.70 g
Number of rows of grains	0.055^{ns}	1.185^{ns}	0.399^{ns}	4.33	31.10
Number of grains per row	0.190^{ns}	0.490^{ns}	1.402^{ns}	4.40	17.31
Grain yield	4.159^{ns}	5.148**	4.956**	6.80	6,280.49 kg ha^{-1}
Rio Verde – GO 2019 second crop (A3)					
Dry weight V6	108.381**	6.712**	3.122*	11.6	16.35 kg ha^{-1}
One-thousand grain weight	0.006^{ns}	3.101*	1.195^{ns}	4.23	321.28 g
Number of rows of grains	0.008^{ns}	0.907^{ns}	1.195^{ns}	4.16	17.23
Number of grains per row	0.188^{ns}	1.556^{ns}	0.660^{ns}	4.65	32.17
Grain yield	2.147^{ns}	7.018**	0.691^{ns}	6.49	3,547.48 kg ha^{-1}
Jataí – GO 2020 second crop (A4)					
Dry weight V6	2.654^{ns}	9.281**	3.242*	19.7	15.98 kg ha^{-1}
One-thousand grain weight	0.592^{ns}	12.050**	0.370^{ns}	4.16	352.65 g
Number of rows of grains	0.00^{ns}	0.359^{ns}	1.316^{ns}	4.31	16.75
Number of grains per row	0.940^{ns}	2.738*	1.984^{ns}	4.00	36.73
Grain yield	1.937^{ns}	5.817**	0.774^{ns}	4.18	6,447.01 kg ha^{-1}
Montividiu – GO 2020 second crop (A5)					
Dry weight V9	8.387**	1.209^{ns}	0.888^{ns}	13.6	87.87 kg ha^{-1}
One-thousand grain weight	4.523^{ns}	1.933^{ns}	1.469^{ns}	9.06	305.98 g
Number of rows of grains	1.893^{ns}	1.313^{ns}	0.927^{ns}	4.85	16.58
Number of grains per row	1.11^{ns}	0.350^{ns}	0.494^{ns}	9.17	36.93
Grain yield	1.178^{ns}	0.301^{ns}	0.482^{ns}	10.6	8,232.60 kg ha^{-1}

In A5, the application of N fertilizer at planting affected only dry weight in the maize V9 stage, with the highest growth found in plants treated with 30 kg ha^{-1} of N at planting (93.4 kg ha^{-1}).

Increases in maize initial growth usually result in increases in production potential, as the crop has a high demand for N at initial development stages; this is an important element in the definition of maize production potential, which is defined at early stages (Resende et al., 2018, Simão et al., 2021). The application of 45 kg ha^{-1} of N at planting resulted in increases in maize grain yield, with values between 805 and 1,506 kg ha^{-1} (Simão et al., 2021). In the present work, increases exclusively due to N at planting were found only in the vegetative stage in one area (A5), which was not sufficient to result in differences in grain yield.

It is important to point out, however, that A5 presented a higher grain yield than the other evaluated areas, with a mean of 8,233 kg ha^{-1}, which is 27% higher than the mean yield of the state of Goiás (6,495 kg ha^{-1}) (Companhia Nacional de Abastecimento - Conab, 2021). One of the possible explanations for this result is that the area presents better chemical fertility due to higher contents of clay, organic matter, and particularly Ca and Mg (Table 2), which, combined with the adequate rainfall distribution, may have limited the differentiation between treatments.

The dry weight data at the vegetative stage were fitted to linear and quadratic models as a function of N topdressing rates in A1 and A2, respectively (Figure 1). In A1, the dry weight at the V6 stage increased as the N rate was increased up to 300 kg ha^{-1}, and in A2, it increased up to the N rate of 108 kg ha^{-1}.

The statistical breakdown of the interaction between fertilizer application at planting and as topdressing for dry weight at the vegetative stage (Figure 2) showed that the application of 30 kg ha^{-1} N at planting seemed to have boosted the N topdressing application, as the dry weight at the V6 stage in both areas (A3 and A4) presented an increasing linear angle coefficient. However, no significant difference was found between fertilizer application at planting (0 and 30 kg ha^{-1}) in the two areas (A3 and A4) when the total rate of 300 kg ha^{-1} was applied; thus, the highest N rate evaluated did not result in large increases in dry weight.

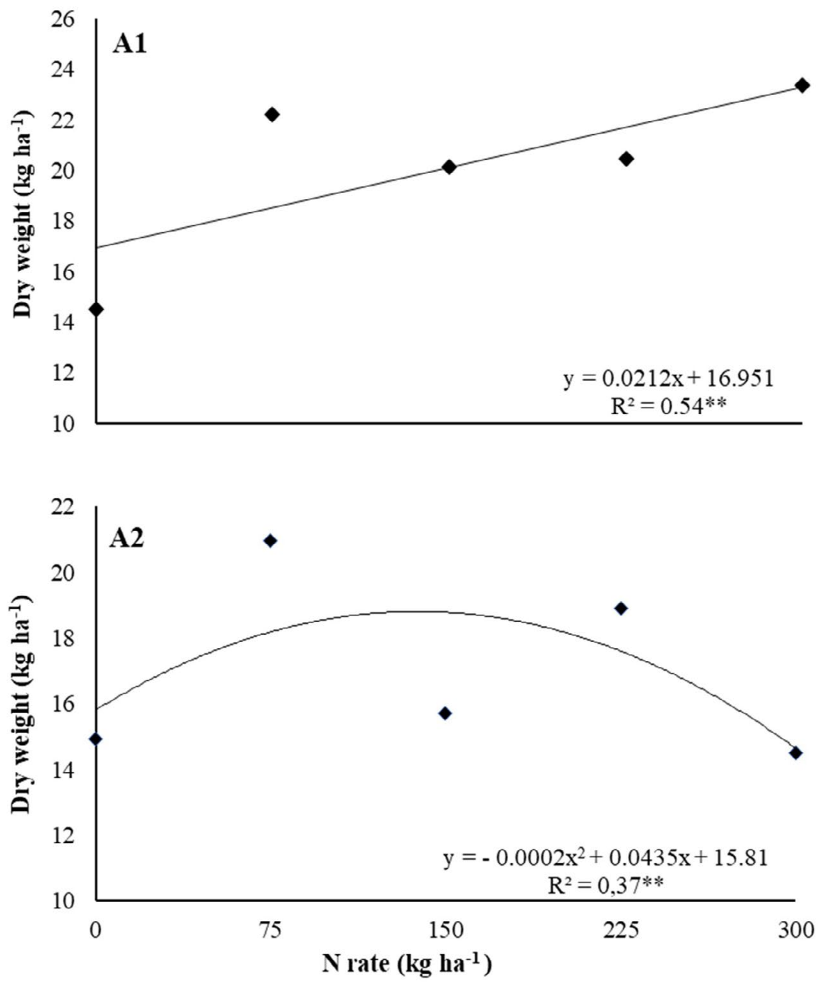

Figure 1: Dry weight of second-crop maize plants (V6 phenological stage) in areas in southwestern Goiás (A1 and A2) as a function of N rates applied as topdressing at the V3 stage.

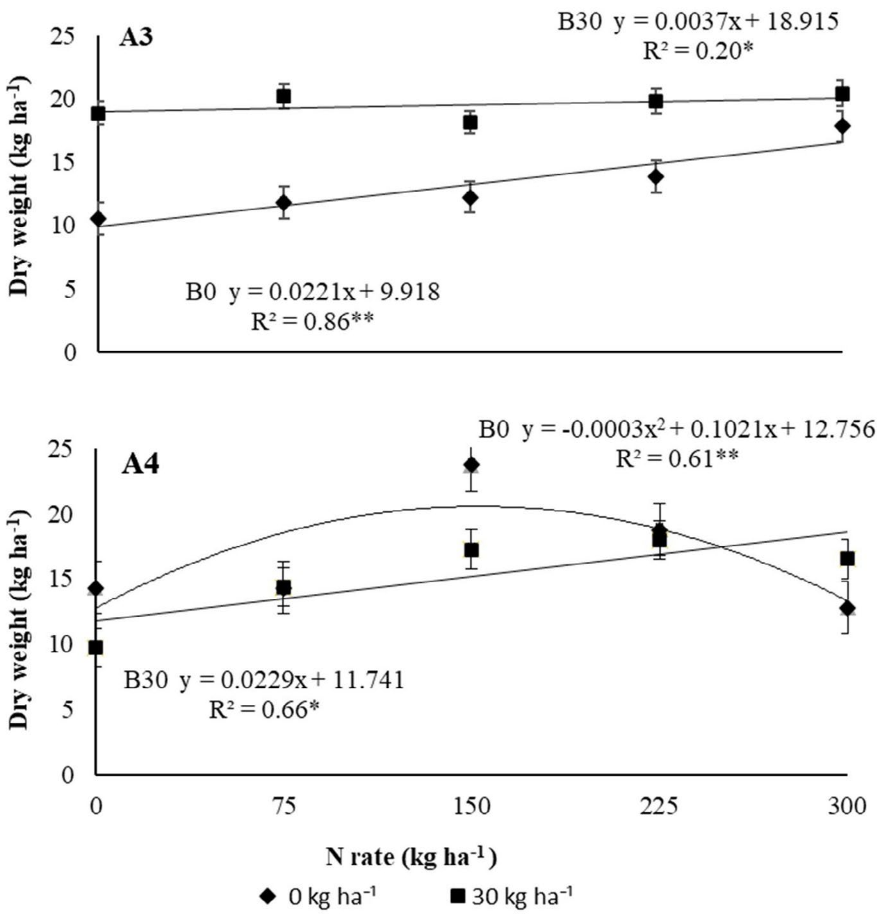

Figure 2: Dry weight of second-crop maize plants (V6 phenological stage) in areas in southwestern Goiás (A3 and A4) as a function of nitrogen rates applied at planting (0 and 30 kg ha^{-1}) and complemented by topdressed nitrogen at the V3 stage.

The results for one-thousand grain weight found in areas A1, A2, A3, and A4 in response to N topdressing rates are shown in Figure 3. Increases in N rates applied as topdressing resulted in positive effects on one-thousand grain weight, and the data fitted to linear (A1 and A4) and quadratic (A2 and A3) equations, with the highest grain weight found for the estimated N rates of 233 and 172 kg ha^{-1}, respectively.

One-thousand grain weight is an important production parameter, as it is possible to achieve higher yields with the same number of fertilized ovules due to the increase in grain reserves (Sponchiado et al., 2020). A1, A2, A3, and A4 presented increases in one-thousand grain weight as the N rates applied were increased, which can be connected to a greater increase in plant photosynthetic activity when using the highest N rates, resulting in large accumulation of reserves in maize grains (Neto et al., 2004).

The N rates applied as topdressing to the maize resulted in linear increases in the number of grains per row in A1 and A4 (Figure 4). The adequate application of N can result in decreases in the abortion of grains, as this nutrient favours the production of photoassimilates, resulting in increases in the number of grains per row (Magalhães et al., 2002; Qi; Hu; Liu, 2020). Maize grain yield is directly related to the number of grains per row; thus, the increase in the number of grains per row in A1 and A4 was directly related to their grain yield (Figure 5).

Topdressing had a positive effect on grain yield in A1, A3, and A4 (Figure 5). A1 and A4 presented positive linear responses to the increases in N rates, with the highest estimated grain yield (6,476 kg ha^{-1} in A1 and 6,700 kg ha^{-1} in A4) found for the highest N rate (300 kg ha^{-1}), whereas the yield results of A3 fitted to a second-degree equation, with the highest estimated grain yield (3,761 kg ha^{-1}) found for the N rate of 174 kg ha^{-1}.

The A1 and A4 treatments were performed at the same place but in different crop seasons (A1 = 2019 and A4 = 2020); thus, the single difference between them was the cumulative rainfall during crop growth. However, this factor had little effect on grain yield, which was stable, with a difference of 224 kg ha^{-1} in the highest yields between these areas. The relatively low highest grain yield found in area A3 may have been due to its lower organic matter and clay contents, which affect the soil cation exchange capacity and may result in a low soil water retention capacity, and to its lower exchangeable base contents, particularly those of K and Ca (Table 2). Organic matter is related to soil buffering and sorption properties, which are associated with the efficient use of nutrients, including N. High soil pH buffering capacities, characterized by high clay and organic matter contents, are related to decreases in the potential loss of N from urea as ammonia (Klimczyk; Siczek; Schimmelpfennig, 2021), which may explain the lower grain yield in A3.

The grain yield of area A2 was significantly affected by the interaction between fertilizer application at planting and as topdressing (Table 3). When N was not applied at planting, the grain yield presented a linear response to N topdressing rates, with the highest estimated grain yield (6,546 kg ha^{-1}) found for the N rate of 300 kg ha^{-1} (Figure 6). When 30 kg ha^{-1} of N was applied at planting, the response to topdressing was quadratic, with the highest estimated grain yield (6,754 kg ha^{-1}) found for the N rate of 142 kg ha^{-1}.

The highest yields achieved when using N rates of 0 and 30 kg ha^{-1} at planting were similar. However, the results show that the application of 30 kg ha^{-1} of N at planting resulted in the highest grain yield with an intermediate total N rate (142 kg ha^{-1}), and when not applying N at planting, the same result was only obtained when using the highest N rate (300 kg ha^{-1}) (Figure 6).

In this case (A2), N fertilizer application at planting seems to have boosted the efficiency of topdressing application, which confirms some results in the literature, highlighting that N fertilizer applications at planting result in the acceleration of vegetative phenological stages of maize crops, resulting in high grain yields (Blandino et al., 2022). When maize is grown as a sole crop or intercropped with *Urochloa brizantha* or *Megathyrsus maximus*, N fertilizer application at planting is important to obtain a greater number of ears per plant, number of grains per ear, one-thousand grain weight, dry weight, and grain yield (Crusciol et al., 2020).

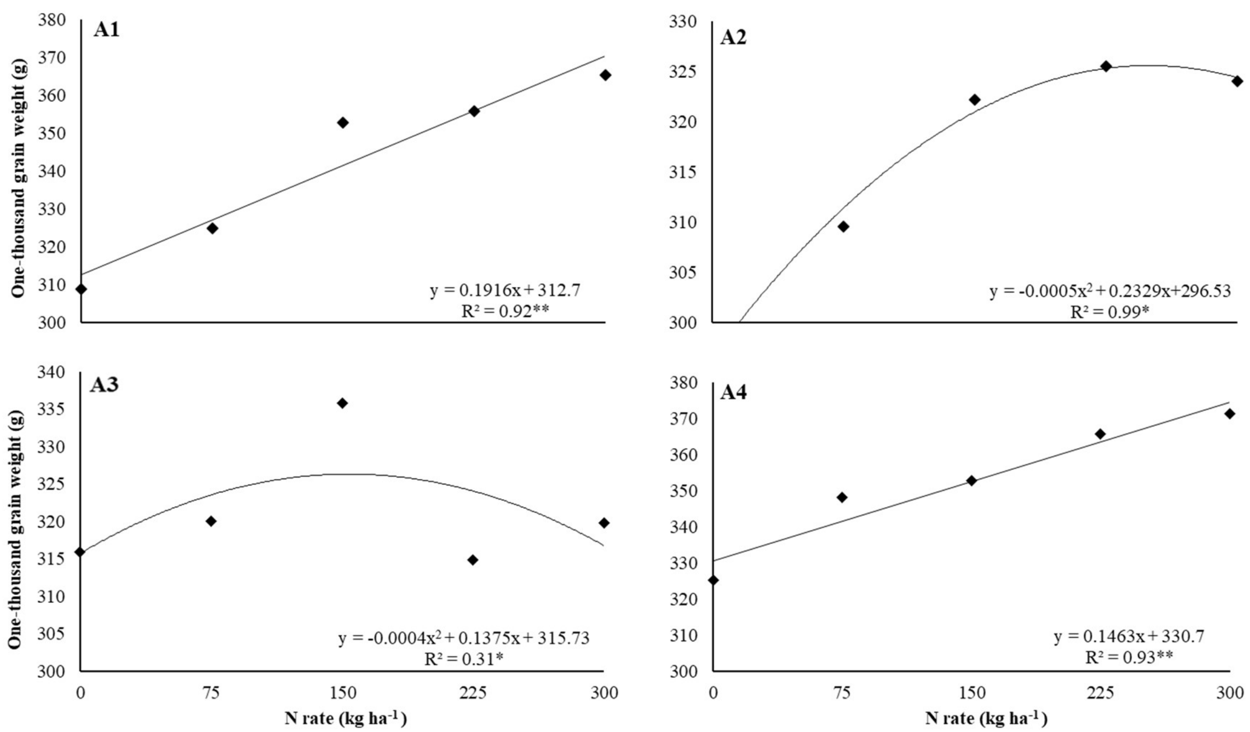

Figure 3: One-thousand grain weight of second-crop maize plants in areas (A1, A2, A3, and A4) in southwestern Goiás as a function of nitrogen rates applied as topdressing at the V3 stage.

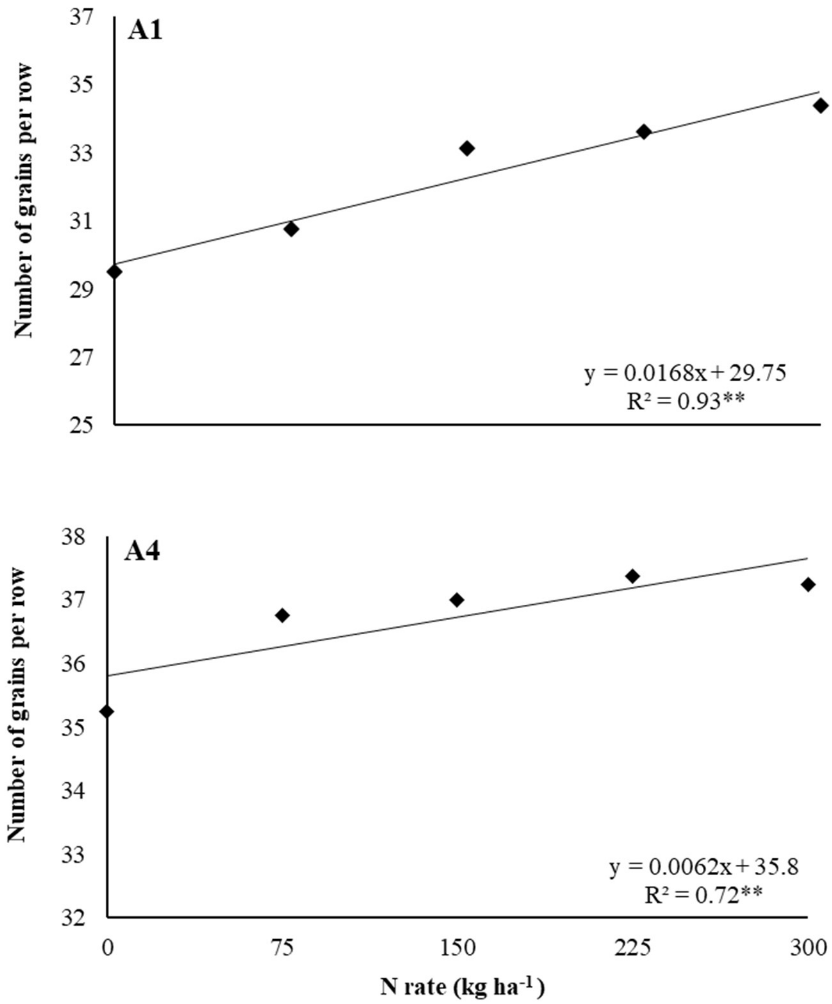

Figure 4: Number of grains per row in ears of second-crop maize plants in areas (A1 and A4) in southwestern Goiás as a function of nitrogen rates applied as topdressing at the V3 stage.

However, these results were found only in A2, which raises the question of how difficult it is to precisely recommend N management for maize crops, as many processes and variables are involved in the response of these plants to N application.

Finally, it should be noted that an analysis of the maximum economic N rate was not carried out, which as a rule, should be considered in decision making. In a simple exercise, however, it could be shown that the increase in grain production – in the areas that positively responded to N – ranged from 1.7 to 8.4 kg for each kg of N applied. Another point that deserves attention concerns the N balance in the soybean–corn system, the base system of the study, since a positive N balance in the system is crucial for the increase in soil organic matter. In Brazil, much is expected from the contribution of soybeans via biological N fixation. However, soybean cultivation results in a surplus of N only when biological fixation supplies at least 72% of the total N demand of the soybean itself (Ciampitti; Salvagiotti, 2018), which is not always possible. In this scenario, analysing the areaf only one crop to determine the real economic efficiency of N fertilization could lead to long-term mistakes.

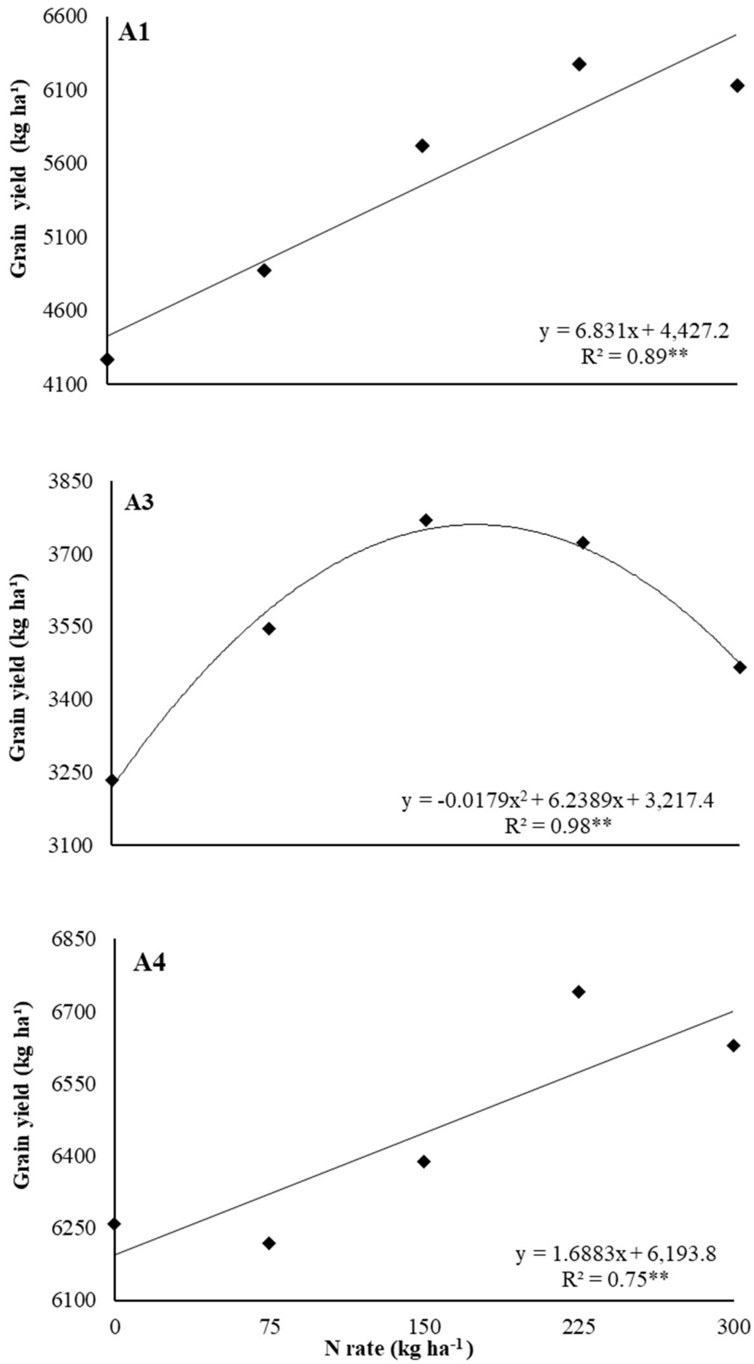

Figure 5: Grain yield of second-crop maize plants in areas (A1, A3, and A4) in southwestern Goiás as a function of nitrogen rates applied as topdressing at the V3 stage.

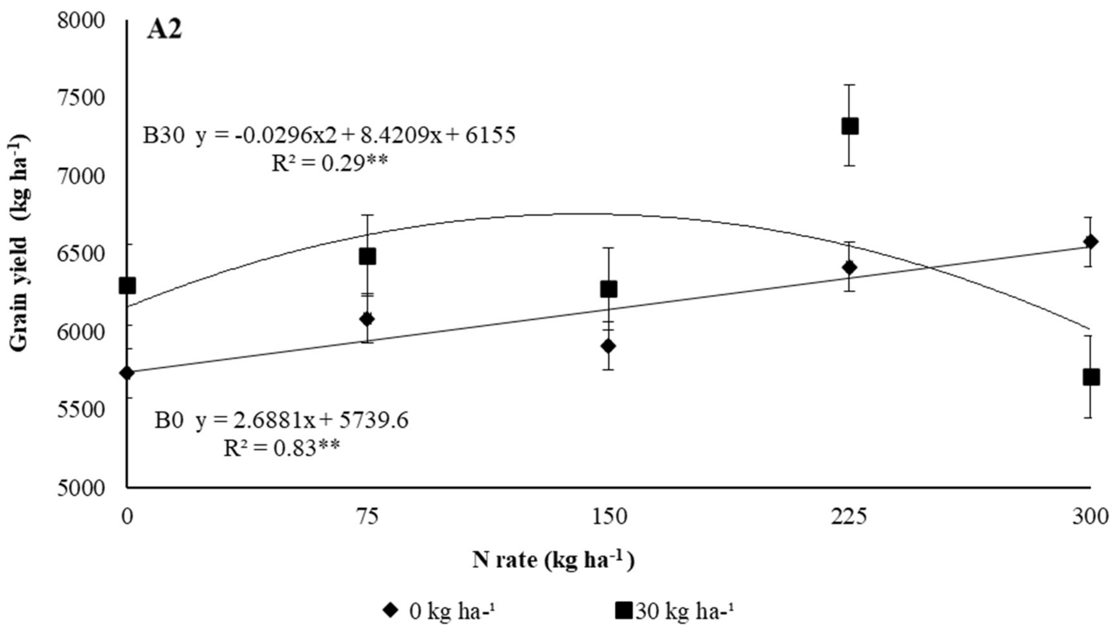

Figure 6: Grain yield of second-crop maize in southwestern Goiás (area A2 – Rio Verde municipality) as a function of nitrogen rates applied at planting (base 0 or 30 kg ha^{-1}) and complemented by topdress nitrogen at the V3 stage.

CONCLUSIONS

Nitrogen (N) fertilizer application for second-crop maize does not affect the number of grain rows per ear but increases the number of grains per row and, particularly, grain weight. N fertilizer application at planting can contribute to boosting the efficiency of topdressing N application. However, the highest yield was found when the plants presented no response to N fertilizer application, which indicates that several factors interact and determine the crop response to N fertilizer application.

AUTHOR CONTRIBUTIONS

Conceptual Idea: Albert, A.M.; Castoldi, G.; Cavalcante, T.J.; Methodology design: Albert, A.M.; Castoldi, G.; Cavalcante, T.J.; Data collection: Albert, A.M.; Cavalcante, T.J.; Nogueira, M.M.; Fonseca, A.O.; Data analysis and interpretation: Albert, A.M.; Castoldi, G.; Cavalcante, T.J.; Rodrigues, C.R., and Writing and editing: Albert, A.M.; Castoldi, G.; Cavalcante, T.J.; Nogueira, M.M.; Fonseca, A.O.; Rodrigues, C.R.

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REFERENCES

AFSHAR, R. K. et al. Agronomic effects of urease and nitrification inhibitors on ammonia volatilization and nitrogen utilization in a dryland farming system: Field and laboratory investigation. Journal of Cleaner Production, 172:4130-4139, 2018.

AHMAD, I. et al. Adaptation strategies for maize production under climate change for semi-arid environments. European Journal of Agronomy, 115:126040, 2020.

ALVARES, C. A. et al. Köppen's climate classification map for Brazil. Meteorologische Zeitschrift, 22(6):711-728, 2013.

AMADO, T. J. C. et al. Yield and nutritional efficiency of corn in response to rates and splits of nitrogen fertilization. Revista Ceres, 64(4):351-359, 2017.

BERTHELOOT, J.; MARTRE, P.; ANDRIEU, B. Dynamics of light and nitrogen distribution during grain filling within wheat canopy. Plant Physiology, 148(3):1707-1720, 2008.

BLANDINO, M. et al. The synergistic effect of nitrogen and phosphorus starter fertilization sub-surface banded at sowing on the early vigor, grain yield and quality of maize. European Journal of Agronomy, 137:126509, 2022.

CANTARELLA, H.; DUARTE, A. P. Manejo da fertilidade do solo para a cultura do milho. In: GALVÃO, J. C. C.; MIRANDA, G. V. Tecnologia de produção de milho. Viçosa, MG: Editora UFV, p.139-182, 2004.

CARVALHO, R. P.; VON PINHO, R. G.; DAVIDE, L. M. C. B. Desempenho de cultivares de milho quanto à eficiência de utilização de nitrogênio. Revista Brasileira de Milho e Sorgo, 10(2):108-120, 2011.

CIAMPITTI, I. A.; SALVAGIOTTI, F. New insights into soybean biological nitrogen fixation. Agronomy Journal, 110(4):1185-1196, 2018.

COMPANHIA NACIONAL DE ABASTECIMENTO - CONAB. Acompanhamento da safra Brasileira de grãos. Brasília, DF, v. 9, safra 2021/22, n. 1 primeiro levantamento, outubro. 2021.

CRUSCIOL, C. A et al. Nitrogen-fertilized systems of maize intercropped with tropical grasses for enhanced yields and estimated land use and meat production. Frontiers in Sustainable Food Systems, 4:544853, 2020.

DUARTE, A. P.; CANTARELLA, H.; KAPPES, C. Adubação de arranque no milho. Revista Cultivar – Grandes Culturas, 213:11-13, 2017.

ELAZAB, A. et al. Detecting interactive effects of N fertilization and heat stress on maize productivity by remote sensing techniques. European Journal of Agronomy, 73:11-24, 2016.

EMPRESA BRASILEIRA DE PESQUISA AGROPECUÁRIA - EMBRAPA. Novo fertilizante deve reduzir custos no emprego de ureia. 2018. Available in: <https:// https://www.embrapa.br/en/busca-de-noticias/-/noticia/34227800/novo-fertilizante-deve-reduzir-custos-no-emprego-de-ureia>. Access in: March 27, 2023.

FERREIRA, D. F. Sisvar: A computer statistical analysis system. Ciência e Agrotecnologia, 35(6):1039-1042, 2011.

GABRIEL, J. L. et al. Airborne and ground level sensors for monitoring nitrogen status in a maize crop. Biosystems Engineering, 160:124-133, 2017.

HAWKESFORD, M. et al. Functions of macronutrients. In: MARCHNER, P. Mineral nutrition of higler plants. 3rd ed. Netherlands: Academic Press Amsterdan, p. 135-189, 2012.

INTERNATION FERTILIZER ASSOCIATION - IFA. Consumption and production of fertilizer. 2022. Available in: <https://www.ifastat.org/databases/plant-nutrition>. Access in: March 27, 2023.

INSTITUTO NACIONAL DE METEROLOGIA - INMET. Banco de dados meteorológicos para ensino e pesquisa, 2022. Available in: <https://portal.inmet.gov.br>. Access in: January 18, 2023.

JANKOWSKI, K. et al. Deep soils modify environmental consequences of increased nitrogen fertilizer use in intensifying Amazon agriculture. Scientific Reports, 8:13478, 2018.

KLIMCZYK, M.; SICZEK, A.; SCHIMMELPFENNIG, L. Improving the efficiency of urea-based fertilization leading to reduction in ammonia emission. Science of The Total Environment, 771:145483, 2021.

KÖPPEN, W. Grundriss der klimakunde. Berlim: de Gruyter, 1931. 400p.

LI, S. X. et al. Nutrient and water management effects on crop production, and nutrient and water use efficiency in dryland areas of China. Advances in Agronomy, 102:223-265, 2009.

LYRA, G. B. et al. Maize growth and yield under nitrogen levels in Coastal Plains of Alagoas, Brazil. Revista Ceres, 61(4):578-586, 2014.

MAGALHÃES, P. C. et al. Fisiologia do milho. Sete Lagoas: Embrapa CNPMS. 2002. 23p. (Circular Técnica, 22).

MARSCHNER, H.; KIRKBY, E. A.; CAKMAK, I. Effect of mineral nutritional status on shoot-root partitioning of photoassimilates and cycling of mineral nutrients. Journal of Experimental Botany, 47:1255-1263, 1996.

NETO, D. D et al. Efeito de boro e nitrogênio na cultura do milho. Insula Revista de Botânica, 33:51-67, 2004.

PANDAY, D. et al. Optimum rates of surface-applied coal char decreased soil ammonia volatilization loss. Journal of Environmental Quality, 49(2):256-267, 2020.

PIRES, M. V. et al. Nitrogen-use efficiency, nitrous oxide emissions, and cereal production in Brazil: Current trends and forecasts. PloS one, 10(8):e0135234, 2015.

QI, D. L.; HU, T. T.; SONG, X. Effects of nitrogen application rates and irrigation regimes on grain yield and water use efficiency of maize under alternate partial root-zone irrigation, Journal of Integrative Agriculture, 19(11):2792-2806, 2020.

QI, D.; HU, T.; LIU, T. Biomass accumulation and distribution, yield formation and water use efficiency responses of maize (*Zea mays* L.) to nitrogen supply methods under partial root-zone irrigation. Agricultural Water Management, 230:105981, 2020.

RESENDE, A. V. et al. Manejo de nutrientes no cultivo de milho segunda safra na região do cerrado. Revista Plantio Direto & Tecnologia Agrícola, 28(166):19-29, 2018.

SHEN, Y. et al. Global warming potential from maize and maize-soybean as affected by nitrogen fertilizer and cropping practices in the North China Plain. Field Crops Research, 225:117-127, 2018.

SIMÃO, E. D. P. et al. Nitrogen fertilization in off-season corn crop in different Brazilian Cerrado environments. Pesquisa Agropecuária Brasileira, 55:e01551, 2021.

SPONCHIADO, J. C. et al. Late nitrogen topdressing increases nutritional and industrial quality of white oat (*Avena sativa*) grain. Australian Journal of Crop Science, 14(9):1355-1361, 2020.

SUI, J. et al. Effect of nitrogen and irrigation application on water movement and nitrogen transport for a wheat crop under drip irrigation in the North China Plain. Water, 7(11):6651-6672, 2015.

VALDERRAMA, M. et al. Fontes e doses de NPK em milho irrigado sob plantio direto. Pesquisa Agropecuária Tropical, 41(2):254-263, 2011.

VON PINHO, R. G et al. Marcha de absorção de sistema e acúmulo de matéria seca em milho. Revista Brasileira de Milho e Sorgo, 8(2):157-173, 2009.

WANG, X.; XING, Y. Effects of irrigation and nitrogen on maize growth and yield components. In: PIRASTEH, S.; LI, J. Global changes and natural disaster management: Geo-information technologies. Springer International Publishing, p.63-74, 2017.