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Maize dry matter production and macronutrient extraction model as a new approach for fertilizer rate estimation

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ABSTRACT

Decision support for nutrient application remains an enigma if based on soil nutrient analysis. If the crop could be used as an auxiliary indicator, the plant nutrient status during different growth stages could complement the soil test, improving the fertilizer recommendation. Nutrient absorption and partitioning in the plant are here studied and described with mathematical models. The objective of this study considers the temporal variation of the nutrient uptake rate, which should define crop needs as compared to the critical content in soil solution. A uniform maize crop was grown to observe dry matter accumulation and nutrient content in the plant. The dry matter accumulation followed a sigmoidal model and the macronutrient content a power model. The maximum nutrient absorption occurred at the R_4 growth stage, for which the sap concentration was successfully calculated. It is hoped that this new approach of evaluating nutrient sap concentration will help to develop more rational ways to estimate crop fertilizer needs. This new approach has great potential for on-the-go crop sensor-based nutrient application methods and its sensitivity to soil tillage and management systems need to be examined in following studies. If mathematical model reflects management impact adequately, resources for experiments can be saved.

Key words: maize, fertilizer rate estimation, nutrient content, nutrient partition.

INTRODUCTION

Maize (*Zea mays* L.) is worldwide the most cultivated cereal, its economic importance being manifested by the different ways of consumption, going from human food and animal feed to the high technology industry (Edwards 2009). Brazil is the world's third largest maize producer, behind the United States and China. The cultivated area in Brazil in the first (2014/2015) and second cropping seasons (2015) was 15,627,300 hectares. The national average maize yield of the 1976/1977 crop (40 years ago) was 1,632 kg.ha^{-1}. In the season 2014/2015 the average Brazil's productivity was more than 3 times higher, i.e. 5,382 kg.ha^{-1} and the projection of the Brazilian agribusiness indicates that the harvest of 2023/2024 maize production

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* Contribution to the centenary of the Brazilian Academy of Sciences.

should be of the order of 104 million tons (Conab 2015). Productivity increases in time of the maize crop are due to the development of agriculture in relation to the breeding of plants and management practices, including the correction and fertilization of soils (Bender et al. 2013, Ciampitti et al. 2013). After productivity increases obtained through breeding, the problem of adequate nutrient supply at the right time, which today is based on current shortcomings in soil nutrient tests, is the key answer for further improvement. Nowadays, nitrogen can be applied at appropriate rates based on crop sensors. Crop sensors are now being developed for other nutrients, based on optical physics to reveal spectra that reflect plant nutrient concentrations in vivo. In this way management decisions could be met much easier, added to solid scientific concepts and to models as presented here.

As an example, in Brazil information on absorption and partition nutrients by the maize plant come from older literature as stated by Ciampitti et al. (2013). The most recent work on the absorption and partition nutrients in maize has been conducted mainly in the United States. Only few studies were performed for modern maize hybrids used in Brazil (Von Pinho et al. 2009). The lime and fertilizer recommendations are still based on studies made many years ago and are organized in books and tables, such as Raij et al. (1997), Ribeiro et al. (1999), SBCS (2004) and Oliveira (2003).

In addition, agricultural production systems have also improved in the past decades, using higher plant densities, reduced seed spacing, new agrochemicals for crop protection and transgenic hybrids (Bender et al. 2013).

The improvement of agronomic practices and the use of increasingly growing high-tech crops may have changed the dynamics of absorption and partitioning of nutrients by the maize crop. Therefore, there is room for studies on the current absorption patterns and partition of nutrients. As stated before, it is important to note that even with the growing development of agriculture, worldwide fertilizer recommendations for the maize crop are still based on the critical content of the nutrient in the soil, which is a static approach for such a dynamic process and that is not specific for each employed management system.

The critical content or critical level of a nutrient may be defined as the nutrient content in the soil which should correspond to the readiness to obtain the maximum economic productivity, considered between 80 and 90% of the maximum yield (Cantarutti et al. 2007).

The determination of the critical content is derived from empirical models that relate the nutrient content extracted by chemical analysis of the soil with the nutrient content in the plant or with productivity (Bray 1948, Cantarutti et al. 2007, Cate and Nelson 1965, Corey 1987). This methodology had its importance and is relatively simple, but does not consider that the critical content in the plant may vary according to species, phenological stage of the crop, expected productivity, soil, and climatic interactions (Santos et al. 2008).

Furthermore, the factors that interact in an agricultural production system can be better analyzed using mathematical models, and so help in the search for appropriate soil management practices in modern agricultural production systems. Mathematical models that are developed based on scientific knowledge are called mechanistic models, and those based on observations are called empirical models (Fancelli and Dourado Neto 1997, Silva et al. 2006, Timm et al. 2004). These models seek to represent the natural processes that determine the availability and absorption of nutrients and thus increase the understanding of the system, allowing a refinement of the recommendations of correctives and fertilizers (Cantarutti et al. 2007), and also helping to manage soils in a way that positively influences the availability of nutrients when the demand of the plant exists.

Following these lines, this study aims to propose a methodology for characterizing the maize crop with respect to: (i) composition and dry matter production of the different organs during plant development, (ii) extraction and distribution of nutrients in these organs, and (iii) estimate the macronutrient concentration in the stalk sap.

MATERIALS AND METHODS

The experiment was carried out in Piracicaba (SP), Brazil (22° 41' 30" South; 47° 38' 30" West, 546 m above sea level). The soil was classified as a Typic Hapludox (Soil Survey Staff 1975). The climate is of the Cwa type according to Köppen´s classification, with rainy summer and dry winter, annual average air temperature 21.4°C and 1,257 mm of average annual rainfall.

The maize (*Zea mays* L.) simple hybrid DKB 390 PRO 2 was chosen because of its high productive potential presenting the technology VT PRO^{TM} 2 which is the combination of the Roundup Ready ^{TM} technology that induces tolerance to the herbicide glyphosate with the YieldGard ^{TM} technology.

The crop was established on March 26, 2013 using a population of 65,000 plants.ha^{-1} at row spacing of 0.45 m. Seeds were treated with Fipronil + Pyraclostrobin + Thiophanate-methyl at a rate of 200 mL per 100 kg of seeds. A single area of 5,000 m^2 considered as homogeneous was sown to the same hybrid and managed in the same way applying 30 kg.ha^{-1} of N, 80 kg.ha^{-1} of P_2O_5, and 40 kg.ha^{-1} of K_2O. Additional 90 kg.ha^{-1} of N was applied at V_4 phenological stage (Ritchie et al. 1996).

The homogeneous area (3,969 m^2) was divided into 315 plots (grid of 21 x 15) used for random sampling the aerial part (shoot) of two whole plants per plot (one of each central row). Each plot of 12.6 m^2 consisted of four maize rows 7 m long. The sampling was made disregarding 0.5 m at the beginning and the end of the two central rows (5 m long), with sampling area of 5.4 m^2. Treatments (16) consisted of plant collection times, established according to the growth stages defined by Ritchie et al. (1996), as follows: V_2, V_4, V_6, V_8 and V_{10}, which occurred, respectively, at 14, 21, 28, 35 and 42 days after sowing (DAS). Sixty plants were collected at each date, using 30 plots chosen randomly over the whole area (30 plots of 315: 9.52%). The 60 sampled plants were divided, also randomly, into six replications of 10 plants each for dry matter and chemical analyses. At 50 (V_{12}), 56 (V_{15}), 70 (R_1), 77 (R_2), 84 (R_2-R_3), 91 (R_3), 104 (R_3-R_4), 111 (R_4), 118 (R_5), 127 (R_5-R_6) and 139 (R_6) DAS, the number of harvested plants was reduced to half, collecting 30 plants per treatment (6 replications of five plants).

In this way, during the whole experimental period a total of 630 plants was sampled, corresponding to 1.93% of the total number of plants, therefore not affecting significantly the final yield, which was however corrected by this factor. To define each development stage of the crop, phonologic observations were performed every two days during the whole crop cycle, according to Ritchie et al. (1996).

Climatologic data were used to calculate degree-days (DD, ºC.day) with 10ºC as the lower base temperature (Fancelli and Dourado Neto 1997). Potential reference evapotranspiration (ETo, mm.day^{-1}), was calculated by the method of Penman-Monteith (Allen et al. 1998), and a climatological water balance was established according to Thornthwaite and Mather (1955).

Plant samples were separated into leaf, stalk, tassel and ear (cob and kernels, style-stigma and corn husk), dried at 65^{0}C until constant weight for dry matter determination using a 0.001 g precision digital scale. Thereafter, samples were homogenized and subsamples were sent for nutrient analysis (N, P, K, Ca, Mg and S) according to Silva (2009).

During crop development, leaf area per plant was evaluated measuring the areas of all leaves of six plants, using a LI-COR® sensor, model Li-3100C. This was made at all growth stages.

Harvest was performed at physiologic maturity (R_6 stage) (Ritchie et al. 1996), collecting all plants of the central two rows of 7 m, disregarding 0.5 m at each border. Grain yield (P, $kg.ha^{-1}$) was estimated based on plant population (Pp, plants. ha^{-1}), prolificacy (Pf, $ears.plant^{-1}$), number of grains per ear (Ge, $grains.ear^{1}$), and the mass (kg) of 1,000 grains at 13% moisture.

Based on dry matter and nutrient concentration of each plant organ, a model was chosen to characterize nutrient absorption (A) and nutrient partitioning among the various organs: root, leaf, stalk and reproductive organs. The model considers that the fertilizer recommendation should be based on the temporal variability of the nutrient absorption rate, in comparison to the classic recommendation based on the critical soil nutrient content.

Considering that at a given time t (DAS) within the crop cycle, plants have accumulated a dry matter Y, with a given nutrient content (*Ti*), the cumulative nutrient absorption A is given by the product Y x T. Following this reasoning, our Y and T data were modeled as a function of time using appropriate equations.

The development of the general model (Fig. 1) is based on the growth curve of the maize plant (Fig. 1a) given by the accumulation of the total dry matter, which is a sigmoidal equation (Eq. 1).

The sigmoidal curve characterizes positively increasing growth rates of dry matter accumulation in the vegetative stages, and thereafter continuing increasing dry matter accumulation but with positively decreasing rates in the reproductive stages, resulting in a typical S shaped curve (Fig. 1a or 1b).

The distinction between these two phases was made by the inflection point of (Eq. 1). The following equation was suggested to represent the maize growth (Y, $kg.ha^{-1}$) curve as a function of time (t, DAS) (Fig. 1a):

$$Y(t)=\left[a+\frac{b}{1+\left[\frac{(t-c)}{d}\right]^2}\right] \qquad 1$$

with empirical parameters a, b, c and d, valid in the interval $t = 1$ (first day after emergence) and $t = t_m$ (maturity). The four model parameters were fitted with aid of the program Table Curve® (SYSTAT Software 2000), based on experimental data of *Y* by minimizing the sum of squared deviations.

For the temporal changes of the concentration of the ith macronutrient in the plant (T_i, $g.kg^{-1}$) (Fig. 1c-1 or 1c-2), we assumed the model of a decreasing power function:

$$T_i(t)=\varepsilon.t^{\theta} \qquad 2\text{-A}$$

with two fitting empirical parameters ε and θ, or a constant linear function with the parameter k (the average value of nutrient content):

$$T_i(t)=k \qquad 2\text{-B}$$

both valid in the interval between t = 14 DAS (first day of T evaluation) and $t = t_m$ (maturity, last day of evaluation).

At each time t (starting at t = 14 DAS), multiplying *Y* (kg[dry matter].ha^{-1} - growth curve) (Fig. 1a) by the respective *T* ($g.kg^{-1}$ - kg of the macronutrient per kg of total dry matter) that can be constant or not (Fig. 1c-1 or 1c-2), we obtain the temporal variation of macronutrient absorption (*A*, $kg.ha^{-1}$ - kg of the macronutrient per hectare) (Fig. 1d), so that:

$$A_i(t)=\frac{Y(t).T_i(t)}{1{,}000} \qquad 3$$

The aim of the proposed model was to obtain the curve of the absorption rate (λ, $kg.ha^{-1}.day^{-1}$) (Fig. 1e) of each macronutrient, that can be calculated multiplying at each time t the value of the growth

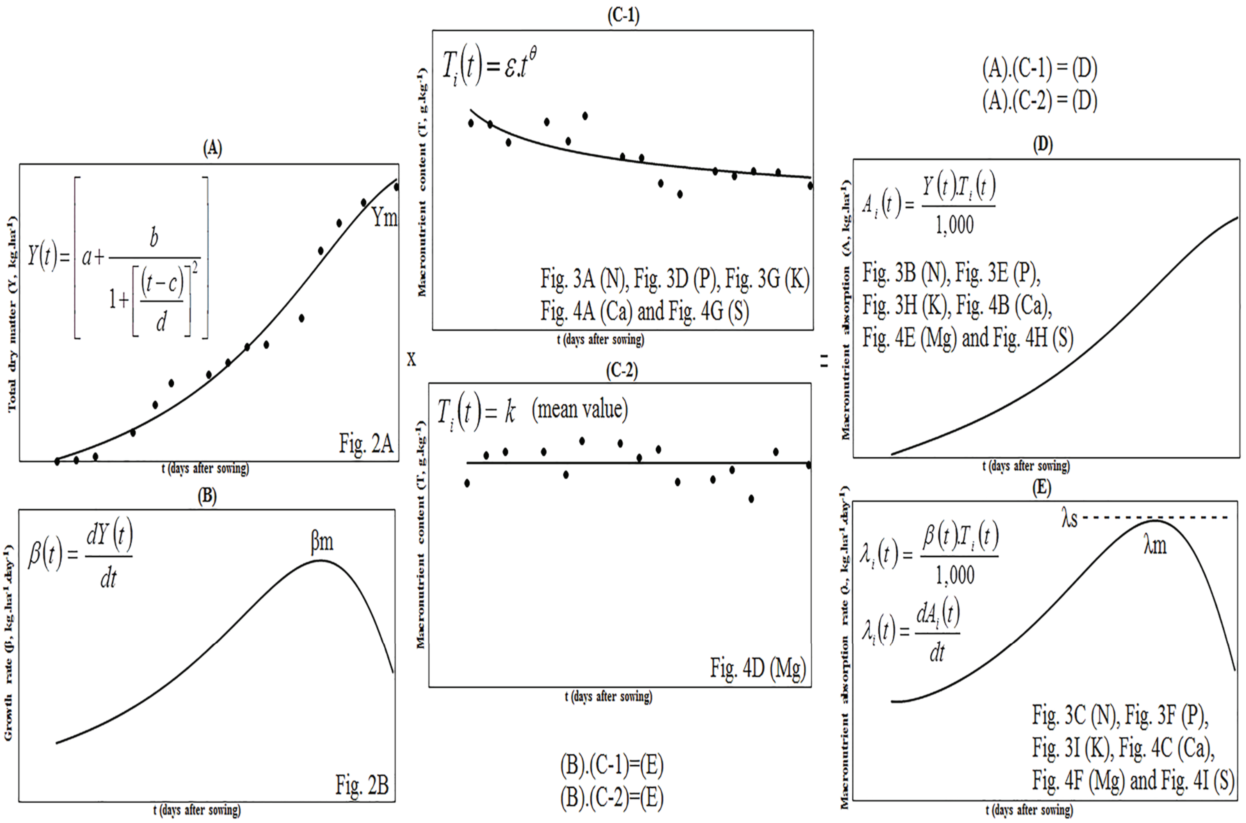

Figure 1 - Basic hypothesis of the macronutrient absorption model: **(a)** crop growth (Y, kg[dry matter].ha^{-1}), **(b)** crop growth rate (β, kg[dry matter].ha^{-1}.day^{-1}) as a function of time (*t*, day - DAS), **(c)** macronutrient content (T, kg[nutrient].kg[dry matter]$^{-1}$) (c-1 or c-2), **(d)** temporal variation of macronutrient absorption (A, kg[nutrient].ha^{-1}), **(e)** crop macronutrient absorption rate (λ, kg[nutrient].ha^{-1}.day^{-1}) and soil macronutrient availability rate offer (λs, kg[nutrient].ha^{-1}.day^{-1} - dashed line represents the soil macronutrient availability rate offer), λ*m* corresponding to the maximum crop macronutrient absorption rate demand (kg[nutrient].ha^{-1}.day^{-1}) and βm maximum crop growth rate (kg[dry matter].ha^{-1}.day^{-1}) related to the corn productivity P.

rate (β, kg[dry matter].ha^{-1}.day^{-1}) (Fig. 1b), which is the first derivative of Y with respect to t, by the respective T (Fig. 1c-1 or 1c-2):

$$\lambda_i(t) = \frac{\beta(t).T_i(t)}{1{,}000} \qquad 4$$

where

$$\beta(t) = \frac{dY(t)}{dt} \qquad 5$$

The model for the calculation of the release rate of the macronutrient by the soil was assumed as at least the maximum absorption rate throughout the growth cycle and is illustrated in Fig. 1e (dashed line).

From the first derivative of the absorption rate of a macronutrient λ (or the second derivative of the temporal variation of macronutrient absorption - A), it is possible to calculate the maximum absorption rate (λm_i, kg.ha^{-1}.day^{-1}) of the ith macronutrient (N, P, K, Ca, Mg or S), which should be related to the critical nutrient content in the plant sap (Cc_i, mg.L^{-1}) and in the soil solution (Fig. 1e). It corresponds to the rate of soil nutrient supply (λ*s*, kg.ha^{-1}.day^{-1}) for the limiting macronutrient in relation to the corn productivity (*Pd*, kg.ha^{-1}), so that:

$$\lambda m_i = \lambda s \qquad 6$$

$$Pd = \frac{HI.Y_m}{1-u} \qquad 7$$

where *HI* is the harvest index ($kg.kg^{-1}$ - kg of grain dry matter per kg of total dry matter), *Ym* is the maximum value of Y ($kg.ha^{-1}$) and u is the seed water content ($kg.kg^{-1}$).

To estimate the critical (maximum) concentration Cc_i of the ith nutrient in the stalk sap, knowing the first derivative λm_i (when first derivative of $\lambda_i(t)$ is zero) (Fig. 1e), the calculation starts with the water flux absorbed by roots (q_r, $mm.day^{-1}$). This flux can be considered as the actual transpiration (Ta, $mm.day^{-1}$), equal to the actual evapotranspiration (ETa, $mm.day^{-1}$), here calculated from the Thornthwaite and Mather (1955) water balance, subtracting the soil surface evaporation (E, $mm.day^{-1}$) and adding the absorbed water responsible for the total dry matter accumulation (α, $mm.day^{-1}$) in the crop. Knowing that a salt flux (here λm_i is the product of a water flux - q_r - by a concentration - Cc), we have:

$$Cc_i = \frac{100.\lambda m_i}{q_r} = \frac{100.\lambda m_i}{Ta+\alpha} = \frac{100.\lambda m_i}{ETa-E+\alpha} \qquad 8$$

Cc_i should also represent the "unknown" critical concentration ($mg.L^{-1}$) of each nutrient "i" in the soil solution. In this way, knowing Cc_i, it should be possible to develop a methodology for characterizing soil fertility and recommending fertilization aiming to reach the maximum productivity of the maize crop as a function of the limiting nutrient.

The statistical analysis was performed using the program SAS® (SAS Institute 2003), including the analysis of variance (ANOVA), to compare averages through the Tukey test ($p < 0.05$) and for the multivariate analysis based on principal components. For regressions and model adjustment the program Table Curve 2D®, version 5.01 (SYSTAT Software 2000) was used.

RESULTS AND DISCUSSION

During the experiment with maize, dry matter samples were collected over time, to evaluate dry matter accumulation until physiologic maturity and quantify the concentrations of macronutrients in respective samples.

CLIMATIC CONDITIONS

The crop grown uniformly on 5,000 m^2 received a precipitation of 409.6 mm, from March to August 2013. From germination until stage V_4, rainfall was excellent for crop development, and from 20 to 56 DAS (V_4 to V_{15} stage) a dry spell occurred.

During the dry spell the available water was reduced from the AWC = 46.4 mm to about 12.0 mm (Fig. 2b), but this water stress was not so severe as observed through growth parameters. Between 57 and 121 DAS, rainfall was sufficient to allow a normal development of the crop (V_{15} to R_5 stage). Thereafter, rainfall stopped until maturity (R_6 stage) and the harvest could be well performed. Maize crop water requirements for our conditions are in the range 350 to 600 mm, so that the total of 409.6 mm is within this range. One reason for a no water stress condition of the crop was the high available water during the first 20 days of crop establishment.

Air temperature and ETa were as expected and adequate considering that the temperature range for maize is between 10 and 30ºC, more specifically, between 26 and 30ºC during day and 16 and 19ºC during night (Edwards 2009).

Calendar dates and DAS referring to the growth stages of the maize crop are listed in Table I together with accumulated DD (using 10ºC as lower basal temperature) and relative development based on dry matter accumulation.

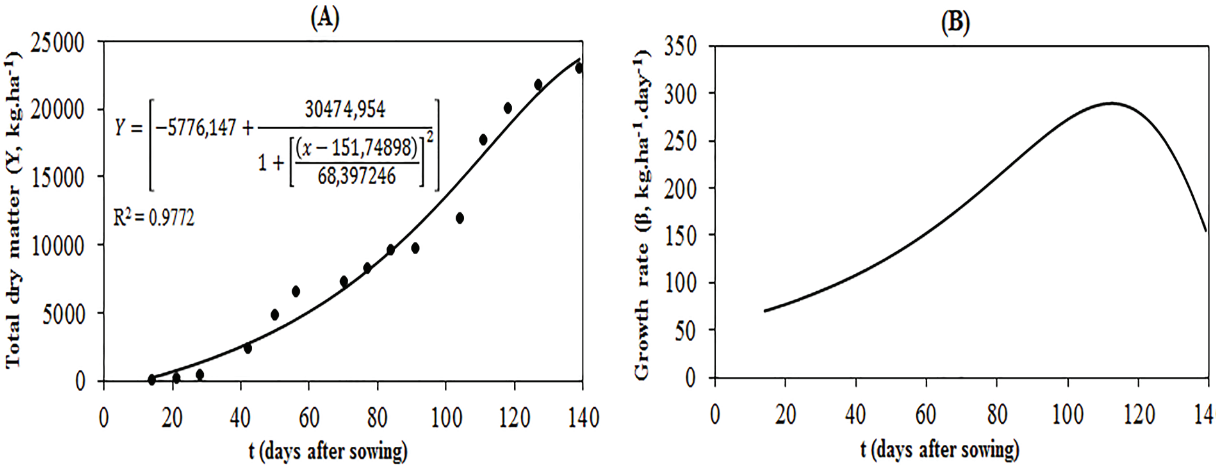

Figure 2 - Total dry matter (Y, $kg.ha^{-1}$) **(a)** and growth rate (β, $kg.ha^{-1}.day^{-1}$) **(b)**, of the maize crop (hybrid DKB 390 PRO 2), as a function of time (t, days after sowing - DAS). Piracicaba (SP), Brazil.

TABLE I

Description of treatments (TT) each referring to a sampling date, growth stages (GS) of the maize crop (hybrid DKB 390 PRO 2), and respective calendar dates (D), days after sowing (DAS), accumulated degree-days (DD, °C.day), and relative development (R_d) based on DD. Piracicaba (SP), Brazil.

TT	Vegetative phase					TT	Reproductive phase				
	GS	D	DAS	DD (°C.day)	R_d		GS	D	DAS	DD (°C.day)	R_d
	Sowing	Mar/26	0	-	-	8	R_1	Jun/04	70	863	0.541
	V_E	Apr/02	7	0	0.000	9	R_2	Jun/11	77	943	0.591
1	V_2	Apr/09	14	215	0.135	10	R_2-R_3	Jun/18	84	1021	0.640
2	V_4	Apr/16	21	307	0.192	11	R_3	Jun/25	91	1097	0.687
3	V_6	Apr/23	28	385	0.241	12	R_4	Jul/08	104	1249	0.783
4	V_8	Apr/30	35	474	0.297	13	R_4-R_5	Jul/15	111	1325	0.830
5	V_{10}	May/07	42	567	0.355	14	R_5	Jul/22	118	1411	0.884
6	V_{12}	May/15	50	653	0.409	15	R_5-R_6	Jul/31	127	1462	0.916
7	V_{15}	May/21	56	728	0.456	16	R_6	Aug/12	139	1596	1.000

TABLE II

Leaf area (LA, $cm^2.plant^{-1}$) and dry matter ($g.plant^{-1}$) for leaf, stalk, tassel, ear (cob and kernels, style-stigma and corn husk) and total in relation to days after sowing (DAS) and growth stage (GS) of the maize crop (hybrid DKB 390 PRO 2). Piracicaba (SP), Brazil.

DAS	GS	Leaf area ($cm^2.plant^{-1}$)	Dry matter (Y, $g.plant^{-1}$)						
			Leaf	Stalk	Tassel	Ear (cob and kernels)	Ear (style-stigma)	Ear (corn husk)	Total
14	V_2	99.80	0.28	0.12	.	.	.	.	0.40
21	V_4	432.54	1.54	0.91	.	.	.	.	2.45
28	V_6	1152.84	4.40	3.13	.	.	.	.	7.53
35	V_8	2400.91	10.08	15.50	.	.	.	.	25.58
42	V_{10}	3807.22	20.04	17.02	.	.	.	.	37.06

TABLE II (continuation)

DAS	GS	Leaf area ($cm^2.plant^{-1}$)	Dry matter (Y, $g.plant^{-1}$) Leaf	Stalk	Tassel	Ear (cob and kernels)	Ear (style-stigma)	Ear (corn husk)	Total
50	V_{12}	5152.32	31.26	42.76	.	.	.	.	74.02
56	V_{15}	6047.51	42.80	58.05	.	.	.	.	100.85
70	R_1	6129.08	37.38	63.90	6.43	0.57	0.35	3.60	112.22
77	R_2	5933.97	35.84	76.66	3.49	2.06	1.00	8.24	127.29
84	R_2-R_3	5927.17	35.42	86.70	2.44	7.21	1.48	14.91	148.16
91	R_3	5680.66	33.72	76.33	2.35	17.23	1.88	19.29	150.80
104	R_4	5345.48	32.36	74.29	2.25	52.26	1.01	22.99	185.16
111	R_4-R_5	5932.09	36.53	106.56	2.61	92.61	3.89	30.72	272.92
118	R_5	5524.86	39.84	102.01	2.36	130.11	1.31	33.06	308.69
127	R_5-R_6	5823.16	43.24	99.94	2.24	154.31	0.85	34.11	334.69
139	R_6	4454.81	39.32	99.69	2.35	179.37	2.35	31.83	354.90

Leaf area and dry matter accumulation

Positive increments of dry matter were observed since the beginning of growth and development up to the beginning of the reproductive phase (R_1) (Ritchie et al. 1996) when the total dry matter accumulated was 112 $g.plant^{-1}$ (Tables I and II).

In relation to leaf area, at the beginning of the growth and development of the crop at 14 DAS (V_2 growth stage) its value was 99.8 $cm^2.plant^{-1}$ and at 70 DAS (R_1 stage) it expanded to 6,129.1 $cm^2.plant^{-1}$. After this date (flowering), the leaf area was maintained practically constant until 127 DAS (R_5-R_6 stage), with a significant drop at 139 DAS (R_6 stage) presenting 4,454.8 $cm^2.plant^{-1}$ (Table II).

In this experiment the total dry matter accumulation was fitted to the model described in Equation 1 (Fig. 2a), with a very high R^2 of 0.9772. Therefore, this model was used in the following calculations.

The growth rate of the maize crop β (dY/dt, $kg.ha^{-1}.day^{-1}$) increased daily during the development according to dY^2/dt^2 (growth acceleration or daily dry matter gain), up to 84 DAS with a value of 227 $kg.ha^{-1}.day^{-1}$ (Fig. 2b). Hereafter, daily gains decreased until they become zero when the growth rate became maximum (βm), at 112 DAS, with a crop growth of 289.4 $kg.ha^{-1}.day^{-1}$ (Fig. 2b).

After 112 DAS, the values of the growth rate continued to be positive, but with negative daily gains, i.e., the maize plant slowed down its dry matter accumulation as a consequence of the senescence process.

Macronutrient content in the whole plant

Regarding macronutrient content in the whole plant, N, P, K, Ca and S started high and decreased almost leveling off at the end of the maize crop cycle (Fig. 3a, d and g and 4a and g). As it can be seen, the exponential model fitted well to most of the macronutrients, excepted for Mg (Fig. 4d).

In general, as there is a low plant biomass during the initial growth, a high concentration of nutrients is found to be derived from the soil for all macronutrients, excepted for magnesium. With the growth of the plant, which usually follows a sigmoidal model, the mass accumulation is more expressive than the capacity of the plant to absorb and concentrate nutrients. Thus, there is an obvious dilution effect due to the growth of the plant. Furthermore, it is known that higher concentrations of N, for example, are related to leaves. Over time,

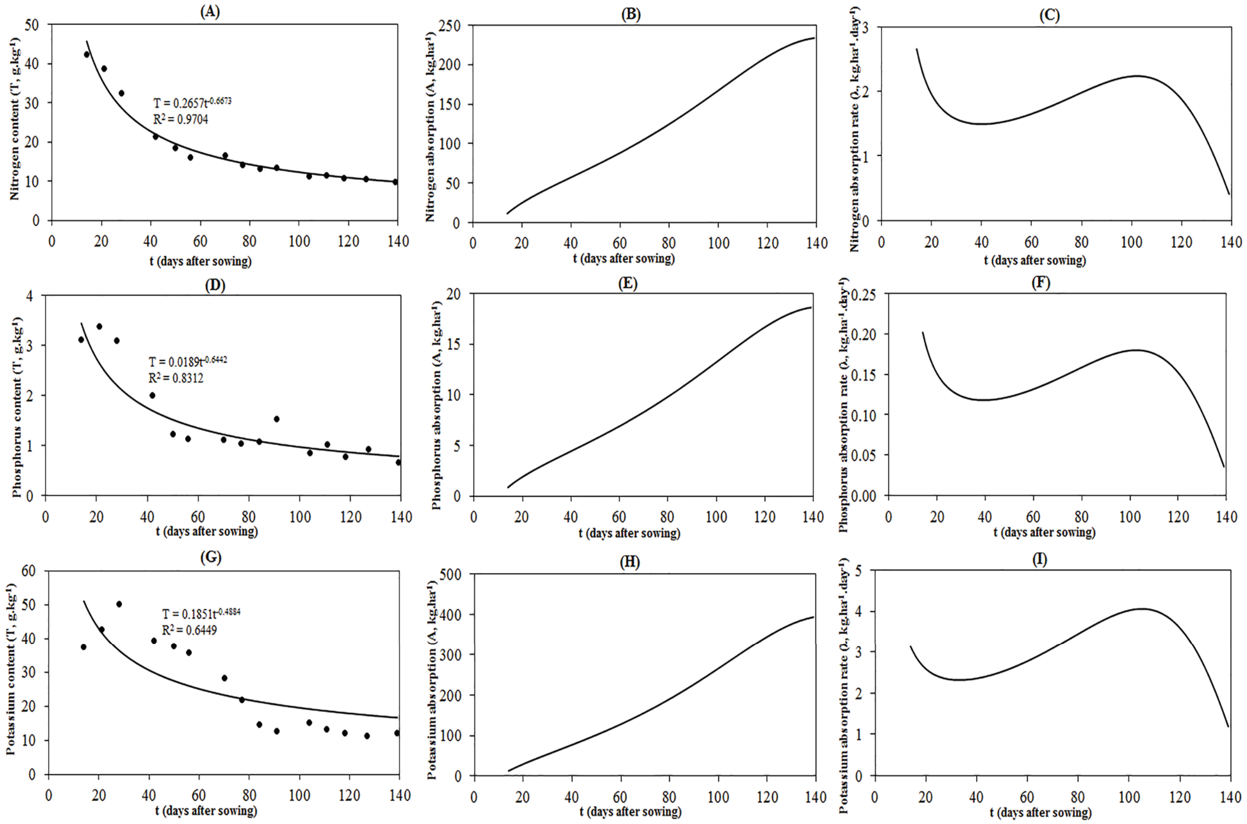

Figure 3 - Macronutrient content of the whole plant (T, g.kg^{-1}), total absorption (A, kg.ha^{-1}) and absorption rate (λ, kg.ha^{-1}.day^{-1}) for nitrogen (**a**, **b** and **c**), phosphorus (**d**, **e** and **f**) and potassium (**g**, **h** and **i**) in the maize (hybrid DKB 390 PRO 2) crop (weighted average of all organs) in relation to the number days after sowing (t, days after sowing). Piracicaba (SP), Brazil.

other structures as mainly the stalk, gain greater proportion in the share of total dry matter thus contributing to part of this dilution effect.

Macronutrient absorption A and absorption rate λ for the whole plant

For the whole maize plant, Fig. 3 and 4 present the total absorption of the macronutrients and their respective absorption rates, together with the macronutrient contents, all as a function of time (DAS). Obviously Equation 2-A fitted well to all nutrients with exception of Mg that presented a constant behavior following Equation 2-B. The total absorption followed well the behavior of Equation 3 for all nutrients but K with a poorer fit. The absorption rate increases for all nutrients from 14 to 139 DAS, as expected. The fact that the function T(t) is a decreasing power function for most nutrients (N, P, K, Ca and S), the temporal variation of macronutrient absorption functions A are not pure sigmoids like the function Y(t) (Fig. 3 and 4). Therefore the absorption rates λ are also not perfectly bell-shaped and present initial high values, which are here not considered as maximum rates due to the early stages of plant growth.

Potassium (K) behaved similar to nitrogen, but with a slightly worse fit. Nevertheless, the power model for K content was chosen, in the same way as for the contents of N and P. The total absorption (A) of K also increased with the growth and development of the maize crop.

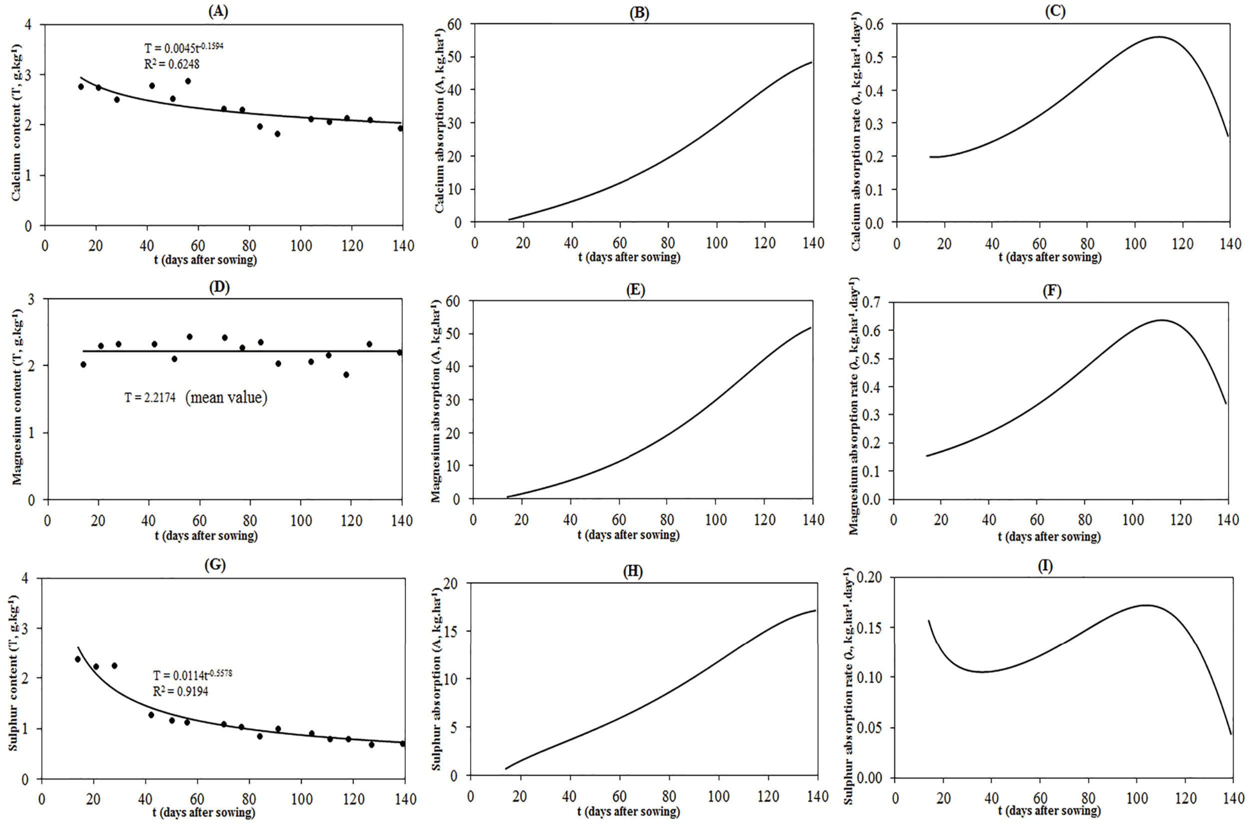

Figure 4 - Macronutrient content of the whole plant (T, g.kg^{-1}), total absorption (A, kg.ha^{-1}) and absorption rate (λ, kg.ha^{-1}.day^{-1}) for calcium (**a**, **b** and **c**), magnesium (**d**, **e** and **f**), and sulfur (**g**, **h** and **i**) in the maize (hybrid DKB 390 VT PRO 2) crop (weighted average of all organs) in relation to the number days after sowing (t, days after sowing). Piracicaba (SP), Brazil.

Macronutrient content in stalk sap

With the aim of estimating the macronutrient concentrations in the maize stalk sap at the time of maximum absorption, the Equation 6 was used. The values for macronutrient contents, the total absorption of macronutrients and the absorption rates of each macronutrient, and calculations are shown in Table III.

The grain productivity of the maize crop was 10,335 kg.ha^{-1} (13% of seed water content). The maximum absorption of the macronutrients occurred between 102 and 112 days after sowing (Table III), i.e., during the R_3 (crop presenting 50% of the plants exhibiting pasty grains) and R_4 (50% of the plants exhibiting farinaceous grains) stages. These stages are therefore the most important with respect to the nutritional needs of the maize crop. In these stages the starch accumulation in the maize grain increases featuring a period of grain filling, resulting in greater dry mass of grain (Edwards 2009).

Experiments carried out with the aim of evaluating the absorption of nutrients by a maize crop also report that the increased absorption of the nutrients N, P, K and S occurred at the R_3 stage, when the crop presented 50% of the plants with pasty grains (Ciampitti et al. 2013).

The ETa values for corresponding days of λn are relatively small because of the winter season in Piracicaba (SP) and due to cloudiness. Estimates of the critical concentration in the gross plant sap were highest for potassium, followed by nitrogen (Table III).

TABLE III
Critical concentration (C_C, mg.L^{-1}) of each macronutrient (Nt) in crude sap (xylem) of the maize crop (hybrid **DKB 390 PRO 2) at the day (DAS, days) of maximum absorption rate (λn, kg.ha^{-1}.day^{-1}) corresponding to the growth stage (GS); as function of the molecular weight (M, g.mol^{-1}), whole plant content (T, g.kg^{-1}), nutrient absorption (A, kg.ha^{-1}) and actual evapotranspiration (ETa, mm.day^{-1}). Piracicaba (SP), Brazil.**

Nt	DAS	GS	T (g.kg^{-1})	A (kg.ha^{-1})	λ_n (kg.ha^{-1}.day^{-1})	ETa (mm.day^{-1})	M (g.mol^{-1})	Cc (mg.L^{-1})
N	102	R_3-R_4	12.1	171.79	2.24	1.8	14	124.4
P	103	R_3-R_4	1.0	13.75	0.18	1.7	31	10.6
K	105	R_4-R_5	19.1	285.80	4.06	1.7	39	238.8
Ca	110	R_4-R_5	2.1	34.78	0.56	1.4	40	40.0
Mg	112	R_4-R_5	2.2	37.28	0.64	1.2	24	53.3
S	104	R_4	0.9	12.53	0.17	1.7	32	10.0

The critical concentration (C_C, mg.L^{-1}) of each nutrient in the xylem sap was here assumed to be related to the soil solution absorbed by plant roots (Table III). Based on the analysis of the results obtained in this research, it is suggested that future studies should be conducted in more than one growing season, with replicates of several years or even at different times. Such experiments may include different genotypes, as well as different regions, varying the population of plants in the experimental area, and simulate high, medium and low technology managements. It may also be considered to test the validity of this new approach under different managements, such as different water and nutrient supply and different soil structural conditions caused by the soil tillage system.

CONCLUSIONS

The highest percentage of dry matter was initially observed to be assigned to leaves. 70 days after sowing (R_1 growth stage), the highest percentage of dry matter was in the stalk, which at this stage was the main storage organ of the maize plant.

From the reproductive phase, the highest dry matter was conferred to the reproductive organs, because after flowering there is intense demand for carbohydrates and nutrients for grain filling.

The macronutrient content followed a power model, with higher values for the initial stages of development, except for Mg that presented a constant value.

The maximum growth rate occurred at 112 days after sowing (R_4-R_5 growth stage). The maximum nutrient absorptions occurred for N, P, K, Ca, Mg and S at 102 (R_3-R_4), 103 (R_3-R_4), 105 (R_4-R_5), 110 (R_4-R_5), 112 (R_4-R_5) and 104 (R_4) days after sowing), respectively.

It was possible to estimate macronutrient concentrations in the maize stalk sap, which are expected to guide methodologies that use the plant as an extractor in future calculations of fertilizer rates for the maize crop. The main focus was on diagnosing a crop and mathematically describing nutrient uptake and partitioning. In future studies, the sensitivity of the approach to different management systems needs to be evaluated. The approach introduced in this study has great potential in cases where sensors for automatic plant nutrient status become available. The proposed modeling approach will have great potential for decision support.

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