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Journal of Plant Nutrition

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/lpla20

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To cite this article: Ane Caroline Melo Ferreira, Henrique Antunes de Souza, Edvaldo Sagrilo, Gabriel Barbosa da Silva Júnior, William Natale, Amanda Hellen Sales Sobral, Geania de Souza Vera & Smaiello Flores da Conceição Borges dos Santos (28 Oct 2023): Absorption, partitioning, and export of nutrients by phenological stage in maize cultivated in Eastern Maranhão, Brazil, Journal of Plant Nutrition, DOI: 10.1080/01904167.2023.2275072

To link to this article: https://doi.org/10.1080/01904167.2023.2275072

Published online: 28 Oct 2023.

JOURNAL OF PLANT NUTRITION
https://doi.org/10.1080/01904167.2023.2275072

Absorption, partitioning, and export of nutrients by phenological stage in maize cultivated in Eastern Maranhão, Brazil

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ABSTRACT

This study aimed to evaluate the absorption, partitioning, and redistribution of nutrients by phenological stage of the maize crop, under the edaphoclimatic conditions of the municipality of Brejo, Maranhão, Brazil. The experiment was carried out in a Yellow Argisol, under a randomized block design, with seven treatments corresponding to the phenological stages V5, V8, VT, R1, R3, R5, and R6, and four replicates. The plant was partitioned into leaves, stalk, reproductive organs (tassel, straw, cob), and grains to determine the concentrations of N, P, K, Ca, Mg, S, B, Cu, Fe, Mn, and Zn. The accumulation of nutrients in each organ in the different phenological stages was estimated based on the values of dry weight and nutrient concentrations. A slow accumulation of dry weight was observed in the maize plant until the flowering stage (VT), a pattern also observed for the nutrients P, Mg, S, and Cu. Nutrients N, K, Ca, B, Fe, Mn, and Zn showed values close or superior to 50% of the maximum accumulated up to VT. The decreasing order of nutrient accumulation was N > K > P > Mg > S>Ca > Fe > Zn > Mn > Cu > B. The nutrients with the highest harvest rates were P > N > Mg > S>Zn (0.84, 0.74, 0.72, 0.69, and 0.51, respectively). N, K, Ca, B, Zn, Fe, and Mn are the most absorbed nutrients in the initial stage of crop development. The nutrients that are absorbed in greater quantity after flowering are P, S, Mg, and Cu. The degrees day sum showed no effects on the maize crop cycle under the edafoclimatic conditions of this study.

ARTICLE HISTORY
Received 11 March 2022
Accepted 11 October 2023

KEYWORDS
degrees day; extraction; maize nutrition; uptake rate; *Zea mays*

Introduction

The MATOPIBA agricultural frontier, formed by the states of Maranhão, Tocantins, Piauí, and Bahia, stands out among the maize-producing regions in Brazil. These states accounted for 8.4 million tons, corresponding to 8.81% of the national maize production of the 2020/2021 harvest (Companhia Nacional de Abastecimento (CONAB) 2020).

Maize productivity has significantly increased due to the research in cropping systems development. The most prominent concern is the nutrient uptake rate by maize, which helps in producer decision-making, especially regarding the crop's proper fertilization and nutrition management

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(Woli et al. 2018). Modern cultivars available are generally more efficient in nutrient use, requiring less fertilizer to produce the same volume of grains (Silva et al. 2018).

These genotypes present different requirements concerning nutrient absorption by the crop and efficiency of sunlight use to produce photoassimilates, changing the production of dry weight, the accumulation, and the export of nutrients (Duarte et al. 2019). However, under suitable conditions, hybrids with similar characteristics generally show similar performances even when cultivated in different environments (Bender et al. 2013).

The time required to reach each phenological event and, consequently, for changes in the demand for nutrients by the plant, varies according to the genotype, the environmental conditions of each region, and the management practices adopted. Oliveira et al. (2013) evaluated the growth of a maize single hybrid (BRS 1030) in a no-till system and verified the linear accumulation of dry weight from 40 to 80 days after emergency (DAE), with maximum accumulation occurring between 100 and 110 DAE. Martins et al. (2017) found a small accumulation of dry weight up to 30 DAE and a linear accumulation up to 140 DAE when working with maize single hybrids.

The accumulation of dry weight and the nutrient uptake rate as a function of the phenological stages of maize is essential to plan fertilizer doses and timing of application (Bender et al. 2013), in addition to the minimum quantities that must be returned to the soil to maintain fertility (Duarte et al. 2019). Therefore, the plant's nutrient dynamics contribute to increasing the crop's management efficiency, consequently increasing productivity and decreasing production costs through the rational use of inputs in the soil.

Bender et al. (2013) demonstrated that more than half of N, K, Mg, Mn, B and Fe are absorbed before the flowering of maize plants under the conditions of Illinois, United States. In Brazil, Silva et al. (2018) demonstrated that more than half of the absorption of N, P, and Mg, in addition to Ca and S, occur before flowering, in Sete Lagoas, Minas Gerais, indicating the need for planning the fertilization management so that there are no nutrient deficiencies.

Research on maize's nutrient uptake rates in Brazil is mainly conducted in the Southern and Southeastern regions, using cultivars and management systems adapted to those regions. However, there are no studies of this nature, under the conditions of the MATOPIBA region, especially in Eastern Maranhão.

Therefore, the aim of this study was to evaluate the absorption and partitioning of nutrients, the growth and development of maize crops by phenological stage, and the thermal sum under the edafoclimatic conditions of Eastern Maranhão.

Material and methods

Site description

The study was carried out at the Barbosa farm (*Fazenda Barbosa*), located in the municipality of Brejo, microregion of Chapadinha, mesoregion of Eastern Maranhão, Brazil (03°42'44" S; 42°55'44′ W), altitude of 104 m (Instituto Nacional de Meteorologia (INMET), 2020). According to the Köppen-Gerger climate classification, the region's climate is Aw, tropical with a well-defined rainy season (January-may) and dry season (June-December). The average annual rainfall is 1613,2 mm, with an average annual temperature superior to 27 °C (Passos, Zambrzycki, and Pereira 2016)

The soil of the experimental area is classified as typical dystrophic Yellow Argisol, with a loamy-sandy texture and the presence of a cohesive horizon, located in a Cerrado-type biome (Savannah) (Dantas et al. 2014). The air temperature data were collected at the weather station of Chapadinha, Maranhão (Instituto Nacional de Meteorologia (INMET), 2020), and the rainfall data were collected from a field rain pluviometer installed in 2019 (Figure 1).

The experiment was carried out in a traditional tillage system under a rainfeed regime, with maize cultivation after four years of soybean planting in succession to millet. Soil samples were

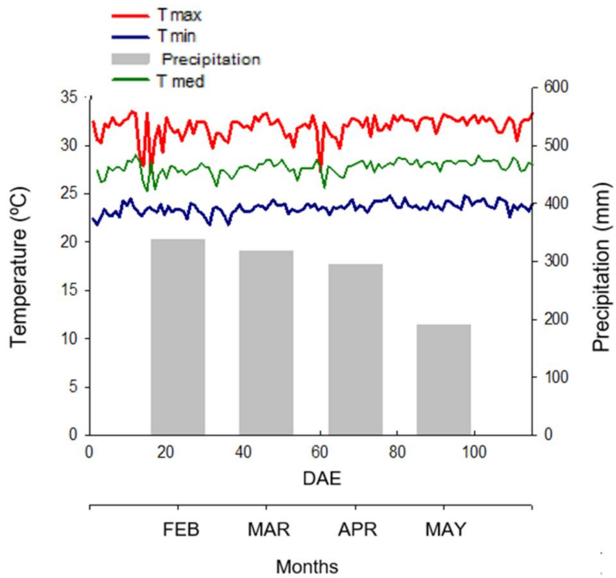

Figure 1. Minimum, maximum, and average air temperature and rainfall in the experimental area during the experimental period. Brejo, Maranhão, Brazil, 2019.

Table 1. Chemical And physical characteristics of the soil of the experimental area, obtained at the depths of 0.0-0.20 and 0.20-0.40 m.

Layers	pH	OM	P	K	Ca	Mg	H + Al	SB	CEC	BS
		dag kg^{-1}	mg dm^{-3}			cmol$_c$ dm^{-3}				%
0-0.20 m	6.6	2.1	38.8	0.24	3.72	0.74	1.64	4.70	6.34	74
0.20-0.40 m	6.0	2.3	21.3	0.03	2.64	0.50	2.41	3.17	5.58	56

Layers	Sand	Silt	Clay	Textural class
		%		
0-0.20 m	72	11	17	Sandy loam
0.20-0.40 m	69	10	21	Clay-sandy loam

pH in water; OM - Walkey and Black (wet oxidation); P; K; Na – Melich1 or double acid; Ca, Mg, and Al – KCL; H + Al – Ca acetate; Sand, silt, clay – pipette method.
Brejo, Maranhão, Brazil, 2019.

collected prior to the installation of the experiment, from the 0.0-0.20 and 0.20-0.40 m layers to characterize the fertility and physical attributes of the soil (Table 1). The soil analysis was performed according to Teixeira et al. (2017).

We used the simple transgenic maize hybrid 30F35, with YieldGard® + Herculex + Roundup Ready (YHR) technology (Pioneer®). The fertilization was carried out by applying 320 kg ha^{-1} from the formula NPK 13-33-08 to the planting line. The top-dressing fertilization was carried out with 360 kg ha^{-1} of the formula NPK 10-00-30, 15 DAE, at the phenological stage V4 and 75 kg ha^{-1} of urea at 33 DAE, in the phenological stage V8. Fertilization was carried out mechanically according to the management used on the farm and similar to that recommended by Sousa and Lobato (2004). Phytosanitary control was carried out according to the requirements of the crop.

Experimental design and data collection

The experiment was arranged in a randomized block design, with seven treatments corresponding to the sampling in times 15, 29, 43, 57, 71, 99, and 113 DAE, and four block. Each block were composed of 20 planting lines spaced with 0.5 m, 10 m length and stand of 3.1 plants per linear meters (62 thousand plants ha^{-1}). The sampling times corresponded to the phenological stages V5, V8, VT, R1, R3, R5, and R6, as described by Ritchie, Hanway, and Benson (2003). The degrees day (DG) were calculated considering the number of days after emergence, using the method proposed by Ometto (1981). The lower basal temperature (Tb) adopted was 10 °C, considering 35 °C for the upper basal temperature (TB) (Renato et al. 2013).

For the temporal evaluations of dry mass accumulation, four competitive plants, in each block, were sampled from the useful area (10 linear meters) in the 18 central lines, leaving 0.5 m from each end of the plots. The average of these four collected plants was use to represent a plant with the intention of reducing experimental error. The samples were partitioned into leaves, stalk, reproductive organs (tassel, straw, and cob), and grains, washed in running tap water, distilled water with neutral detergent (0.1%), hydrochloric acid (0.3%), and, again, with pure distilled water (Boaretto et al. 2009). Subsequently, the samples were placed in paper bags and dried in a forced-air circulation oven at 65 °C (until reaching constant weight). From this stage, the dry weight of the different fractions of the plants were determined. The weigth of dry weight of the entire plant was calculated by the sum of the weigth of the respective fractions.

Chemical analysis

The plant tissue samples were ground in a Wiley mill at two millimeters and subjected to chemical analysis to determine the macro and micronutrient concentrations in the different fractions of the aerial part of the plants. The nitrogen (N) concentration was determined using the Kjedahl method; phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), sulfur (S) were mineralized by nitroperchloric digestion, and the P concentration was determined by colorimetry, K by Flame photometry, S by turbidimetry, and Ca and Mg by atomic absorption spectrophotometry, according to the procedures described by Bataglia et al. (1983).

The micronutrients cupper (Cu), iron (Fe), manganese (Mn) and zinc (Zn) were mineralized by nitroperchloric digestion, and the concentrations were determined by atomic absorption spectrophotometry. Boron (B) concentration in the plant tissue was determined using the azomethine-H method, according to Bataglia et al. (1983).

The accumulation of nutrients in the different phenological stages was calculated by multiplying their concentration by the respective dry weight of each fraction of the plant. The harvest index was calculated from the ratio of the total nutrients absorbed by the grain that contained in the aerial part.

Statistical analysis

After checking for normality by the Shapiro-Wilk test, the data were submitted to analysis of variance through the F-test ($p \leq 0.05$). When the effects of sampling time were significant for the response variables (dry weight and nutrient accumulation), nonlinear regression analysis was used, with model parameters estimated using the adjustment function with a dynamic curve. The model that expressed statistical significance (for model parameters) and a higher coefficient of determination (R^2) was chosen for each variable. The three-parameter Gaussian, normal log, and lorentzian models for peak curve and the three-parameter sigmoid model are described in Eqs. (1–4), respectively.

$$y = ae^{\left[-0.5\left(\frac{x-x0}{b}\right)^2\right]} \tag{1}$$

$$y = ae^{\left[-0.5\left(\frac{ln\left(\frac{x}{x0}\right)^2}{b}\right)\right]} \tag{2}$$

$$y = \frac{a}{1+\left(\frac{x-x0}{b}\right)^2} \tag{3}$$

$$y = \frac{a}{1 + e^{-\left(\frac{x-x0}{b}\right)^2}} \tag{4}$$

in which:

y: growth or accumulation variable;

a: maximum value of the variable (regardless of the chosen model);

x0: value of x at the DAE that provides the maximum value for the peak or inflection point equations of the curve at DAE for the sigmoidal equation;

b: amplitude in the value of x at DAE between the inflection point and the maximum point for the peak or growth rate equations or accumulation (mean) for the sigmoidal equation.

The adjusted model determined the value of the inflection point (IP) in the curve (Eq. 5), for the peak models:

$$\mathrm{IP} = \mathrm{x0} - \mathrm{b} \tag{5}$$

IP corresponds to the value of x at which the curvature of the adjusted model changes signal, corresponding to the value of x at DAE, at which the daily maximum accumulation rate, although positive, decreases.

The analysis of variance, models adjustment and drawing of figures were performed using the R (R Core Team 2018) statistical software.

Results

Dry weight accumulation

There was an accumulation of dry weight in the plant up to the sum of 591 DG, at 29 DAEs. From this point, there were greater increases in all plant organs, especially in the reproductive structures and grains, which together represented 62.9% of the total dry weight at the end of the cycle (Figure 2). In total, the dry weight production in this study was 16,190 kg ha^{-1} at the physiological maturity (R6).

The accumulation of dry weight in the leaves and stalk presented maximum values estimated at 66 DAE, after stage R1 (1,085 DG) and at 77 DAE, after stage R3 (1,334 DG), respectively

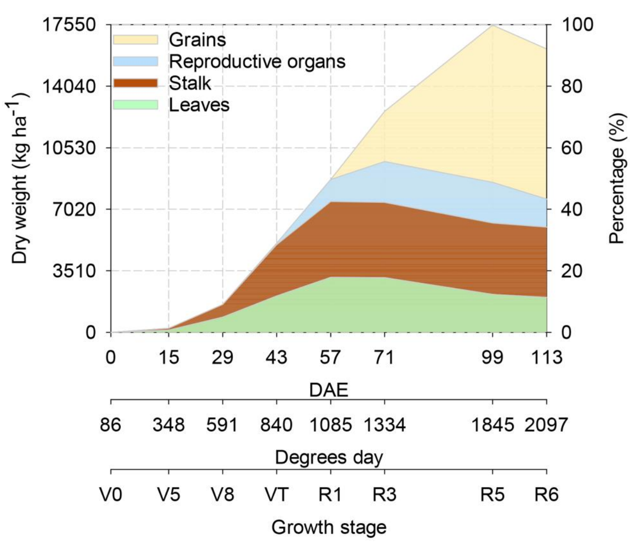

Figure 2. Accumulation and partitioning of dry weight in the maize crop as a function of thermal sum and phenological stage. Brejo, Maranhão, Brazil, 2019.

Table 2. Estimation of the model parameters adjusted to the dry weight of leaves, stalk, reproductive structures, grains, total dry weight, inflection point (IP), and coefficient of determination (R^2), throughout the maize development cycle.

Partitions	Dry weight					Model
	Model parameters[(1)]			IP	R^2	
	a[(2)]	b[(3)]	x_0[(4)]			
	kg ha^{-1}	DAE				
Leaves	3,152.97**	0.5**	66**	65.5	0.98	Normal log
Stalk	4,658.68**	0.5**	77**	76.5	0.97	Normal log
Reproductive structures	2,763.43**	0.3**	83**	82.7	0.99	Normal log
Grains	9,163.42**	0.2**	103**	102.8	0.99	Normal log
Total	16,814.02**	0.5**	108**	107.5	0.99	Normal log

(1) Values represent the average of the biometrics evaluations of the cultivar.
(2) Maximum observed value in kg ha^{-1}.
(3) Amplitude at the value of x at DAE between the inflection point and the maximum point.
(4) Days after the emergence (DAE) that provided the highest values.
**, *, and ns: significant at 1%, 5%, and not significant by the T test ($p < 0.05$), respectively.
Brejo, Maranhão, Brazil, 2019.

(Figure 2). The plant's maximum estimated total dry weight accumulation was observed in stage R5, adding 1,845 DG, at 98 DAE (16,814 kg ha^{-1}) (Table 2).

There was a reduction in dry weight values after the maximum estimated partition for each plant fraction, mainly in leaves and stalks at the beginning of the reproductive stage. This occurs due to the translocation of carbohydrates and nutrients to the reproductive structures and the loss of plant material in the field due to the senescence of the structures of each organ. At the end of the cycle, the dry weight of the leaves and stalk represent 9.2 and 22.5%, respectively, of the total dry weight (Figure 2).

Nutrient accumulation

The model parameters for nutrient accumulation in the fractions of maize plants were adjusted to the variables of the model used, with determination coefficients greater than 0.90 (Tables 3, 4).

In the physiological maturity phase (R6), 74% of the N contained in the plant was present in the grains (Table 3; Figure 3a). The export of N by grains was 138.2 kg ha^{-1}.

P absorption occurred until the final stages of plant development, with maximum accumulations observed between stages R5 and R6. Accumulated amounts of P decreased considerably in vegetative parts and reproductive structures, with a total of 84% of P redistributed to grains at stage R6 (Table 3; Figure 3b). The amount of P exported was of 4.53 kg t^{-1} of grain produced (Table 5).

The absorption of K by plants was maximum between stages R3 and R5. Still, more than 80% of nutrient accumulation occurred until tasseling (Table 3; Figure 3c).

Similar to N and K, the absorption of the greatest amount of Ca occurred before flowering (VT), with 74% of the accumulated total, reaching the maximum at 70 DAE, in stage R3, with 20.54 kg ha^{-1} (Figure 3d). The Ca was accumulated in greater proportions in the leaves (~50%), and the harvest index of this nutrient per maize grain was approximately 0.20 (Table 5).

Maize plants absorbed approximately 28% of Mg until reaching the VT phenological stage, presenting a harvest index of 0.72 (Table 5). The export of Mg by the grains was of 18 kg ha^{-1} and, for each tonne of grain produced, 3.34 kg was extracted by the plant and 1.9 kg Mg was exported by the grains (Table 5; Figure 3).

The maximum accumulation of S occurred in the R3 stage, with 10.84 kg ha^{-1}, (Table 3) whereas the accumulation during the tasseling was 40% of the accumulated in R3 (Figure 3f).

Table 3. Estimates of the parameters of the models adjusted to the accumulation of macronutrients in the leaves, stalk, reproductive structures, grains, and the entire plant, inflection point (IP), and coefficient of determination (R^2), throughout the MAIZE development cycle.

Partitions	Model parameters[(1)] a[(2)] kg ha^{-1}	b[(3)] DAE	x_0[(4)]	IP	R^2	Model
		NITROGEN				
Leaves	79.80**	0.4**	53**	52.6	0.97	Normal log
Stalk	30.62**	0.7**	53**	52.3	0.90	Normal log
Reproductive structures	15.31**	0.3**	78**	77.7	0.97	Normal log
Grains	140.31**	0.26**	106**	105.74	0.99	Normal log
Total	193.64**	43**	98**	55	0.97	Gaussian
Partitions			PHOSPHORUS			
Leaves	11.80**	0.3**	57**	56.7	0.97	Normal log
Stalk	8.95**	0.4**	52**	51.6	0.90	Normal log
Reproductive structures	3.45**	0.3**	69**	68.7	0.93	Normal log
Grains	34.89**	0.3**	111**	110.7	0.99	Normal log
Total	42.79**	39**	99**	60	0.98	Gaussian
Partitions			POTASSIUM			
Leaves	58.56**	0.4**	54**	0.53	0.91	Normal log
Stalk	78.07**	0.6*	56**	55.4	0.88	Normal log
Reproductive structures	21.76**	0.3**	80**	79.7	0.99	Normal log
Grains	61.01**	23**	108**	85	0.99	Normal log
Total	159.81**	0.7**	71**	70.3	0.97	Normal log
Partitions			CALCIUM			
Leaves	12.31**	0.5**	70**	69.5	0.95	Normal log
Stalk	6.86**	0.4**	57**	56.6	0.95	Normal log
Reproductive structures	1.30**	0.3**	84**	83.7	0.99	Normal log
Grains	3.25**	0.2**	103**	102.8	0.99	Normal log
Total	20.54**	0.5**	70**	69.5	0.96	Normal log
Partitions			MAGNESIUM			
Leaves	11.25**	0.3**	71**	70.7	0.93	Normal log
Stalk	6.87**	0.5**	67**	65.5	0.98	Normal log
Reproductive structures	2.22**	0.3**	79**	78.7	0.93	Normal log
Grains	17.90**	0.2*	113**	112.8	0.99	Normal log
Total	28.32**	0.5**	92**	91.5	0.99	Normal log
Partitions			SULFUR			
Leaves	5.65**	13**	56**	43	0.90	Lorentzian
Stalk	7.05**	11**	76**	65	0.96	Gaussian
Reproductive structures	0.93**	0.2**	75**	74.8	0.97	Normal log
Grains	3.50**	30*	98**	68	0.94	Gaussian
Total	10.84**	25**	77**	52	0.96	Gaussian

(1) Values represent the average of the evaluations of the cultivar.
(2) Maximum observed value in kg ha^{-1}.
(3) Amplitude at the value of x at DAE between the inflection point and the maximum point.
(4) Days after the emergence (DAE) that provided the highest values.
**, *, and ns: significant at 1%, 5%, and not significant by nonlinear regression analysis, respectively.
Brejo, Maranhão, Brazil, 2019.

The extraction of this element was 5.2 kg and the export of 3.6 kg for each tonne of grain produced, with a harvest index corresponding to 0.69 (Table 5).

Maize plants accumulated 69% of all B until reaching the VT stage in relation to the total absorbed of this nutrient, obtaining a maximum accumulation of 147 g ha^{-1} estimated between stages R1 and R3 (Figure 4a). The accumulation of this micronutrient decreased after this phenological stage, remaining approximately 40% of the total accumulated (72 g ha^{-1}) at physiological maturity, mainly being present in the leaves and stalk. The allocation of this micronutrient from

Table 4. Estimates of the parameters of the models adjusted to the accumulation of micronutrients in the leaves, stalk, reproductive structures, grains, and the entire plant, inflection point (IP), and coefficient of determination (R^2), throughout the maize development cycle.

	Model parameters [1]			IP	R^2	Model
	a[2]	b[3]	x_0[4]			
Partitions	g ha^{-1}	DAE				
		COPPER				
Leaves	56.82**	24**	78**	54	0.98	ce
Stalk	34.59**	29**	98**	69	0.91	Gaussian
Reproductive structures	21.48 **	0.2**	83**	67	0.98	Gaussian
Grains	39.95 **	0.3**	113**	112.7	0.96	Normal log
Total	136.72**	27**	91**	64	0.99	Gaussian
Partitions			IRON			
Leaves	144.24 **	0.6**	53**	52.4	0.96	Normal log
Stalk	112.32 **	0.6**	71**	70.4	0.96	Normal log
Reproductive structures	72.51**	0.3**	99**	98.4	0.99	Normal log
Grains	222.46**	24**	111**	87	0.99	Gaussian
Total	455.89**	45**	104**	59	0.98	Gaussian
Partitions			MANGANESE			
Leaves	193.57 **	0.7**	56**	55.3	0.94	Normal log
Stalk	172.31**	28**	78**	50	0.91	Gaussian
Reproductive structures	66.73**	0.2**	87**	86.8	0.97	Normal log
Grains	31.35**	0.3*	99**	98.7	0.91	Normal log
Total	434.81**	32**	77**	45	0.92	Gaussian
Partitions			ZINC			
Leaves	185.07 **	0.4**	63**	63.6	0.99	Normal log
Stalk	116.03 **	0.6**	69**	68.4	0.93	Normal log
Reproductive structures	66.04**	18**	87**	69	0.97	Gaussian
Grains	190.31**	0.3**	107**	106.7	0.99	Normal log
Total	431.53**	0.6**	88**	87.4	0.98	Normal log
Partitions			BORON			
Leaves	66.81 **	0.5**	58**	57.5	0.94	Normal log
Stalk	53.35**	0.5**	60**	59.5	0.90	Normal log
Reproductive structures	32.89**	0.3**	75**	74.7	0.99	Normal log
Grains	10.13**	0.3**	92**	91.7	0.91	Normal log
Total	147.33 **	0.5**	64**	63.5	0.98	Normal log

[1]Values represent the average of the evaluations of the cultivar.
[2]Maximum observed value in g ha^{-1}.
[3]Amplitude at the value of x at DAE between the inflection point and the maximum point.
[4]Days after the emergence (DAE) that provided the highest values.
**, *, and ns: significant at 1%, 5%, and not significant by nonlinear regression analysis, respectively.
Brejo, Maranhão, Brazil 2019.

the vegetative parts to the grains was low, with an HI of 0.11, representing the lowest harvest index found in the present study (Table 5).

A slow initial accumulation of Cu was observed until reaching the VT phase, with an accumulated volume corresponding to 28% of the total accumulated at the maximum point. The maximum accumulation of Cu in the maize plant in the present study was 136 g ha^{-1} at 91 DAE, at the R5 stage (Table 4 and Figure 4b). There was a reduction in the value of accumulated Cu at physiological maturity, with a total equivalent of 99.8 g ha^{-1} and 41.2 g ha^{-1} in the grains, resulting in a harvest index of 0.41 (Table 5).

Unlike what was observed for Cu, which presented slow accumulation until the flowering stage (VT), the other micronutrients presented earlier accumulation dynamics, with 69, 47, 64, and 54% of the total accumulation verified in VT for B, Fe, Mn, and Zn, respectively (Table 5).

The maximum estimated accumulation of Fe was observed in R5, with 455 g ha^{-1}. The absorption of this nutrient up to VT was relatively fast, with approximately 50% of the accumulated

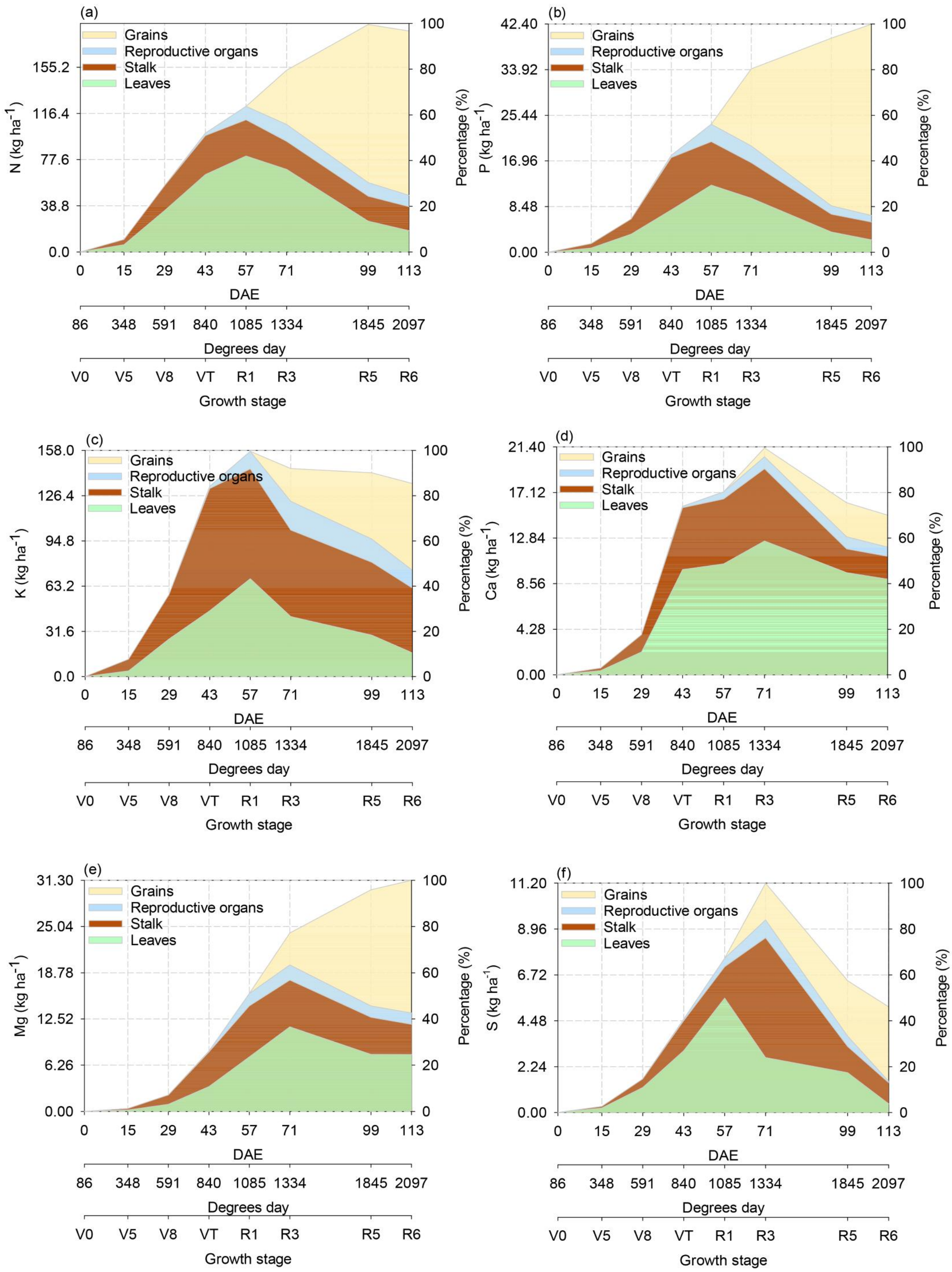

Figure 3. Accumulation and partitioning of N (a), P (b), K (c), Ca (d), Mg (e), and S (f), during the maize development cycle. Brejo, Maranhão, Brazil, 2019.

maximum. The maximum accumulation in the grains occurred in the stage of physiological maturity, in R6, at 111 DAE (Table 4; Figure 4c), contributing to the high nutrient harvest index, 0.49 (Table 5).

Table 5. Total nutrient accumulated in the grain, harvest index, removal coefficient, absorption up to VT, and phenological stage of the maximum accumulation associated with the productivity of 9.35 t ha^{-1} in maize crop.

Parameters	Total Accumulated (R6)(1)	Accumulation in the grain (R6)	Harvest index (2)	Removal coefficient (3)	Absorption up to VT	Phenological stage of maximum accumulation
	kg ha^{-1}			kg t^{-1}	%	
DM	16,166	8,571	0.53	–	29	
N	185.7	138.2	0.74	20.53	52	R5
P	42.3	35.5	0.84	4.53	42	R5
K	134.9	60.6	0.45	16.89	84	R3-R4
Ca	15	3.0	0.20	2.28	74	R3
Mg	24.8	18	0.72	3.34	28	R5
S	5.2	3.6	0.69	1.19	41	R3
	g ha^{-1}			g t^{-1}	%	
B	77.9	8.9	0.11	16.3	69	R1-R3
Cu	99.8	41.2	0.41	13.9	28	R4-R5
Fe	459	224	0.49	49.2	47	R6
Mn	221.3	31.9	0.14	42.1	64	R3
Zn	377.3	191.2	0.51	48.12	54	R4-R5

(1)Dry weight.
(2)Percentage of the total accumulated nutrients that are present in the grain in R6.
(3)Amount of nutrients required to produce a tonne of grain (maximum absorbed by the plant/productivity).
Brejo, Maranhão, Brazil, 2019.

The absorption process was fast for Mn, with 64% of the maximum absorbed and accumulated in the VT phase (Table 5), and maximum accumulation estimated at R3, with 434 g ha^{-1} (Table 4; Figure 4d). The total accumulated in physiological maturity was 221 g ha^{-1}, remaining approximately 47% of the total absorbed in the leaves and stalk. This micronutrient presented the second lowest harvest index (0.14), superior only to the harvest index observed for B (0.11).

The maximum accumulation of Zn occurred between stages R4 and R5, with 477 g ha^{-1}, presenting fast absorption until reaching VT, with 54% of the estimated maximum (Table 5). At the end of the cycle, the cumulated total was 377 g ha^{-1}, with a high harvest index (0.51), requiring 48.12 g of Zn to produce one tonne of grain. Zn was the second most absorbed micronutrient.

The extraction of macro and micronutrients, in decreasing order, was N > K>P > Mg > Ca > S, and Fe > Zn > Mn > Cu > B, respectively. The export of macro and micronutrients, in decreasing order, was N > K>P > Mg > S>Ca, Fe > Zn > Cu > Mn > B, respectively. The nutrients with the highest harvest indices were P, N, Mg, S, and Zn, with values of 0.84, 0.74, 0.72, 0.69, and 0.51, respectively.

Discussion

The dry weight production obtained in this study was similar or lower than the values obtained by authors in similar studies, but with different genotypes (Table 6). This may be related to different planting densities, the productive performance of the genotypes, fertilization levels, soil management and cultivation environments since the accumulated thermal sum of the different environments influences the crop cycle and may interfere with dry mass accumulation.

The reduction in the accumulation of dry weight of maize plants was also mentioned from the R5 stage (Sayre 1948; Andrade et al. 1975; Vasconcellos et al. 1983), and reported in more recent research carried out in Brazil and the United States (Duarte et al. 2003; Bender et al. 2013).

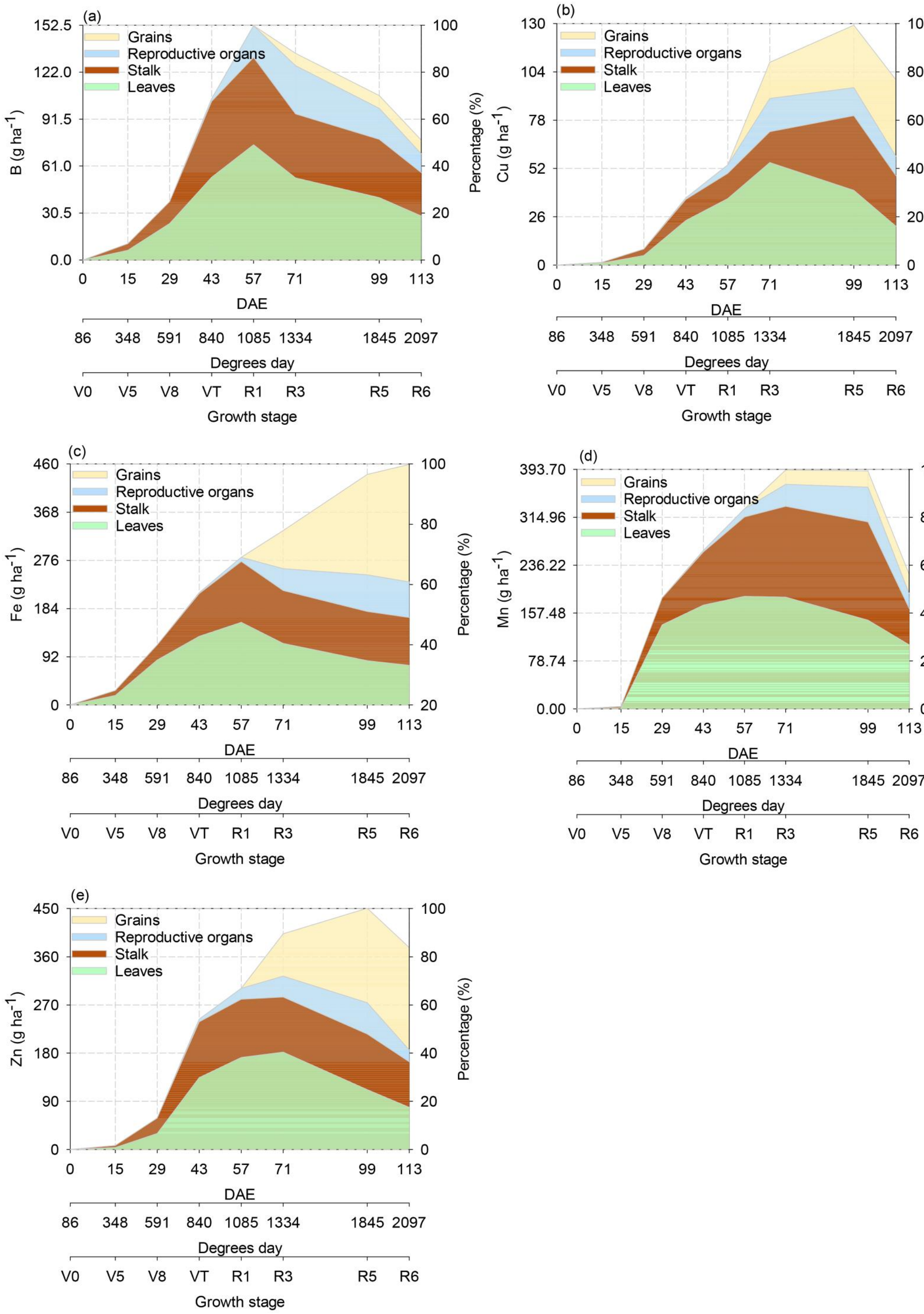

Figure 4. Accumulation and partitioning of B (a), Cu (b), Fe (c), Mn (d), and Zn (e), throughout the maize development cycle. Brejo, Maranhão, Brazil, 2019.

The differences in the ability to use light and in the production of each genotype are consequences from breeding. No significant differences between locations were observed in research using six transgenic maize hybrids at two production sites. However, the

Table 6. Grain and dry weight productivity and accumulation of macronutrients in the aerial part of the maize.

Studies	Grains	DW	N	P	K	Ca	Mg	S
				kg ha^{-1}				
Current study[1]	9,352	16,166	185	42	134	15	24	5
Andrade et al. (1975)[2]	6,200	16,300	181	31	218	34	36	32
Duarte et al. (2003)[3]	7,700	10,950	146	15	134	19	26	–
Pinho et al. (2009)[4]	14,100	31,300	364	84	314	60	42	27
Borin, Lana and Pereira (2010)[5]	–	11,907	123	18	126	13	25	10
Bender et al. (2013)[6]	12,000	23,200	286	49	168	–	59	26
Martins et al. (2017)[7]	10,300	23,100	171	13	285	34	37	12
Silva et al. (2018)[8]	11,070	25,600	291	27	134	49	37	20

[1]Simple transgenic hybrid 30F35; population of 62,000 plants ha^{-1}, Brejo, Maranhão, Brazil.
[2]Mean of five cultivars; population of 50,000 plants ha^{-1}, Piracicaba, São Paulo, Brazil.
[3]Mean of three cultivars of tropical climate; population of 55,000 plants ha^{-1}, Palmital, São Paulo, Brazil.
[4]Mean of two cultivars; population of 60,000 plants ha^{-1}, Lavras, Minas Gerais, Brazil.
[5]Field-grown sweet maize; population of 62,500 plants ha^{-1}, Jataí, Goiás, Brazil.
[6]Mean of six hybrids produced in two locations, population of 84,000 plants ha^{-1}, Ilinois, United States of America.
[7]Simple hybrid DKB 390 PRO 2; population of 65,000 ha plants^{-1}, Piracicaba, São Paulo, Brazil.
[8]Mean of four hybrids under medium and high fertility levels; population of 70,000 plants ha^{-1}, Sete Lagoas, Minas Gerais, Brazil.

genotypes showed different performances in the same planting environment (Bender et al. 2013).

The dry weight production differed only 10.8% when assessing the level of medium and high soil fertility. On average, maize hybrids produced 24,159 and 27,095 kg ha^{-1} in medium and high investment environments, respectively. However, there were no significant differences in grain production between fertility levels (Gutierrez et al. 2018).

The grain production in this study was 9,365 kg ha^{-1}, correcting the grain moisture to 13%. The average grain production in an experiment carried out on the same farm to evaluate the dynamics of water in the soil and the yield of maize intercropped with Brachiaria was 5,500 kg ha^{-1} (Silva et al. 2020). These productivities are above the average recorded in Brazil and Maranhão, of 4,858 and 5,030 kg ha^{-1}, respectively, in the 2020/2021 harvest (Companhia Nacional de Abastecimento (CONAB), 2020).

The absorption patterns for each nutrient present different amounts, time, and partition for the different plant organs. Each nutrient exhibited a specific absorption model associated with the stage of vegetative or reproductive growth. Before flowering, quantities close to 50% or more of N, K, Ca, B, Fe, Zn, and Mn were accumulated. More than half of the total of N, K, B, Fe, Zn, and Mn were absorbed up to the phenological stage R1. This behavior was similar to the absorption pattern described by Bender et al. (2013), with values of 65%, 63%, 63%, 91%, 48%, and 64%, respectively. The same authors observed a fast absorption of Mg (65%) up to stage R1. The other nutrients are extracted more from flowering and have a large share in what is accumulated in the grains. For example, P and S, and N and Zn have high harvest indices, 0.84 and 0.69, and 0.74 and 0.51, respectively (Table 5).

Quickly absorbed nutrients are required in greater quantities during the vegetative phase and typically play a key role in plant growth. Despite this, the nutrients absorbed in greater quantity after flowering supply the needs throughout the plant cycle (Silva et al. 2018). Thus, it can be inferred that the elements absorbed later (P, S, and Zn) are the most exported by the crop, along with N.

This study showed a higher percentage of nitrogen in the grains (74%) at the end of the cycle. Similar studies indicated values of approximately 64% (Bender et al. 2013; Silva et al. 2018). This higher percentage of N found in the grains may have been influenced by cultivating maize in succession to soybeans whose contribution of N from biological fixation may have provided greater absorption of the element.

According to the fertilizer recommendation manuals used in the Cerrado region (Sousa and Lobato 2004), cultivating maize in succession to soybeans allows the reduction in nitrogen fertilization by up to 40%, for expected productivities around 8 Mg ha^{-1} of grain. For each tonne of soybeans produced, approximately 17 kg ha^{-1} of N are deposited in the soil after harvesting, which suggests a significant reduction in the application of nitrogen fertilizer for the production of maize in succession (Duarte, Cantarella, and Kappes 2017).

The plants absorbed 42% of the total accumulated P until tasseling, which is within the limits found by Silva et al. (2018) under Cerrado conditions in Minas Gerais. However, most of this nutrient was absorbed after flowering and directed to the grains, containing the largest amount of the absorbed P at the end of the cycle. This behavior occurs because P participates in compounds that transfer energy to transform sugar into starch in maize grains (Vilar and Vilar 2013).

The extraction, productivity and export data reported here indicate that there have been advances in maize breeding and management systems compared to older hybrids and production systems. The hybrid cultivated under the climate conditions of the Northeastern region of Brazil competes with the performance of maize produced both in the United States and in the Cerrado of Minas Gerais (Bender et al. 2013; Silva et al. 2018).

Potassium plays an important role in opening and closing stomata and activating enzymes (Ahmad et al. 2018), thus presenting a fast absorption by the plant, with most nutrients being absorbed in the vegetative stages. This indicates that a possible K deficiency at the beginning of crop development complicates its correction *via* fertilization. For this reason, potential cover fertilization with K must be carried out during the first 40 days of the plant cycle.

The highest amount of accumulated K is present in the stalk. This is an important characteristic since high-yield hybrids have a large transport capacity for photoassimilates from the stem to the grains (Woli et al. 2018). On the other hand, crops deficient in K can subject the plants to greater lodging since the vines are weakened, with a thinner cellular wall (Silva et al. 2018).

Several authors, from the classics such as Sayre (1948), Andrade et al. (1975), Vasconcellos et al. (1983), even the more current ones, such as Duarte et al. (2003), Pinho et al. (2009), Bender et al. (2013) and Silva et al. (2018) reported the reduction of K accumulated in the plant from the R2 stage, regardless of the environment and management system used (Figure 3c). The authors attributed this decrease to nutrients washing from the leaves by rainwater or irrigation since the nutrient is not a part of structural components of the plant, thus being easily removed.

This study presented a high K harvest index (0.45) in the maize plant (Table 5), which is higher than that observed by Silva et al. (2018) in an environment with maize grown under medium (0.26) and high (0.11) fertilization levels. The authors state that the higher level of fertilization in the crop did not increase the nutrient concentrations in the grains since 8.5 and 15.8 kg of K were required to produce a tonne of grains, and the export of the nutrient corresponded to 3.5 and 3.4 kg t^{-1} of grain, in medium and high investment environments in fertilization, respectively. Thus, higher fertilization levels do not correspond to increased productivity (Silva et al. 2018), generating loss of nutrient use efficiency, mainly due to the negative interaction between essential elements.

Calcium is a nutrient with low mobility in the plant, which explains its limited redistribution to the grains (Bender et al. 2013). Therefore, the export of the nutrient by the maize crop is considered low (0.32 kg t^{-1} of grain produced), as observed by Silva et al. (2018). Furthermore, calcium is a constituent of the cell wall, acting as a structural component (Marschner 2012), therefore having a relevant role in all plant fractions, especially vegetative ones.

The present study showed a slow accumulation of magnesium up to VT (28%), contradicting the data from the literature, which show that the greatest absorption of this nutrient by the maize plant occurs until flowering (Duarte et al. 2003; Pinho et al. 2009; Bender et al. 2013, and Silva et al. 2018). Although there are differences between the studies, it is important to emphasize that the availability of this nutrient should not be neglected since magnesium is a central component of the chlorophyll molecule, acting directly on the efficiency of photosynthetic activity. Hence the importance of performing correction liming to correct soil pH and providing Ca and Mg.

High values of S harvest index (between 45 and 60%) were observed by Pinho et al. (2009), Bender et al. (2013), and Silva et al. (2018). Like sulfur, nitrogen has a high harvest index, although their absorption processes differ. Nitrogen is absorbed in greater quantities until flowering, while the greatest absorption of S occurs after this phenological stage. This indicates that, although the harvest rates are high for both nutrients, they do not present a single pattern of accumulation and the physiological mechanisms involved are distinct. The absorption of S after flowering is directed mainly to the grains. On the other hand, N is accumulated in greater quantity in the grains despite mainly originating from the remobilization of the concentration stored in the vegetative fractions of the maize. Part of this remobilized N concentration comes from the absorption process still in the vegetative phase of maize development.

The Cu extraction pattern extends to the end of the cycle of maize plants, with maximum values obtained at the end of the cycle. This indicates that, regardless of the hybrid used and the cultivation environment, adequate supply conditions for this micronutrient must be ensured during the grain filling phase of the crop (Andrade et al. 1975; Borges, Von Pinho, and Pereira 2009).

The study conducted by Bender et al. (2013) demonstrated that most micronutrients were absorbed until reaching R1, presenting values of 48%, 64%, 63%, 91%, and 45% for Zn, Mn, B, Fe, and Cu, respectively. The fast absorption of micronutrients by maize was also mentioned by Gutiérrez et al. (2018).

Iron was the micronutrient most extracted by plants (Table 5), corroborating the results obtained by Bender et al. (2013), Gutiérrez et al. (2018), and Oliveira et al. (2019). Gutiérrez et al. (2018) observed continuous absorption of Fe until physiological maturity of maize plants, totaling 2,513 and 1,880 g ha^{-1} in environments with high and medium investment in fertilization, respectively. These values were superior to those obtained in the present study. Other authors also found high values of Fe accumulation in the physiological maturity of this crop, such as an average of 1,376 g ha^{-1} (Bender et al. 2013) and 3,283 g ha^{-1} (Duarte et al. 2003).

The presence of iron oxides in tropical soils is more predominant due to the greater weathering. These oxides have low Fe solubility, resulting in lower availability of this nutrient to plants, although without generating deficiency (Mielki et al. 2016). In this context, the plant absorbs only the necessary amount, without luxury consumption, defined as the concentration range of a given nutrient in which excess is observed in the plant without causing toxicity symptoms (Silva et al. 2018).

The extraction pattern of Mn in this study resembles that observed by Karlen, Flannery, and Sadler (1988), who accounted for more than 70% of the total extraction of Mn up to the R1 stage, and Gutiérrez et al. (2018), who observed intense absorption during the vegetative phase in an

Table 7. Grain and dry weight productivity and accumulation of micronutrients in the aerial part of the maize.

Studies	Grains	DW	Zn	Mn	B	Fe	Cu
	kg ha^{-1}		g ha^{-1}				
Current study1	9,352	16,166	377	221	77	459	99
Duarte et al. (2003)2	7,700	16,200	231	679	146	3283	78
Bender et al. (2013)3	12,000	23,200	498	542	83	1376	141
Gutiérrez et al. (2018)4	11,024	25,600	441	639	–	2,196	85
Oliveira et al. (2019)5	15,000	25,646	606	578	–	9,714	232

[1]Simple transgenic hybrid 30F35; population of 62,000 plants ha^{-1}, Brejo, Maranhão, Brazil.
[2]Mean of three cultivars of tropical climate; population of 55,000 plants ha^{-1}, Palmital, São Paulo, Brazil.
[3]Mean of six hybrids produced in two locations, population of 84,000 plants ha^{-1}, Ilinois, United States of America.
[4]Mean of four hybrids under medium and high fertility levels; population of 70,000 plants ha^{-1}, Sete Lagoas, Minas Gerais, Brazil.
[5]Mean of hybrids cultivated under a conventional planting system; population of 83,500 plants ha^{-1};Alto Parnaíba region, Minas Gerais, Brazil.

environment with high investment in fertilization. These data suggest that the supply of Mn in the early stages of maize crop development is an important strategy to increase the use of this element by plants (Gutiérrez et al. 2018). The total extraction of Mn during the maturity phase in this study was lower than that observed by other authors (Table 7).

Unlike what was observed by Bender et al. (2013) and Gutiérrez et al. (2018), Mn was not the second most extracted micronutrient by maize plants (Table 5), whose total accumulation in the present study was lower than that of Fe and Zn. However, a similar result was observed by Oliveira et al. (2019).

In physiological maturation, leaves and stalks are the tissues with the highest proportion of Mn, as reported by Duarte et al. (2003) and Gutiérrez et al. (2018). According to these authors, the stalk is the main compartment of accumulation of Mn in the mature plant, acting as a storage structure of this micronutrient.

The absorption of Zn was increased at the end of the vegetative phase and beginning of the reproductive phase, corroborating the results obtained by Bender et al. (2013) and Gutiérrez et al. (2018), which reinforces the idea that fertilization must be planned correctly to avoid the deficiency of this nutrient between these critical absorption periods. This is justified by the fact that Zn is the micronutrient that has the highest harvest index, being part of the elements that are most exported by maize grains, along with N, P and S (BORGES; Borges, Von Pinho, and Pereira, 2009; Bender et al. 2013; Gutiérrez et al. 2018; Oliveira et al. 2019).

Breeding has allowed maize hybrids to evolve into the market, changing the demand for nutrients (Tables 6 and 7). However, the results obtained and the information from the literature show that the extraction and export rates of macro and micronutrients by maize are variable according to the genotypes used and the edafoclimatic conditions and management practices applied to the crop.

The differences in the extraction and export of nutrients by the studied hybrid under the climate conditions of Eastern Maranhão compared to those found in the literature reinforce the need for constant updating for the different maize-cultivating regions in Brazil, especially for the MATOPIBA-producing regions. The confirmation of the nutritional requirements of modern hybrids allows updating the fertilization programs adopted by the producers to assist in the adoption of management practices that guarantee nutritional balance and adequate soil fertility during the crop cycle. In this context, this approach should gain relevance as new field results are obtained, especially in intensive production systems.

Conclusions

The thermal sum showed no effects on the maize crop cycle under the conditions of this study. Nutrients P, S, Mg, and Cu are absorbed in greater quantity after maize flowering. Nutrients N, K, Ca, B, Zn, Fe, and Mn are absorbed in greater amounts until the VT phase of maize. Nutrients absorbed early in plant cycle are required in greater quantities during the vegetative phase and play a key role in plant growth. However, nutrients absorbed later such as P and S are the most exported by harvest. Exception is reported for N that is mostly absorbed in early stages and remobilized from vegetative organs to grains. Fertilization must be carefully planned to avoid deficiency in the critical absorption phases. Overall, our results show the importance of accessing site-specific effects on plant growth and nutrient absorption, partitioning and export in order to optimize nutrient supply and replacement to the soil, especially in agricultural frontiers. The results call for the need of further investigation on the role of maize genotypes with different growth patterns and subjected to different cropping systems on nutrients use efficiency and the development of techniques for timing nutrient supply in order to optimize crop performance.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This study was funded by the National Council for Scientific and Technological Development - CNPq (431305/2018-8). Ane Caroline Melo Ferreira has received research grants from Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – Brasil (CAPES).

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