

Macronutrients uptake rate and biomass partitioning during early growth of *Jatropha* plants¹

Taxa de absorção de macronutrientes e partição de biomassa durante o crescimento inicial do pinhão-mansô

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ABSTRACT - *Jatropha* seeds oil can replace fossil fuels, but the nutrient supply management for this species is not fully described. The objective with this work was to establish curves of macronutrient (nitrogen - N; phosphorus - P; potassium - K; calcium - Ca; magnesium - Mg and sulfur - S) content in leaves, stem and roots, and to evaluate the relative growth rate (RGR), absolute growth rate (AGR) and the foliar mass ratio (FMR). The experiment was arranged in completely randomized design with five replications. *Jatropha* plants were grown in nutrient solution and collected at intervals of 14 up to 119 days after treatments started. The period of highest uptake of nutrients occurred from 7 to 35 days after treatments started, which coincides with highest AGR, RGR, FMR and accumulation of dry biomass. The highest Ca and Mg accumulation occurred in the leaves (respectively 48% and 47% of the total taken up), while N, K, S and P were mostly accumulated in the stem (58%, 56%, 56% and 53%, respectively). The nutrients more taken up by *Jatropha* plants were N and Ca, and the order of macronutrients uptake was: N > Ca > K > Mg > S > P. *Jatropha* plants have shown high macronutrients content on its early development, indicating the importance of nutritional management to achieve reliable biomass yield.

Key words: *Jatropha curcas*. Nutrient uptake. Relative growth rate. Macronutrients uptake curves. Macronutrient uptake rates.

RESUMO - O óleo das sementes de pinhão-mansô possui potencial para substituir combustíveis fósseis, porém o manejo nutricional para a espécie ainda não é totalmente descrito. O objetivo com esse trabalho foi estabelecer curvas de acúmulo de macronutrientes em folhas, caule e raiz, bem como avaliar a taxa de crescimento relativo (TCR), taxa de crescimento absoluto (TCA) e relação de massa foliar (RMF) do pinhão-mansô. O experimento foi inteiramente casualizado com cinco repetições. Plantas de pinhão-mansô foram cultivadas em solução nutritiva e coletadas em intervalos de 14 dias até 119 após o início do tratamento. O período de maior absorção de macronutrientes ocorreu entre 7 a 35 dias após o início dos tratamentos, que coincidiu com a maior TCR, TCA, RMF e acúmulo de biomassa seca. O maior conteúdo de Ca e Mg ocorreu nas folhas (respectivamente 48% e 47% do total absorvido), enquanto N, K, S e P foram mais acumulados no caule (58%, 56%, 56% e 53%, respectivamente). Os nutrientes mais absorvidos pelo pinhão-mansô foram N e Ca, e a ordem de conteúdo de macronutrientes foi: N > Ca > K > Mg > S > P. O pinhão-mansô apresentou alto acúmulo de macronutrientes no seu desenvolvimento inicial, indicando a importância do manejo nutricional para alcançar a produção adequada.

Palavras-chaves: *Jatropha curcas* L.. Absorção de nutrientes. Taxas de crescimento relativo. Curvas de absorção de macronutrientes. Taxas de absorção de macronutrientes.

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INTRODUCTION

The constant increases in crude oil prices and environmental concerns have led to the search for renewable fuels, such as biodiesel. *Jatropha* plants (*Jatropha curcas* L.) has great potential as a feedstock for biofuel and can be cultivated in regions of low water availability, high temperatures and low natural fertility (SILVA *et al.*, 2015; YONG *et al.*, 2010). The species presents some desirable characteristics, such as high oil concentration (33–38% in seeds) and the possibility of insertion into the production chain of family agriculture. However, the global cultivation of *Jatropha* plants has greatly increased without prior adequate agronomic knowledge of the species and with limited genetic diversity (ROSADO *et al.*, 2010).

Technical limitations have prevented full insertion of *Jatropha* plants as an energy source in the world. In addition to the non-uniform maturation of fruits and low production observed in different edaphoclimatic conditions (EDRISI *et al.*, 2015), better crop management during early growth of *Jatropha* plants is essential. The establishment of large cropped areas with *Jatropha* plants depends on the appropriate initial growth of the species. Therefore, information concerning nutritional requirement during early development of the species is needed to establish highly productive *Jatropha* plants (ROSADO *et al.*, 2010; SANTOS *et al.*, 2013; SOUZA *et al.*, 2011).

The adequate cultivation of the species requires determining its nutritional status for better planning and implementation of fertilization (CHAUDHARY; GHOSH, 2013; YONG *et al.*, 2010). Therefore, *Jatropha* plants is still in the domestication process, and since this species offers potential for biodiesel production, studies on the characterization of nutritional *uptake and biomass partitioning* during its initial growth should be intensified to ensure the optimum establishment of plants and to meet its nutritional requirements (GARRONE *et al.*, 2016; SANTOS *et al.*, 2013).

The macronutrients uptake and partitioning are strongly influenced by the plant development (LIMA *et al.*, 2011; MOREIRA; FAGERIA, 2009; NASCIMENTO *et al.*, 2012). In the most of species, the macronutrients are usually considered as having high phloem mobility, except calcium (Ca) and sulfur (S). However, a new tissues formation in plants alters the source-sink relation in plants. Moreover, the content of nutrients in plants are frequently associated with foliar senescence, which makes nutrients available for younger plant tissue and contributes to nutrient use efficiency (ABDALLAH *et al.*, 2010). In addition, the nutrients redistribution is influenced by plant species (MAILLARD *et al.*, 2015). Therefore, studies that investigate the content (uptake) and redistribution of

nutrients according to the plant development are very pressing, as pointed by Maillard *et al.* (2015).

Evaluation of the nutritional requirements of seedlings is necessary, as this can benefit the proper establishment of *Jatropha* plants crops, and indicate the period when the plant has a greater demand for nutrients, as well as show changes in nutrient uptake during plant development and the relative concentration of nutrients in the biomass. These results can lead to a more efficient fertilization program and consequently, result in greater crop productivity. Thus, the objective with this study was to establish the curves of accumulation of N, P, K, Ca, Mg, and S in leaves, stem and roots of *Jatropha* plants and to identify the rates of biomass content.

MATERIAL AND METHODS

Initiation and development of experiments

The study was carried out under greenhouse conditions at University of São Paulo (USP), Piracicaba, São Paulo State, Brazil, from March to July 2013. The maximum, minimum and average temperatures during the experimental period were 39.8, 19.7; and 29.6 °C, respectively. Seeds of *Jatropha* plants (*Jatropha curcas* L.) were previously selected by the same size (± 5.0 cm) and weight (± 0.6 g), germinated in sand and irrigated with deionized water. When seedlings reached about 5 cm in height, they were transferred to a plastic tray (40 L) containing nutrient solution diluted of Hoagland and Arnon (1950), diluted at 20 % of the usual concentration. After one week, seedlings of similar size (± 10 cm) were transferred to individual pots, where they were grown in nutrient solution with 100% concentration (SANTOS *et al.*, 2013; SILVA *et al.*, 2015). The cultivation solutions remained under constant aeration and were monitored on a daily basis, with the pH being adjusted to 6.0 ± 0.5 with NaOH (1 mol L^{-1}) and HCl (1 mol L^{-1}) whenever necessary. The nutrient solutions were renewed every seven days.

The complete nutrient solution (HOAGLAND; ARNON, 1950) was composed of $12.0 \text{ mmol L}^{-1} \text{ N-NO}_3^-$; $4.0 \text{ mmol L}^{-1} \text{ N-NH}_4^+$; $2.0 \text{ mmol L}^{-1} \text{ P}$; $6.0 \text{ mmol L}^{-1} \text{ K}$; $4.0 \text{ mmol L}^{-1} \text{ Ca}$; $1.0 \text{ mmol L}^{-1} \text{ Mg}$; $1.0 \text{ mmol L}^{-1} \text{ S}$; $25.0 \text{ } \mu\text{mol L}^{-1} \text{ B}$; $50.0 \text{ } \mu\text{mol L}^{-1} \text{ Cl}$; $0.5 \text{ } \mu\text{mol L}^{-1} \text{ Cu}$; $53.7 \text{ } \mu\text{mol L}^{-1} \text{ Fe}$; $2.0 \text{ } \mu\text{mol L}^{-1} \text{ Mn}$; $0.5 \text{ } \mu\text{mol L}^{-1} \text{ Mo}$ and $2.0 \text{ } \mu\text{mol L}^{-1} \text{ Zn}$.

The experiment was arranged in completely randomized design with five replications. The treatments were composed of nine sampling times throughout the experimental period at intervals of 14 days, and the first sampling occurred seven days after the treatment started

(DAT), so after seedling transferred to full nutrient solution. The experiment was conducted for 119 days, and three plants were harvested per treatment, and were separated into leaves, stem and roots.

Dry-mass production and chemical analyses of plant tissues

After each plant sampling, the material was separated into leaves, stems and roots. Plant material was oven-dried at 65 °C for 72 h, weighed and crushed in a Wiley-type mill (sieved through a 1-mm mesh). The concentrations of N, P, K, Ca, Mg, and S was determined in the plant tissues. The extract to determine the N concentration was obtained via sulfuric digestion and total N was determined by the analytical method of micro-Kjeldahl. The analysis of P, K, Ca, Mg, and S was performed following perchloric-nitric digestion; the amount of P was determined by colorimetry of ammonium metavanadate, K by flame photometry, Ca and Mg by atomic absorption spectrometry and S by Ba chloride turbidimetry (MALAVOLTA; VITTI; OLIVEIRA, 1997). Nutrient content was calculated by multiplying the dry-mass by the element concentration of the respective plant part. The uptake rate of macronutrients was calculated based on nutrient content during the assessment period and the quantities extracted from the aerial parts (stem + leaves) or roots.

The results for dry mass allowed the following growth parameters to be determined: absolute growth rate (AGR), relative growth rate (RGR) and foliar mass ratio (FMR), according to the equation of Radford (1967):

$$AGR = \frac{Dw_2 - Dw_1}{t_2 - t_1} \quad (1)$$

$$RGR = \frac{\ln Dw_2 - \ln Dw_1}{t_2 - t_1} \quad (2)$$

$$FMR = \frac{DwLeaves}{DwTotal} \quad (3)$$

where: $Dw_2 - Dw_1$ = difference between a total dry mass of the plants of each experimental unit; $t_2 - t_1$ = Number of days between sampling times; Dw_{total} = total dry mass of each experimental unit; Dw_{Leaves} = dry mass of the leaves of each experimental unit; \ln = natural logarithm.

Statistical analysis

The results were analyzed statistically using the SAS statistical program for Windows 9.2. The means of AGR, RGR, FMR, nutrient uptake rate and macronutrient amount (accumulation) were compared using the Tukey's when F was significant ($p \leq 0.05$). The means of AGR, RGR and FMR were

compared according to evaluation time. The means of macronutrients uptake were compared between the thirds of experiment evaluation times, indicating in which third of experiment evaluation times the highest uptake of each nutrient occurred. The means of macronutrients content of plant harvested at the end of experiment (119 DAT), were compared between of plant tissue (leaves, stem and roots), in order to find out which plant tissue takes up more macronutrients. The effects of the days of evaluation in the macronutrients content were adjusted using regression models for linear or quadratic orthogonal polynomials, when F was significant ($p \leq 0.05$), to establish the content curves of N, P, K, Ca, Mg and S in the leaves, stem and roots.

RESULTS AND DISCUSSION

Dry-mass production

The content of dry mass in leaves, stem and roots, as well as the macronutrients content in these plant tissues were affected according with time course of the experiment. The parameters of growth (AGR, RGR and FMR) were also influenced by the evaluation days. In addition, the macronutrient uptake rate was different in each thirds of the experiment time evaluation (0-35 DAT; 36-77 DAT; 78-119 DAT). The macronutrients accumulation was also different in the different plant parts (leaf, stem and root) at the end of the experiment (Table 1).

The total dry mass production and the dry mass of roots and stems increased throughout the assessment period (Figure 1). Thus, plants were still in the process of biomass accumulation at the end of the experiment. The assessments considered only the vegetative stages of the growth period, and at the end of the experiment, there was no sign of the onset of flowering

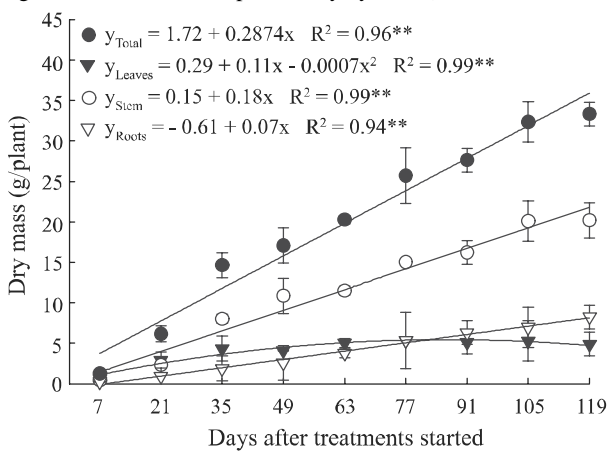
The AGR, which represents the growth rate of *Jatropha* plants, was influenced by the sampling time, and the highest AGR occurred at 35 DAT (Table 2). However, the RGR showed high values in the first few weeks, with a maximum at 21 DAT, followed by a large decrease after 49 DAT, with a subsequent gradual reduction, tending to stability. The values of AGR and RGR were very low at 49 DAT, indicating a large reduction in dry-mass accumulation at sampling time. Therefore, in the initial growth phase, *Jatropha* plants exhibited pronounced growth until 49 DAT, with a tendency to reduce the daily growth of the seedlings. From 49 DAT onwards, biomass accumulation in the stem started to provide a greater contribution to the total dry-mass production (Figure 1), explaining the reduction of growth and the results of AGR and RGR (Table 2).

Table - 1 F-values and level of statistical significance for: Dryer mass (DW), nitrogen (N), phosphorus (P), potassium (K), magnesium (Mg), calcium (Ca) and sulfur (S) content in leaves, stem, roots and total of the *Jatropha* plants according with the days after treatments started (DAT); Absolute growth rate (AGR), Relative growth rate (RGR) and Foliar mass ratio (FMR) according the DAT; Macronutrients Uptake Rate (content of period/content %) according the third time evaluation (0-35 DAT; 36-77 DAT; 78-119 DAT); and Macronutrients content taken up by the plant tissue (leaves, stem and roots) according with DAT

Variation Source	Variables						
----- Leaves Content -----							
Days after treatments started	DW	N	P	K	Ca	Mg	S
	425.28**	102.62**	7350.80**	504.58**	1221.83**	1154.18**	1016.04**
----- Stem Content -----							
Days after treatments started	DW	N	P	K	Ca	Mg	S
	3680.36**	1456.77**	3528.86**	3349.29**	2178.44**	3084.24**	3921.72**
----- Roots Content -----							
Days after treatments started	DW	N	P	K	Ca	Mg	S
	3847.63*	79.85**	3200.86**	3434.89**	3954.57**	3000.58**	3576.28**
----- Total Content -----							
Days after treatments started	DW	N	P	K	Ca	Mg	S
	3168,11**	122.84**	2646.13**	2600.85**	1941.72**	2056.85**	3155.99**
----- Growth Parameters -----							
Days after treatments started	AGR		RGR		FMR		
	325.41*		333.52*		136.25*		
----- Macronutrients Uptake Rate (119 DAT) -----							
Third Time Eevaluation	N		P	K	Ca	Mg	S
	138.42*		232.74*	196.96*	115.89*	204.27*	33.45*
----- Macronutrients Content (119 DAT) -----							
Plant Tissue	N		P	K	Ca	Mg	S
	127.75*		139.76*	170.03*	129.30*	126.68*	173.76*

*and ** Significant at 5 and 1% probability

Figure 1 - Dry matter (DM) content in leaves, stem, roots and total dry matter of the *Jatropha* plants according with time course of the experiment ($n = 5 \pm$ standard deviation) (* and ** Significant at 5 and 1 % probability by F-test)



A high FMR was observed in the early growth of *Jatropha* plants (7–21 DAT), followed a subsequent decrease, which indicates increased C allocation to the stem from 49 DAT onwards, contributing to the total biomass accumulation (Table 2). The FMR represents the dry-mass fraction that is not exported from the leaves to other plant parts. A low RMF during the development of *Jatropha* plants reflects a possible reduction in photosynthetic activity in relation to the total plant biomass accumulation, representing increased energy use and redistribution of the photoassimilates of plant growth, at the expense of leaf production (RADFORD, 1967). This result corroborates that observed for the production of leaf dry mass (Figure 1) where the development of *Jatropha* plants generated a greater C allocation (biomass) in the stem, explaining a reduction in the FMR due to growth.

Table 2 - Absolute growth rate (AGR) Relative growth rate (RGR) and Foliar mass ratio (FMR) ($n = 5 \pm$ standard deviation) of *Jatropha* plants grown in solution nutrition, according with time course of the experiment (the days after treatments started - DAT)

Evaluation time	AGR	RGR	FMR
	g g ⁻¹ day	g g ⁻¹ day	g g ⁻¹
7 DAT	0.181±0.012 c	0.034±0.001 c	0.473±0.021 a
21 DAT	0.349±0.152 b	0.113±0.003 a	0.472±0.030 a
35 DAT	0.780±0.011 a	0.073±0.004 b	0.253±0.015 bc
49 DAT	0.017±0.031 e	0.011±0.002 d	0.278±0.014 b
63 DAT	0.401±0.021 b	0.023±0.002 c	0.248±0.021 c
77 DAT	0.389±0.011 b	0.017±0.003 c	0.208±0.013 d
91 DAT	0.138±0.021 cd	0.005±0.001 c	0.185±0.024 de
105 DAT	0.335±0.021 b	0.011±0.005 c	0.163±0.031 ef
119 DAT	0.071±0.021 d	0.002±0.001 c	0.147±0.018 f

Different letters within the same column indicate significant differences by Tukey's test ($p \leq 0.05$)

Macronutrient content

During initial growth, *Jatropha* plants showed a higher rate of macronutrient uptake between 7–35 DAT, except for N (Table 2). This reflects the higher rate of dry-mass increase per day during this period (Figure 1; Table 1), indicated by the RGR, AGR and FMR. In general, the high biomass accumulation of *Jatropha* plants between 7–35 DAT demanded a high uptake rate of macronutrients (Table 2). *Jatropha* plants showed a continuous uptake rate of N, which demonstrates the importance of N for *Jatropha* plants seedlings throughout the experimental period (Table 3). The descending content order of macronutrients during the initial growth of *Jatropha* plants at 119 DAT was: N > Ca > K > Mg > S > P according of the macronutrient accumulation (Table 3).

The content of N increased in all plant parts with plant growth (Figure 2A), and the largest relative N content was observed initially in leaves (Figure 2B). At 7 DAT, N content in leaves was 68% of the total absorbed by plants; however, this relative content decreased to 28% at the end of the experiment, due to the lower proportion of leaves in total plant dry mass compared to the stem. In stems, the relative N content increased from 19% (7 DAT) to 56% (119 DAT); however, the relative N content in roots was stable and showed a mean of 14% of the total content of plants at every evaluation point. The variation in the content relative of N in leaves due to plant growth was high in the first few weeks and decreased from 21 DAT onwards (Figure 2B). After 77 DAT, the N content in stems increased sharply (Figure 2A), which is consistent with the high mobility of this nutrient in the phloem.

The content of P increased in all plant parts during plant growth (Figure 2C). However, only P content in the

stem suggested that P uptake might continue to increase in assessment periods longer than those used in this study. The greatest P uptake by plants occurred initially in leaves and P was redistributed to the stem (Figure 2D). Therefore, content of P in the leaves decreased during the growth of *Jatropha* plants, and increased in the stem. The relative P content in leaves decreased from 51% to 19% from the beginning (7 DAT) to the end of the experiment (119 DAT); conversely, that in the stem increased from 29% to 53%. The relative P content in roots was constant, showing a mean of 16% of the total content at all time-points assessed, similar to that observed for N.

The K content increased with *Jatropha* plants growth in all plant parts (Figure 2E). Similar to that for P, the K content relative at 21 DAT decreased in leaves due to redistribution to the stem (Figure 2F), which is explained by the high mobility of this element in the nutrient redistribution or by needs of the plant to increase the stem mass production on 21 DAT, as highlighted also for N and P. The relative K content in leaves decreased from 44% at 7 DAT, to 18% at 119 DAT. In contrast, the relative K content in the stem increased from 32%, at 7 DAT, to 56%, at 119 DAT. The relative K content in roots was constant during initial growth of *Jatropha* plants, accounting for a mean of 17% of the total content in the plants at each assessment time.

The content of Ca increased linearly in all plant parts during plant growth (Figure 3A) and the largest relative content occurred in leaves in all experimental periods, followed by in the stem and roots (Figure 3B). The mean relative Ca content was 58%, 31% and 11%, for leaves, stem and roots, respectively. Similarly, the content of Mg increased in all plant parts during *Jatropha* plants

Table 3 - Uptake rate (content of period/content %) of macronutrient ($n = 5 \pm$ standard deviation) during the evaluation period and amounts taken up by the leaves, stem and roots of *Jatropha* plants grown in solution nutrition, according with time course of the experiment (the days after treatments started - DAT)

Nutrient	Days after treatments started (DAT)			Content in leaves	Content in stem	Content in roots
	0 to 35	36 to 77	78 to 119	----- 119 DAT -----		
	Uptake rate of nutrient (%)			----- mg/plant -----		
N	24±0.9 c	41±1.5 a	35±1.4 b	76.0±3.5 b	143.4±3.1 a	56.2±1.2 c
P	56±1.5 a	36±1.5 b	8±0.5 c	5.9±0.8 b	16.2±2.2 a	8.5±0.4 b
K	53±1.6 a	38±1.6 b	10±0.8 c	31.2±1.1 b	94.1±2.3 a	43.7±0.9 b
Ca	51±2.2 a	21±2.2 b	28±1.8 b	102.9±2.1 a	75.6±1.5 b	32.8±1.4 c
Mg	54±1.9 a	36±2.5 b	10±1.1 c	41.1±8.7 a	33.0±2.4 a	13.1±1.2 b
S	41±1.1 a	34±2.1 b	25±2.2 c	10.2±1.3 b	29.3±1.5 a	12.6±0.5 b

Different letters within the same line indicate significant differences by Tukey's test ($p \leq 0.05$)

growth (Figure 3C). The mean of relative Mg content was 59%, 29% and 12%, for leaves, stem and roots, respectively (Figure 3D).

The content of S by *Jatropha* plants increased according to the length of cultivation (Figure 3E). Similarly, N, P and K showed the largest relative content initially in leaves and were subsequently redistributed to the stem (Figure 3F). At 7 DAT, the relative S content was 59% and decreased to 20% at the end of the experiment, unlike the relative content increase observed for the stem, which was 23% at 7 DAT and 53% at 119 DAT. The relative S content in roots was continuous during the initial growth, accounting for a mean of 20% of the total content of plants at every sampling point. However, at the end of the experiment, the relative S content in roots increased (Figure 3E). From 21 DAT onwards, the relative S content began to decrease in leaves, and the greatest relative content was observed in the stem (Figure 3F).

Analyzing the results of content, it is clear the redistribution of N, P, K and S for the stem of the leaves with the aim of developing stem. The results indicate that during the early growth of *Jatropha* plants, the leaves act as a strong sink and as the plant grows, they become highly mobile sources of nutrients (N, P and K) and notably S, in the phloem.

The macronutrients content of *Jatropha* plants throughout the growth days was characterized by a sigmoid pattern (Figure 4) in all plant tissues analyzed (leaves, stem and roots). The most macronutrients accumulation rate is between 35 and 49. Furthermore, for all macronutrients, except calcium and magnesium (Figures 4D e E), the content of the stem begin to be the most significant in *Jatropha* plants.

The greater accumulation of dry mass in leaves during initial growth than at the end of the experiment (Figure 1) can be explained by a higher carbon allocation for stem growth. This relationship tends to reverse as the stem grows and becomes more lignified. Stem growth promoted the redistribution of photoassimilates, leading to a reduction in dry mass in the leaves (SANTOS *et al.*, 2013). The C allocation to the stem in *Jatropha* plants seedlings represented an inflection point in dry-mass production in leaves, which was estimated to occur at 78 DAT. According to Nascimento *et al.* (2012), the inflection point corresponds to the assessment period in which the daily accumulation within plant organs begins to decrease. Changes in plant tissues responsible for a greater accumulation of dry mass are common, due to the change in the growth period in which the sink ratio of younger tissues increases, mainly in reproductive tissues (BIANCO; CECÍLIO FILHO; CARVALHO, 2015).

The results observed for the AGR, RGR and FMR indicate that 35 DAT is the period of maximum leaves biomass accumulation, and after this period, the leaves are no longer a sink, but become a source of photoassimilates for growth. In the early growth stages raging from 7 to 21 DAT of *Jatropha* plant growth, the stem develops little, and leaves represent a greater proportion of the total dry mass accumulation of the plant (Figure 4). This relationship tends to reverse as the stem grows and lignifies.

The reduction in AGR and RGR with plant growth observed in the first few weeks occurred because in early growth, the predominance of biomass in young leaves (high FMR) provides a high rate of C fixation and consequently, leads to an increase in dry

mass accumulation (RADFORD, 1967). As the plant grows, the allocation of assimilates to the production of structures other than leaves compromise the AGR and RGR. For *Jatropha* plants, the allocation of assimilates

occurred for stem growth. However, the reduction in the growth parameters evaluated was reflected in the inflection point of biomass accumulation in leaves at 78 DAT (Figure 1).

Figure 2 - Nitrogen content [A]; nitrogen relative content [B]; phosphorus content [C]; phosphorus relative content [D]; potassium content [E] and potassium relative content [F] in leaves, stem and roots of the *Jatropha* plants according with time course of the experiment ($n = 5 \pm$ standard deviation) (* and ** Significant at 5 and 1 % probability by F-test)

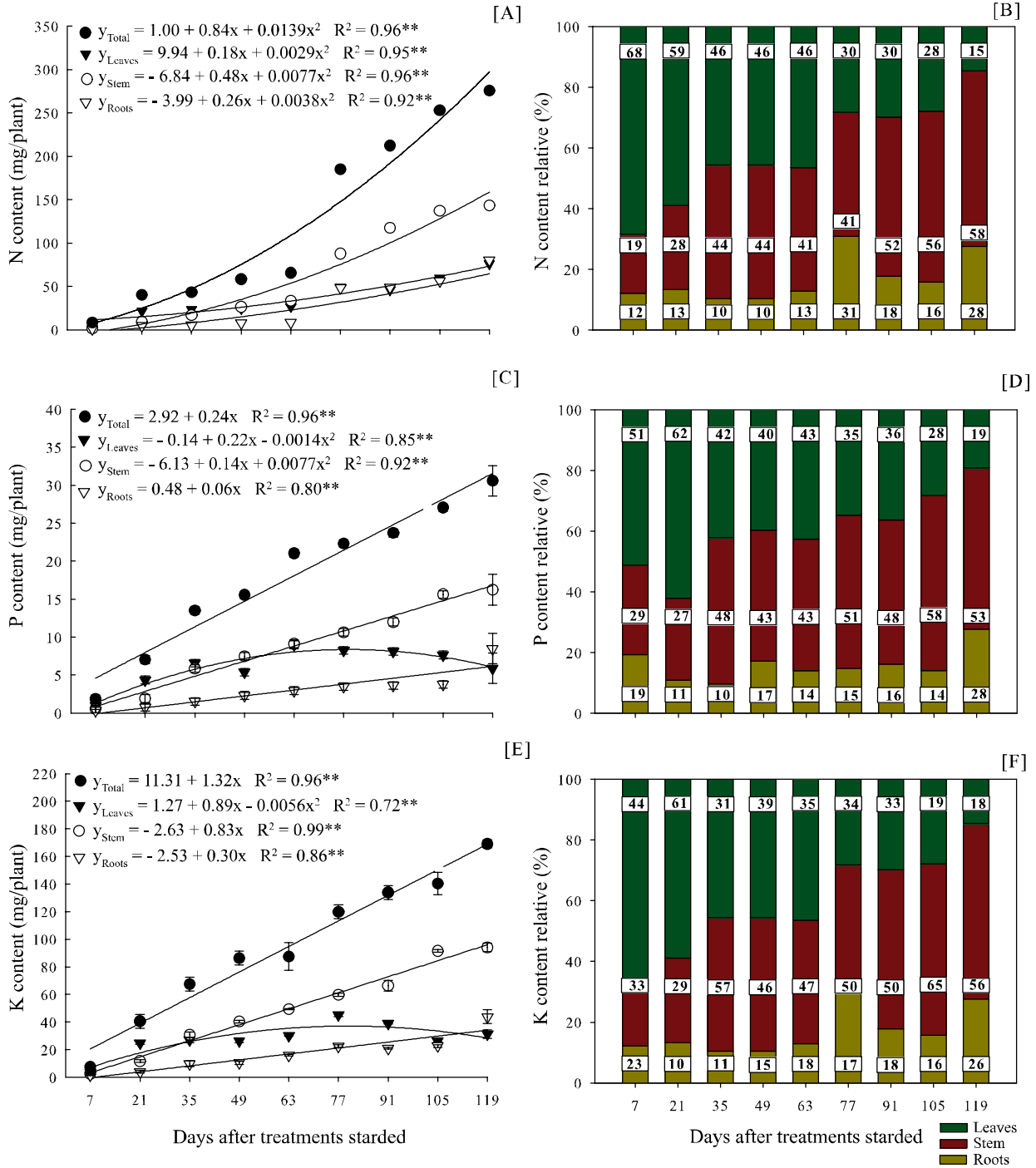
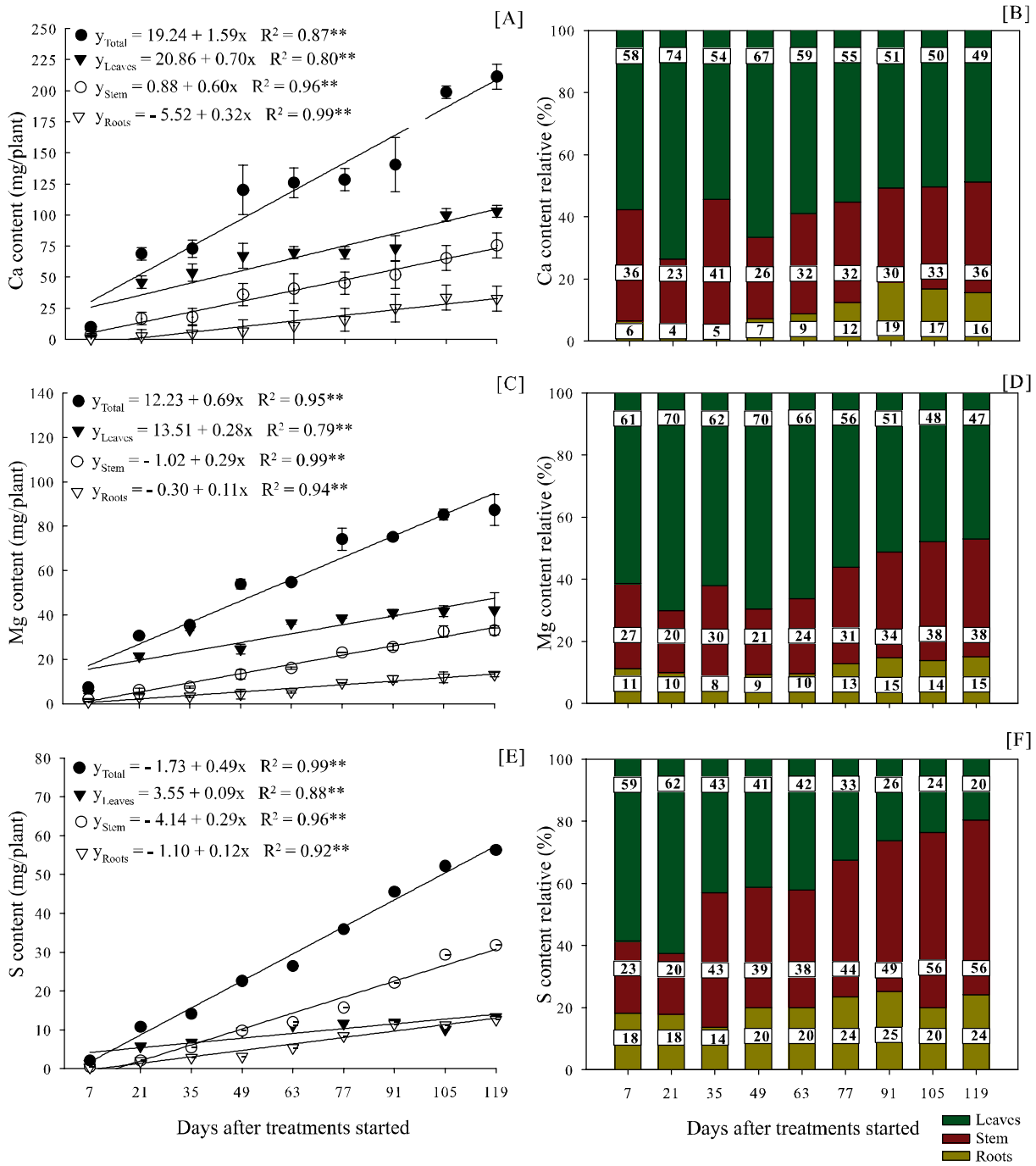


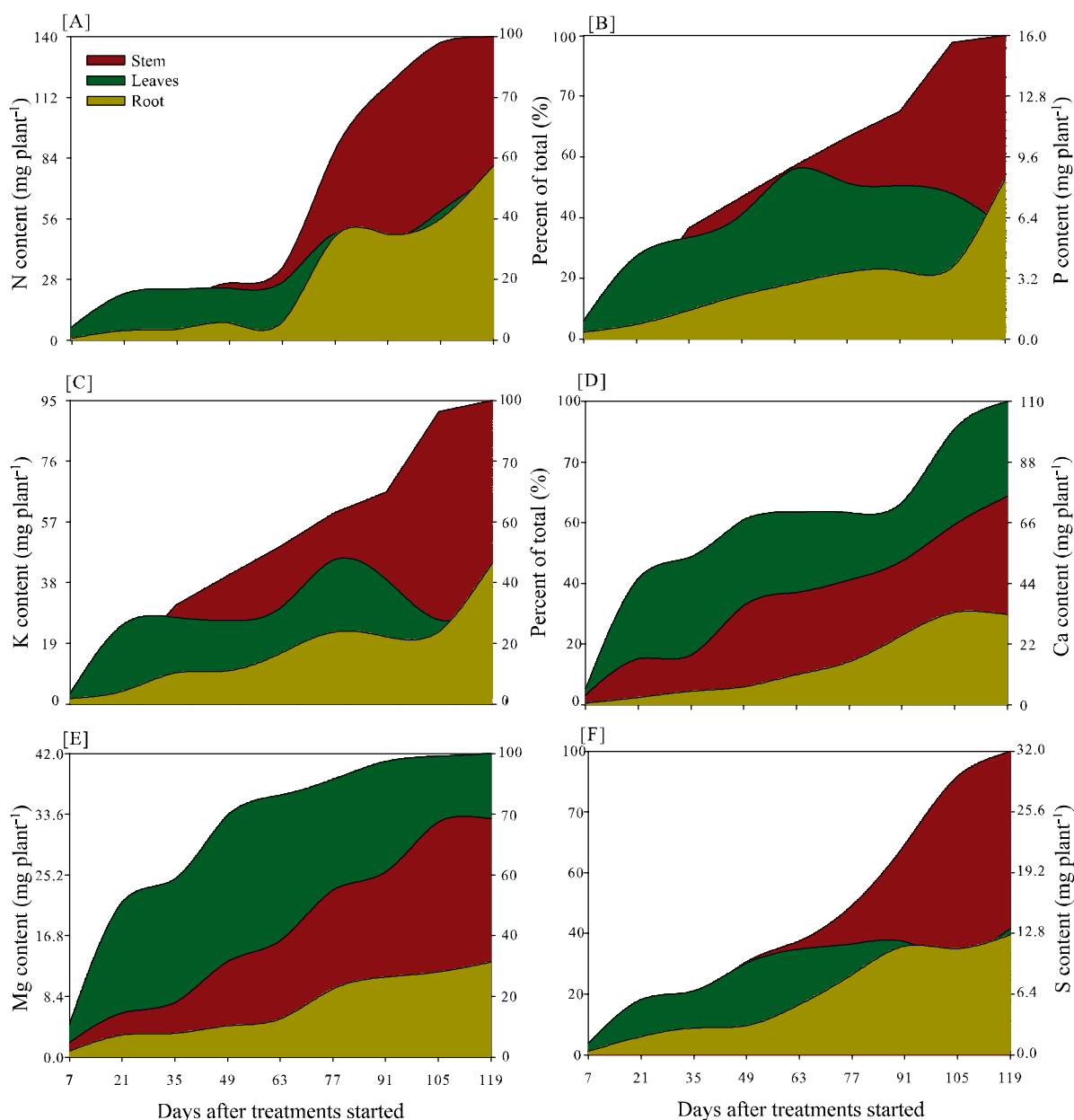
Figure 3 - Calcium content [A]; calcium relative content [B]; magnesium content [C]; magnesium relative content [D]; sulfur content [E] and sulfur relative content [F] in leaves, stem and roots of the *Jatropha* plants according with time course of the experiment ($n = 5 \pm$ standard deviation) (* and ** Significant at 5 and 1 % probability by F-test)



The relative contents of N P, K and S followed the same pattern of dry-mass production during the assessment period and they increased in the stem, decreased in the leaves and remained constant in the roots (Figures 2B, 2D, 2F, 3F, 4A, 4B, 4C and 4F). This is explained in part by

the increased contribution to the dry mass by the stem at the experiment, in relation to other plant parts (Figure 1). Similar to C redistribution, *Jatropha* plants redistributed N, P, K, and S to the stem to ensure plant growth. The concentration of nutrients in stems occurs in three ways:

Figure 4 - Model of content of nitrogen [A], phosphorus [B], potassium [C], calcium [D], magnesium [E] and sulfur [F] in leaves, stem and roots of the *Jatropha* plants according with time course of the experiment. ($n = 5$)



nutrient content for the formation of structural organs, via element absorption (xylem), and from redistribution of these nutrients from older leaves for stem elongation and the production of new leaves (WHITE, 2012). Lima *et al.* (2011) reported that N, P, K and S are intensely redistributed the older leaves to other tissues of the *Jatropha* plants, as is little redistribution of Ca and Mg. In this study, the N, P, K and S were redistributed, or more allocated for training the stem. Thus, the stem represented strong drain on the early development of *Jatropha* plants.

Jatropha plants have a high initial growth rate, and N is essential for C assimilation at the beginning of the growth cycle of this species, which explains the linear absorption pattern of N. A high photosynthetic rate during the early growth of *Jatropha* plants, reported by Yong *et al.* (2010), helps to explain the increase in late relative content of N in the stem (77 DAT) (Figure 2B) compared to the increase in the relative content of P, K, and S in the stem (DAT 21) (Figures 2D, 2F and 3F) observed in this study. Thus, we support the hypothesis

that plant growth during this period is sustained by a high photosynthetic rate, which causes a greater need for N in leaves (the main photosynthetic organ), leading to a greater relative N content in leaves until 77 DAT. Subsequently, N redistribution occurred, to ensure proper plant growth. The relative N content decreased after 21 DAT; however, the relative N content in the stem was higher than in the leaves only at 77 DAT, (Figure 2B). The low mobility of Ca in the phloem explains the greater relative content of this element in the foliar tissue (Figures 3B and 4D). This latter pattern is consistent with the general assumption that Ca shows a low phloem mobility (BIDDULPH; CORY; BIDDULPH, 1959; WHITE, 2012).

Although S is not considered to be mobile in terms of redistribution, *Jatropha* plants showed the relocation of S from the leaves to the stem (Figures 3F and 4F) and even greater amounts of S accumulated in the stem, due to the higher rate of biomass allocated to this plant part. The high capacity for S redistribution from the leaves to the stem might indicate efficient S use by *Jatropha* plants. However, the species shows no remobilization pattern of S. In addition, intraspecific or genotypic variation in redistribution via the phloem might exist (ROSE *et al.*, 2015). The relative Mg content was highest in the leaves (Figures 3D and 4E). Thus, the Mg content by different *Jatropha* plants tissues did not follow the same pattern as that observed for N, P, and K – nutrients that are also considered to be highly mobile in the phloem. Under adequate supply conditions, Mg is concentrated most highly in the chloroplasts (LOPES JÚNIOR; MAZZAFERA; ARRUDA, 2014), explaining the higher content of this element in leaves and its importance in photosynthesis.

Nascimento *et al.* (2012) reported that N, P, K and S are intensively redistributed from older leaves to other castor bean tissues, whereas Ca and Mg show little redistribution. In this study, N, P, K and S were redistributed, or more allocated to stem formation. Thus, the stem represents a strong sink during the initial growth of *Jatropha* plants. Maillard *et al.* (2015) also reported phloem mobility of N, P, K and S in *Zea mays* and *Quercus robur*, and low mobility of Ca in phloem for these species.

The high content of N and Ca in *Jatropha* plants is highly relevant and these should be supplied appropriately during the growth period, when its concentration in the soil is low, because under natural conditions, Brazilian soils have low availability in both nutrients (GARRONE *et al.*, 2016). Despite *Jatropha* plants is considered to be a plant that is well adapted to low soil fertility (SILVA *et al.*, 2015; YONG *et al.*, 2010), a sub-optimal supply

of N and Ca during the early growth period, followed by subsequent planting in nutrient-deficient soils, can lead to malnourished plants and consequently, would hamper the plant establishment. *Jatropha* plants have been considered high nutritional N and Ca required specie (GARRONE *et al.*, 2016).

In this study, the *Jatropha* showed content of 275, 30, 169, 211, 87 and 52 mg/plant at 119 DAT. These results are greater than the average extract from the vegetative growth period of such nutrients for *Ricinus communis* (NASCIMENTO *et al.*, 2012), *Glycine max* (MAUK; NOODÉN, 1992), *Phaseolus vulgaris* (BIDDULPH; CORY; BIDDULPH, 1959) and *Helianthus annuus* (LOPES JÚNIOR; MAZZAFERA; ARRUDA, 2014). *Jatropha* plants showed a high content of macronutrients during early growth, demonstrating the importance of the nutritional management of these elements for the establishment of *Jatropha* plants crops in large areas. The establishment of content curves for macronutrients in *Jatropha* plants indicates the dynamics of nutrient uptake during cultivation, highlighting the need to optimize nutritional management during the early growth of the species.

CONCLUSIONS

1. The highest Ca and Mg accumulation occurred in the leaves, while N, K, S and P were mostly accumulated in the stem;
2. The nutrients more taken up by *Jatropha* plants were N and Ca, and the order of macronutrients uptake was: N > Ca > K > Mg > S > P;
3. *Jatropha* plants have shown high macronutrients accumulation rates on their early development, indicating the importance of nutritional management to achieve reliable plant establishment as well as biomass yield.

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