Effect of nitrogen and potassium on plant height and stem diameter of *Jatropha curcas* L. in Colombian tropical dry forest

Efecto del nitrógeno y el potasio en la altura de la planta y el diámetro del tallo de *Jatropha curcas* L. en el bosque seco tropical de Colombia

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ABSTRACT

The use of raw materials of *Jatropha curcas* L. to produce biofuel is of increasing interest in Colombia; little information is available on this species as a crop. This research evaluated plant height (Hp) and basal stem diameter (BSD) of *J. curcas* as affected by different rates of nitrogen (N) and potassium (K) during the first 435 days of growth (DAP). The experiment involved a repeated measures design with inter-subject factors of fertilization (N dose, K_2O dose nested in N dose) and an intra-subject factor of evaluation time. The Hp varied both as a function of N dose and the K_2O dose nested in the N dose. The tallest plants were obtained with 150 kg ha^{-1} N and 180 kg ha^{-1} K_2O treatment. With simultaneous confidence intervals of Bonferroni, we compared the evaluation times indicating for Hp non-overlapping intervals at 435 DAP (150 kg ha^{-1} N and remaining levels of this factor) and at 255 DAP (180 kg ha^{-1} K_2O and remaining levels of this factor). The application of N fertilizers resulted in thicker stems as compared to control plants. Mathematical predictive models were obtained for Hp and BSD in *J. curcas* using a multiple regression analysis. These models permitted future rapid and non-invasive predictions for *J. curcas* growth in the field.

Key words: growth, modeling, macronutrients, mineral nutrition, Euphorbiaceae.

RESUMEN

El uso de materias primas vegetales de *Jatropha curcas* L. para producir biocombustibles es de creciente interés en Colombia, mientras que hay poca información disponible sobre esta especie como cultivo. Este estudio evaluó la altura de la planta (Hp) y el diámetro del tallo basal (BSD) de *J. curcas* según lo afectado por las diferentes dosis de nitrógeno (N) y potasio (K) durante los primeros 435 días de crecimiento (DAP). El experimento incluyó un diseño de medidas repetidas con factores de fertilización entre sujetos (dosis de N, dosis de K_2O anidadas en la dosis de N) y un factor de tiempo de evaluación. La Hp varió tanto en función de la dosis de N como de la dosis de K_2O anidada en la dosis de N, obteniéndose las plantas más altas con aplicación de 150 kg ha^{-1} N y 180 kg ha^{-1} K_2O. Con los intervalos de confianza simultáneos de Bonferroni, se compararon los tiempos de evaluación indicando para Hp intervalos no superpuestos a 435 DAP (150 kg ha^{-1} N y niveles restantes de este factor) y a 255 DAP (180 kg ha^{-1} K_2O y el resto niveles de este factor). La aplicación de fertilizantes N dio como resultado tallos más gruesos en comparación con las plantas de control. Los modelos de predicción matemática se obtuvieron para Hp y BSD en *J. curcas* utilizando un análisis de regresión múltiple. Estos modelos permiten en futuro predicciones rápidas y no invasivas del crecimiento de *J. curcas* en campo.

Palabras clave: crecimiento, modelación, macronutrientes, nutrición mineral, Euphorbiaceae.

Introduction

In the search for sustainable sources of energy, plant materials for the production of biofuel have recently attracted attention. *Jatropha curcas* (Euphorbiaceae) produces seeds containing 27-43% inedible oil that can be converted into biodiesel (Chhetri *et al.*, 2008). This shrub adapts easily to various tropical climatic conditions and can grow on marginal lands of low fertility and does not compete with

traditional crops (Matos *et al.*, 2014). These characteristics extend perspectives for the plant's cultivation in northwestern South America. However, these features (low requirements in mineral nutrients and water, low labor demand, and tolerance for salinity, pests and diseases) were recorded for genotypes from the wild. Little information on these characteristics is available in the field under Colombian conditions (Campuzano, 2008; Arévalo *et al.*, 2011).

One of the factors that limits growth and dry mass production in *J. curcas* is a deficiency of macronutrients in the soil (Silva *et al.*, 2009; Ahmed *et al.*, 2016). Fertilization that is nitrogen-poor could severely diminish biomass production in *J. curcas*, reducing plant height and affecting leaf formation (Wang *et al.*, 2011). Mohapatra and Panda (2011) found that growth and yield of *J. curcas* in poor soils were highly influenced by the application of NPK fertilizers. According to Kalannavar *et al.* (2009), seed yield in *J. curcas* treated with 100-100-150 kg ha^{-1} per year of N-P$_2$O$_5$-K$_2$O increases 4.5-fold, reaching 3,937 kg seeds ha^{-1} per year as compared to absolute control without fertilization (875 kg ha^{-1} per year). Also, Patil and Parameshwarappa (2007) report significant increases in plant height, basal stem diameter, number of branches, and a respective seed yield of 1,475 kg ha^{-1} per year following the application of 80-80-80 kg ha^{-1} N-P$_2$O$_5$-K$_2$O. In Thailand, a significant increase in seed yield up to 1,559 kg ha^{-1} per year was achieved in plants of 75 cm height and fertilized with 15-15-15 N-P$_2$O$_5$-K$_2$O at a rate of 312.5 kg ha^{-1} (Suriharn *et al.*, 2011). Several studies carried out in Brazil emphasize the need for N fertilization in *J. curcas*, mainly due to the high losses of N caused by its volatilization and leaching in tropical soils (Collier *et al.*, 2006; Lara and Souza, 2008).

Plant height (Hp) and basal stem diameter (BSD) are used in *J. curcas* to estimate plant biomass as reported by Makungwa *et al.* (2013), who obtained an allometric model to estimate woody biomass using BSD under field conditions. These authors do not recommend a generalized application of models since these are determined for each specific site and, as far as possible, according to the authors should be applied on fully developed trees. In the wild this species can reach a height of more than 5 m with stems of a sympodial growth, since several stems produce branches close to the soil surface (Tigere *et al.*, 2006). Bártoli (2008) states that a *J. curcas* crop should be pruned to a maximum of 2.5 m height to induce lateral branching. This increases the number of fruits per plant, facilitates control of pests and weeds, and provides easy harvesting by gaining access to all sectors of the crop canopy. According to de Lima *et al.* (2016), *J. curcas* tends to increase height at high sowing densities due to interspecific competition, a condition that accelerates plant development and fruit production in this species. The same authors obtain the minimum seed yield per plant at the highest sowing density (2,500 plants ha^{-1}). In this context, plant height is determined by agronomic practices that influence growth and dry mass allocation and in *J. curcas* has a direct influence on crop yield (Tjeuw *et al.*, 2015).

In Colombia, there are few studies on *J. curcas* growth. Pedraza and Cayón (2010) evaluate environmental effects on growth and plant morphometry of *J. curcas* (Brazil ecotypes) in the provinces of Vichada and Santander. The plants at these locations did not significantly differ in height or number of secondary stems per plant; however, leaf dry weight and leaf area vary according to leaf strata (Pedraza and Cayón, 2010). These results suggest that *J. curcas* could increase leaf area to intercept more solar radiation, an aspect reported in other woody species of C3 photosynthesis (Larcher, 2003).

More than 600,000 ha of land in Colombia are considered to be appropriate for the cultivation of *J. curcas*, with the upper Magdalena region of the country exhibiting high potential for crop production (Campuzano, 2008). The growth response of *J. curcas* to fertilizer treatments should be studied with emphasis on arid soils of low fertility, such as the ones present in this region. The objective of the present study was to evaluate the effect of N and K rates on Hp and BSD of *J. curcas* under agroclimatic conditions of Colombian tropical dry forests in order to contribute to agronomic practices that would allow predictable levels of productivity.

Materials and methods

Experimental site and plant material

The study was conducted between March 2012 and August 2013 beginning from planting at day one to day 435 of field growth. The research took place at the Nataima Experimental Center, Colombian Corporation of Agricultural Research (AGROSAVIA) located in Espinal (Tolima province, Colombia). The crop was established in a tropical dry forest (bs-T) zone according to Holdridge (1967). The area was located at coordinates 4°11'14" N and 74°57'22" W at 371 m a.s.l. and characterized by mean 28°C air temperature, 70% relative air humidity, and 1,270 mm annual precipitation (IDEAM, 2017).

Jatropha curcas seeds of elite ecotype M-3 were obtained from the "Genetic Improvement Program of *Jatropha curcas*" of Corpoica 2006-2011. The seeds were planted in black plastic bags with a 4 kg capacity and were placed under a plastic mesh providing 60% shading. The substrate was a 2:1:1 mixture (v/v/v) of sandy loam soil: rice husk 60% burnt: compost. The substrate had pH 5.5, 4.1% organic matter, and available contents of 67.7 mg kg^{-1} phosphorus and 0.55 cmol$^+$ kg^{-1} potassium.

Sprinkler irrigation was applied twice a week and seedlings emerged 4 d after planting (DAP). Eight days later, the plastic mesh was removed and seedlings were left free to solar exposure. At 45 DAP the plants had between 5 and 6 true leaves and a height of 35 cm and were transplanted into a field during the rainy season that was characterized by a mean air temperature of 28°C and a mean precipitation rate of 80 mm m^{-2}. From May 2012 to July 2013, the mean air temperature was 27.8°C and relative air humidity oscillated between 70 and 85%. In June-August 2012, the experimental area had supplementary irrigation to avoid a water deficit balance. During 2013, the dry season had low precipitation during January and February (28.9°C mean air temperature and 65.3 mm m^{-2} monthly precipitation) and a rainy period during March-May had a mean air temperature of 27.0°C and a monthly precipitation of 160.4 mm m^{-2}.

Plant establishment in the field and fertilizer treatments

The planting distance in the field was 3x2 m which is considered adequate for monoculture of *J. curcas* for providing high yields, reducing intraspecific competition, and facilitating fruit harvest and weed control (Ghosh *et al*., 2007). A randomized complete block design was established with 4 replicates and 24 plants per experimental unit, separated by a border row, for a total of 1,184 plants ha^{-1}. The experiment was carried out in an inceptisol sandy loam soil identified as Typic Haplusterts with 1.2% organic matter (Tab. 1) and good drainage capacity.

Considering the soil characteristics and responses to fertilizer applications reported for *J. curcas* in earlier studies (Patil and Parameshwarappa, 2007; Kalannavar *et al*., 2009; Suriharn *et al*., 2011), the doses of fertilizers were established between 0 and 150 kg ha^{-1} per year for N and between 0 and 180 kg ha^{-1} per year for K$_2$O. These doses were arranged in a scheme comprising 12 treatments including control treatments with either N or K applied and an absolute control without NK application (Tab. 2). The

sources of fertilizers were urea and potassium chloride. Other mineral elements were applied pre-transplant in equal doses for all treatments: 46 kg ha^{-1} P$_2$O$_5$, 44 kg ha^{-1} Ca, 18.8 kg ha^{-1} Mg, 27.2 kg ha^{-1} S, 3.18 kg ha^{-1} Mn, 2.4 kg ha^{-1} Zn, and 1 kg ha^{-1} B.

The annual doses of fertilizers in each treatment were fractioned into four applications starting one month after transplanting; fertilizers were applied evenly around the stem and covered with a soil layer of approximately 1 cm. Weed control was accomplished manually and complemented with a tractor-operated drag scraper between the rows. No pruning was performed on plants during the development of the experiment.

Plant sampling

Five destructive plant samplings (45 d after each fertilization) were carried out at 75, 165, 255, 345, and 435 DAP. Four plants were evaluated in each treatment for a total of 48 plants at each sampling moment. The plants were cut at soil level and plant height (Hp) was measured (cm) from the stem base at soil level to the apex of the principal orthotropic stem. Basal stem diameter (BSD) was measured at the base of the principal stem with an electronic digital caliper (Mitutoyo Absolute Digital Caliper 500-197-20, Japan).

Data analysis

Statistical analyses involved descriptive and inferential components using bivariate and univariate approaches. Initially, descriptive statistics (mean, standard error of mean, and standard deviation) for Hp and BSD were applied for each treatment and each moment of evaluation associated with factors of N and K$_2$O doses. A three-dimensional dispersion diagram visualized Hp and BSD at each evaluation time for two contrasting treatments, absolute control and a treatment combining high rates of N (150 kg ha^{-1}) and K$_2$O (120 kg ha^{-1}). The experiment involved a repeated measures design with inter-subject factors of fertilization rates (K$_2$O dose was nested in N dose due to the origin

TABLE 1. Chemical characteristics of Ap horizon of soil at the experimental site.

Horizon	pH	Organic matter (%)	P	S	Exchangeable cations				CEC	Micronutrients				
					Ca	Mg	K	Na		Fe	Cu	Mn	Zn	B
			(mg kg^{-1})		(cmol$^+$ kg^{-1})					(mg kg^{-1})				
Ap (0-18 cm)	6.3	1.21	39.8	2.6	4.7	1.12	0.24	0.13	6.19	36.0	1.27	2.6	0.14	0.2

TABLE 2. Combination of N and K$_2$O doses in fertilizer treatments.

	N (kg ha^{-1})											
	0		50			100				150		
K$_2$O (kg ha^{-1})	0	120	60	120	180	0	60	120	180	60	120	180

of the K_2O dose, so that different levels of the K_2O factor shared a single level of the N factor) and an intra-subject factor of evaluation time (75, 165, 255, 345, and 435 DAP) (Davis, 2002; Montgomery, 2013). The Hp and BSD were used as response variables. A bivariate analysis of variance was applied to adjusted linear model. *P* values less than 5% were considered significant but the effects with significance less than 10% were taken into account; this was done in order not to rule out any effect that might be significant in the model. With simultaneous confidence intervals of Bonferroni, the evaluation moments were compared using error bars, since it is usual in growth models to search for significant interactions between inter-subject factors and evaluation time. Comparisons using error bars were made on the response profiles for each factor (Cumming *et al*., 2007). To complement the descriptive analysis, bar diagrams for Hp and BSD were constructed at the end of the evaluation period (435 DAP), combining factors to generate a single label of "treatments". This was done to obtain information on the behavior of 12 treatments (Tab. 2) at the end of the experiment for each response variable separately; in this case, the Tukey's test (*P*<0.05) was applied to compare the mean values. Finally, a multiple regression model was fitted for each response variable (Hp, BSD) using as predictors the N and of K_2O doses and the moments of evaluation; this was done only by predictive interest and not to compare the effects. With this, while setting the evaluation time to 435 d, a cross-table was generated to present the estimates of combinations of N and K_2O doses that were not originally used in the experiment.

Results and discussion

Effects of N and K applications on plant height and stem diameter

The vegetative growth phase of *J. curcas* in the field comprised 165 DAP indicating the moment at which the first flowering appeared. Mean Hp of *J. curcas* varied significantly between absolute control and the treatments with joint application of high N doses (100 or 150 kg ha^{-1}) and K_2O (120 or 180 kg ha^{-1}) at 75, 165, 255, and 345 DAP, while at 435 DAP these differences were not observed (Tab. 3). The BSD had minimum values in plants deprived of N fertilization throughout the experiment (Tab. 3). For both Hp and BSD variables, their behavior against NK rates presented significant differences at 435 DAP, in which the absolute control had the lowest Hp and BSD (Fig. 1). In the final evaluation, the plants treated with the highest doses of N and K_2O had maximum Hp and BSD compared to absolute control (Fig. 1).

A three-dimensional diagram indicated the simultaneous relationship between variables Hp and BSD as a function of fertilizer rates and moments of evaluation (Fig. 2). Two treatments contrasting in Hp and BSD behavior, such as absolute control and N=150 kg ha^{-1} plus K_2O=120 kg ha^{-1} (Tab. 3 and Fig. 1), were used in the diagram. It showed progressive increases in each variable in time and confirmed that plants were taller and thicker when treated with NK, while the lowest Hp and BSD were observed in absolute control without NK fertilization (Fig. 2). The

TABLE 3. Average plant heights (Hp, cm) and basal stem diameters (BSD, cm) of *J. curcas* at five evaluation moments.

Dose N+K₂O kg ha⁻¹	Days after planting (DAP)									
	75		165		255		345		435	
	Hp±SD	BSD±SD	Hp±SD	BSD±SD	Hp±SD	BSD±SD	Hp±SD	BSD±SD	Hp±SD	BSD±SD
50+60	52.0 ±6.5abc	2.4±0.1 ab	121.5±12.3 ab	5.1±0.2 a	184.5±10.8 cde	8.7±0.7 a	230.0±7.1 abc	10.1±0.5 ab	244.0±6.4 ab	12.2±1.1 abc
50+120	53.5± 10.8abc	2.4±0.2 ab	129.8±16.0 ab	4.5±0.3 abc	189.0±2.7bcd	8.1± 0.5ab	245.3±26.1 ab	10.5± 0.4ab	266.3±15.5 ab	11.8±0.8 bc
50+180	56.3±1.0 ab	2.0±0.3 bc	126.8± 2.5ab	4.8±0.4 ab	207.3±5.7ab	7.8 ±0.3 a b	254.0±4.2 a	10.7±0.5ab	255.0±12.9 ab	12.2±0.4 abc
100+60	61.8± 9.8ab	2.6±0.3 a	130.8±6.4 ab	4.9±0.1 ab	195.8±7.5 abcd	8.5±0.3 a	224.8± 17.5abc	10.0±0.5 ab	247.0±17.4ab	13.0±0.3 ab
100+120	59.5±5.1 ab	2.0±0.2 abc	132.0±7.3a	5.1±0.5 a	209.5±6.7 ab	8.2±0.7 a	250.0±1.6 ab	10.1±0.7 ab	248.8±13.1 ab	12.3±0.7abc
100+180	61.0±2.2 ab	2.0±0.2 bc	133.0±4.8 a	4.6±0.3 abc	204.0 ±5.7 abc	7.9± 0.4ab	241.5±16.4 ab	10.5±0.7 ab	263.8±37.7 ab	11.7±0.5 bc
150+60	62.0±4.6 ab	1.9±0.3bc	129.8± 5.1ab	4.8±0.5 ab	205.3± 18.0abc	8.3±0.4 a	256.3± 13.1a	10.9± 0.6ab	274.5±8.8 a	11.3± 0.4cd
150+120	65.0±5.8 a	1.9±0.1 bc	134.3± 3.3a	4.8± 0.2ab	191.0±8.4 bcd	8.1±0.6 ab	244.3±14.4 ab	11.1±0.4 a	263.5±8.5 ab	12.4±0.5abc
150+180	65.5±3.9 a	1.9±0.1bc	136.0 ±2.2a	4.8±0.3 ab	213.8±7.1 a	8.4±0.3 a	247.0±18.6 ab	10.6±0.4 ab	267.5±41.7 ab	13.4±0.3 a
0+120	49.5±3.1 bc	2.02±0.1 bc	119.5±6.9 a	4.2±0.1 bc	180.3±7.5 de	7.0±0.2 b	220.0± 3.6bc	9.8±0.7 bc	220.5±20.2 b	10.2±0.5 d
100+0	58.3±2.2 ab	2.2± 0.1ab	122.0±7.6 ab	4.8±0.4 ab	195.0±10.5 abcd	8.6±0.4 a	233.3±8.5 ab	10.5±0.5 ab	252.8±13.5 ab	13.2±0.4 ab
0+0	43.8±2.2 c	1.6±0.3 c	110.0±13.2 b	3.8±0.3 c	165.3±4.9 e	7.1± 0.3b	208.0±7.6c	8.7±0.1 c	221.8±14.3 b	10.2±0.4 d

Hp - Plant height (cm), BSD - Basal stem diameter (cm), SD - standard deviation. Letters following standard deviations of each treatment identify the homogeneous groups generated from multiple comparisons (Tukey's test, *P*<0.05).
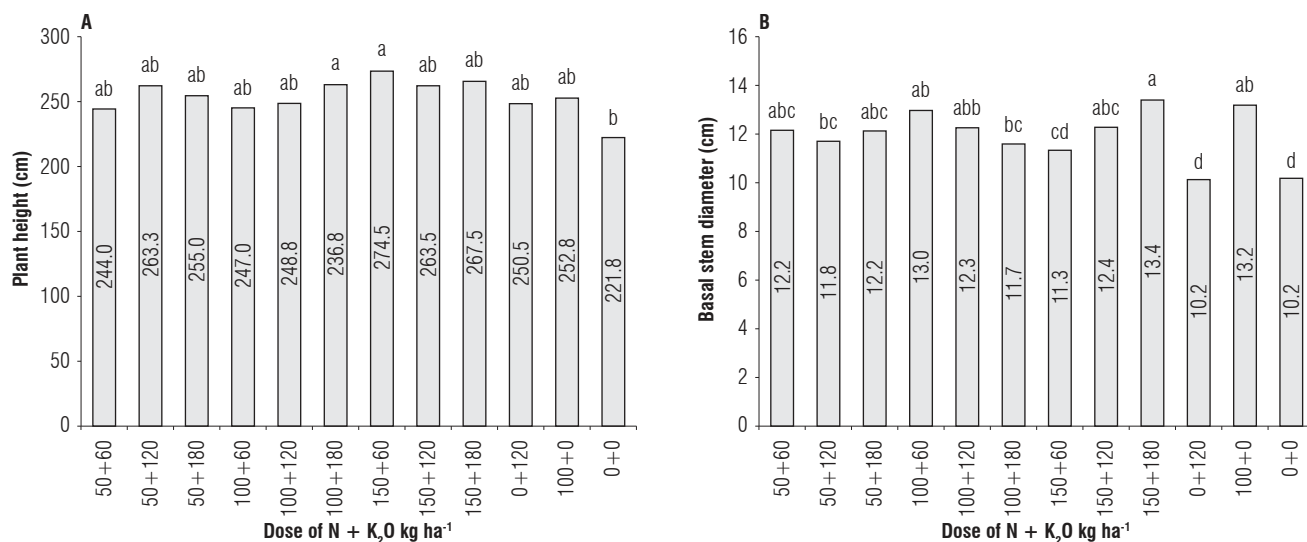
FIGURE 1. Plant height (A) and basal stem diameter (B) of *J. curcas* at 435 DAP treated with different doses of N and K_2O (Tukey's test, $P < 0.05$).

highest dispersion in variables Hp and BSD occurred in the reproductive phase of growth at 345 and 435 DAP. Both variables possessed a similar growth pattern over time, as shown by Reis *et al.* (2018), but stood out in the treatment with the highest rate of N (150 kg ha^{-1}) at 345 and 435 DAP. The diagram of dispersion did not reflect a trend, since the variable "treatments" was of nominal scale; however, an increasing trend in time for Hp and BSD could be observed for both treatments (Fig. 2).

To evaluate the effect of N and of K_2O doses nested in N ($K_2O(N)$) on Hp and BSD at different moments of growth, Wilks' Lambda statistics was used. It revealed the interactions of second and third order, both significant ($P < 0.05$) and highly significant ($P < 0.01$) for the main effects associated with doses of N, doses of K_2O nested in N, and evaluation moments (Tab. 4). In order to use the results of the bivariate analysis of variance, it was necessary to recognize the presence of significant interactions; these interactions made it impossible to interpret the main effects (Tab. 4), so that one could appeal for the graphs of interaction (Sokal and Rohlf, 2012). Table 4 presents the summary of the two-way ANOVA of repeated measures design of some of the effects. It highlights the interactions and justifies the use of interaction profiles to select the best N doses at each evaluation time. Table 4 shows the effects of the reduced model eliminating effects with a significance level greater than 5%. The values close to 5% were left in the model, although they were higher than this limit. In double interactions of inter-subject factors with "time", the effect of $K_2O(N)$ could be interpreted,
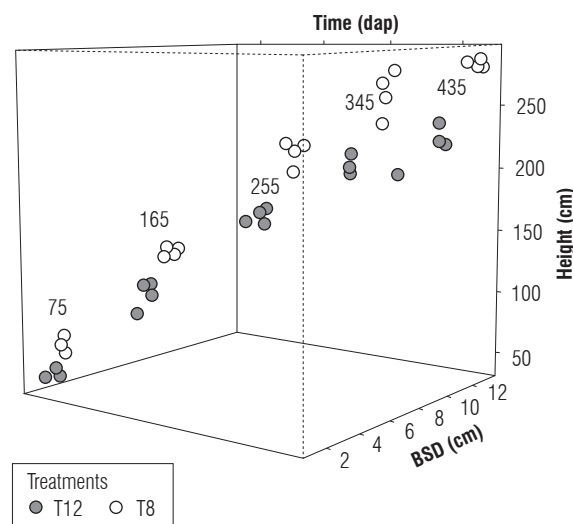

FIGURE 2. Three-dimensional dispersion diagram of plant height (cm) and basal stem diameter (cm) according to the moment of evaluation (DAP) and N+K_2O treatments (kg ha^{-1}). T8 denotes the treatment N=150 kg ha^{-1} plus K_2O=120 kg ha^{-1} and T12 corresponds to absolute control.

since the interaction was not significant ($P = 0.0589$) (Tab. 4). In the absence of a significant interaction between "time" and "dose of K_2O nested in N", the values of Hp and BSD at 435 DAP corresponded to 266.7 and 12.2 cm, respectively, for 180 kg ha^{-1} K_2O nested in different N doses, while control plants had Hp of 239.1 cm and BSD of 11.2 cm. As for the effect of N, the interaction of "N dose" with "time" was revealed. This makes it impossible to select the best dose of N for all moments, so that the use of profiles facilitated choosing the best dose at each evaluation time (Figs. 3 and 4).

TABLE 4. Significance levels for individual effects and interactions in bivariate analysis of variance.

Effect	Pr<F
Responses (Hp; BSD)	<.0001
Responses (Hp; BSD) x (N)	<.0001
Responses (Hp; BSD) x $K_2O(N)$	0.0017
Time	<.0001
Time x N	<.0001
Time x $K_2O(N)$	0.0573
Responses (Hp; BSD) x Time	<.0001
Responses (Hp; BSD) x Time x N	<.0001
Responses (Hp; BSD) x Time x $K_2O(N)$	0.0589

Hp - plant height (cm); BSD - basal stem diameter (cm); N - dose of N; $K_2O(N)$ - dose of K_2O nested in dose of N. The effects, whose significance was higher than 5%, were not considered. The effects close to 5% significance were left in the model, although being higher than this limit.

The behavior of Hp discriminated by moments of evaluation (DAP), dose of N, and dose of K_2O nested in N confirmed the major increases in plant height of *J. curcas* during the vegetative phase between 75 and 255 DAP (Fig. 3), a period when plants allocated most of their carbon resources to new branches and leaves. According to the slopes of the curves, the gain in height of 0.78 cm/day was observed for plants treated with N=150 kg ha^{-1} plus K_2O=180 kg ha^{-1}, while the absolute control gained 0.71 cm/day in height (Fig. 3A). A slower growth was detected during the reproductive phase between 345 and 435 DAP, probably due to translocation of nutrients from leaves, branches, and stem towards flowers and fruits (Larcher, 2003). The plants gained only 0.35 cm/day in height in
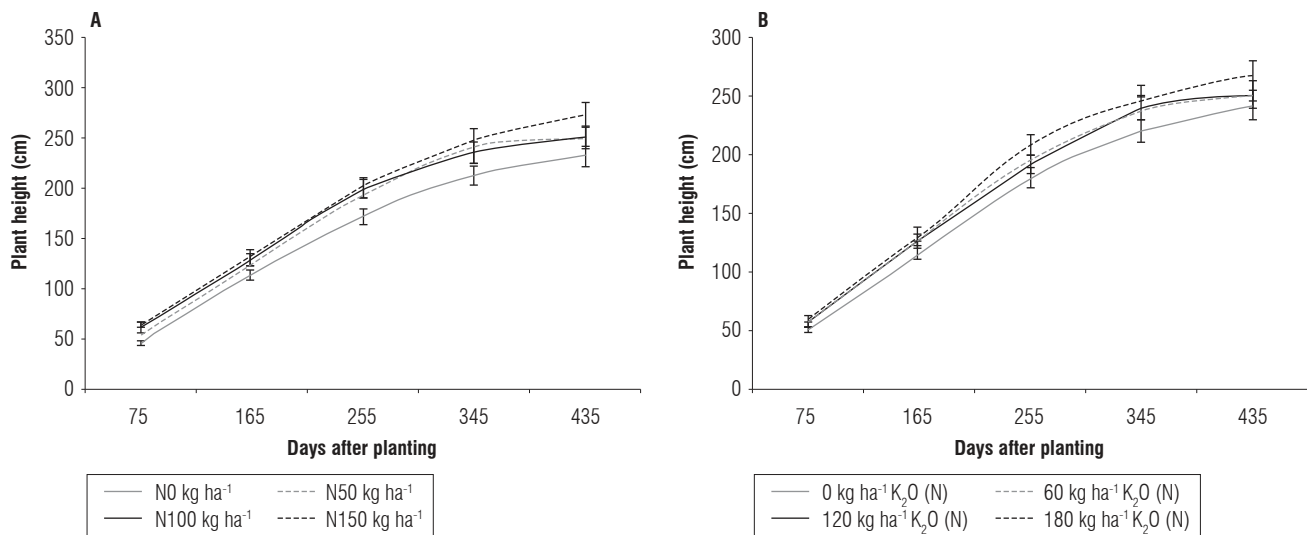

FIGURE 3. Plant height (cm) of *J. curcas* affected by different doses of N (**A**) and doses of K_2O nested in N (**B**). The bars correspond to standard errors of the means.
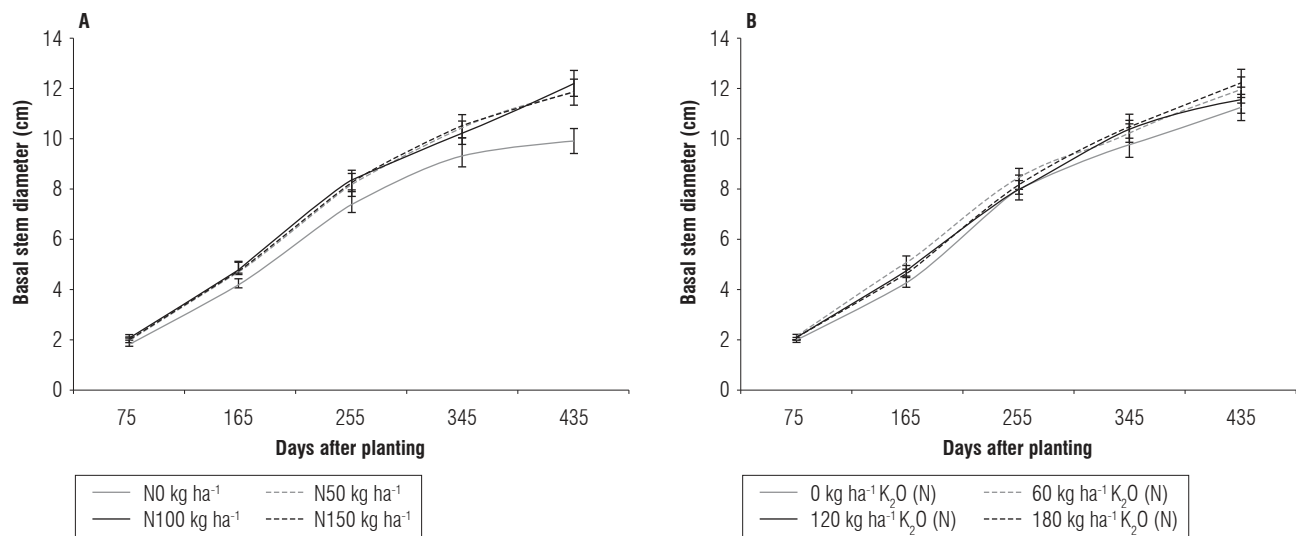

FIGURE 4. Basal stem diameter (cm) of *J. curcas* affected by different doses of N (**A**) and doses of K_2O nested in N (**B**). The bars correspond to standard errors of the means.

this period when treated with 150 kg ha⁻¹ N and 180 kg ha⁻¹ K$_2$O and only 0.17 cm/day in control plants without NK fertilization (Fig. 3A). The plants were taller in all treatments with N application presenting the highest Hp at all moments of the evaluation and reaching 285 cm at 435 DAP when treated with 150 kg ha⁻¹ N. In contrast, the lowest heights of 228 cm corresponded to the treatments without N (Fig. 3A), which agrees with Su *et al*. (2013), who reports increases in height, stem diameter, and total number of branches in *J. curcas* as the doses of 15-15-15 NPK fertilizer increase. However, very high doses of N could prolong the vegetative phase of growth, thus, delaying the start of fruit production (Larcher, 2003). Likewise, increases in height above 2.5 m might affect agronomic practices in *J. curcas* by requiring pruning and obstructing crop harvest, since fertilization could affect branching in *J. curcas* (Nirala *et al*., 2017). When analyzing the effect of the K$_2$O dose nested in N (K$_2$O(N)) on Hp, a similar trend was observed, with the largest heights (267 cm) obtained with application of 180 kg ha⁻¹ K$_2$O for the average N doses, whereas the lowest heights (239 cm) corresponded to control plants without K application (Fig. 3B).

The plants were not significantly different in BSD during the first two evaluation moments according to values of standard errors (Fig. 4). It should be noted that BSD increased progressively in time. Thus, starting from 165 DAP all plants treated with NK differed in BSD from the absolute control; however, no differences in BSD were detected among the plants treated with non-zero doses of N or K (Fig. 4A). A similar result in BSD was observed affected by K$_2$O dose nested in N but with fewer differences, with smaller BSD corresponding to control plants without K fertilization (Fig. 4B).

Multiple regression models for prediction of plant height and stem diameter

Multiple regression models for Hp and BSD were developed. These permitted predicting responses according to the levels of each factor and the development of two formulae as presented in Table 5. The models served to assess untested levels of factors (dose of N or dose of K$_2$O or moment of evaluation) fitting these within their range of operation (an example highlighted in Table 6). According to the multiple linear regression analysis, the behavior of Hp fit this model well and explained 92.99% of the variability and, analogously, the model for BSD adjusted to 94.68% of the variability. These mathematical models allow estimating Hp and BSD for any dose of N and K$_2$O at five evaluation moments within the evaluated range (Tab. 5). Therefore, N and K fertilization rates can be adjusted to a desired plant height and, thereby, they can be used to schedule some agronomic labors, such as pruning. In *J. curcas*, Hp and BSD could be further used to estimate the plant biomass (Makungwa *et al*., 2013).

Hp had a highly significant (*P*<5%) correlation with BSD. As the doses of N and K increased, both Hp and BSD increased progressively, an aspect observed for all moments of evaluation. These allometric relationships vary considerably by species (Clough and Scott, 1989), but are especially important for trees (Lott *et al*., 2000; Wang *et al*., 2000; Salis *et al*., 2006; Levia, 2008), where stem diameter is used to calculate some parameters, such as plant height and biomass, an aspect that could be used in *J. curcas*. In this sense, tree growth is supported by the trunk and must be biomechanically balanced (Montagu *et al*., 2005); in other words, stem diameter is related to the length and distribution of branches and should prevent uprooting or branch split. In *J. curcas*, stem diameter and number of branches (Laviola *et al*., 2012) as well as plant height (Laviola *et al*., 2012; Shabanimofrad *et al*., 2013; De Lima *et al*., 2016) were shown to correlate positively with seed yield per plant.

Employing the models obtained, the values of Hp and BSD for *J. curcas* at 435 DAP were estimated for different levels of N and K fertilizers. Also, randomly chosen and experimentally untested doses (N=75 kg ha⁻¹ and K$_2$O=90 kg ha⁻¹) were introduced within the operational ranges of each dose to verify the predictive behavior of the models (Tab. 6).

TABLE 5. Multiple regression models for the prediction of plant height and basal stem diameter of *J. curcas* as a function of N dose (kg ha⁻¹), K$_2$O dose (kg ha⁻¹), and moment of evaluation (DAP).

Response	Model	R²
$\hat{Y}_1$: Hp	$\hat{Y}_1 = 8.71659 + 0.07722 \times K_2O + 0.17786 \times N + 0.56276 \times t$	0.93
$\hat{Y}_2$: BSD	$\hat{Y}_2 = -0.60192 + 0.00232 \times K_2O + 0.00803 \times N + 0.02738 \times t$	0.95

Range of settings of prediction models: $0 \leq K_2O \leq 180$, $0 \leq N \leq 150$, $75 \leq t \leq 435$, where K$_2$O - dose of K$_2$O (kg ha⁻¹), N - dose of N (kg ha⁻¹), t - time (DAP). $\hat{Y}$ corresponds to estimated model and R² denotes the adjusted coefficient of determination.

TABLE 6. Plant height (cm) and basal stem diameter (cm) of *J. curcas* estimated at 435 DAP with different combinations of N and K₂O doses including a dose not tested experimentally (highlighted).

K₂O (kg ha⁻¹) N (kg ha⁻¹)	Variables	0	60	(90)	120	180
0	Hp	253.52	258.15	(260.47)	262.78	267.42
	BSD	11.31	11.44	(11.52)	11.58	11.73
50	Hp	262.41	267.04	(269.36)	271.68	276.31
	BSD	11.70	11.84	(11.91)	11.98	12.12
(75)	Hp	(266.86)	(271.49)	(273.81)	276.12	280.76
	BSD	(11.91)	(12.04)	(12.11)	12.18	12.32
100	Hp	271.30	275.94	278.25	280.57	285.20
	BSD	12.11	12.25	12.32	12.38	12.52
150	Hp	280.20	284.83	287.15	289.46	294.10
	BSD	12.51	12.65	12.72	12.79	12.93

The values estimated by the models for both evaluated doses and untested doses experimentally showed a clear increase in Hp and BSD for *J. curcas* with increasing doses of N and/or K fertilizer (Tab. 6). Therefore, these models could be applied for easy, rapid and non-invasive predictions of *J. curcas* growth in the field for the region.

Conclusions

The growth of *J. curcas* was influenced by doses of N and doses of K₂O nested in N during the vegetative and reproductive phases. The tallest plants with the largest stem diameters were those subjected to the highest rates of N and K fertilizers. For the management of fertilization of *J. curcas* in the given edaphoclimatic conditions of Colombia, doses of 100 kg ha⁻¹ N and 120 kg ha⁻¹ K₂O can be recommended. Both basal stem diameter and plant height in *J. curcas* increased proportionally during growth. The predictive models for plant height and basal stem diameter integrated rates of N, rates of K₂O, and time had an adjusted coefficient of determination R^2 over 92%. The fertilizer rates N=75 kg ha⁻¹ and K₂O=90 kg ha⁻¹ were not evaluated in the field, but they fitted well within the operational ranges of the models and data generated were consistent with the behavioral tendencies of the studied variables. The models obtained could be used for rapid and non-invasive predictions of *J. curcas* growth in the field.

Acknowledgments

Literature cited

Ahmed, D.M.M., A.R.M. Yousef, E.A.M. Ali, and M.A. El-Hady. 2016. Potassium forms as a macronutrient application to maximize fruit and oil productivity of *Jatropha curcas* (Part 1: The use of mono potassium phosphate (MKP)). Int. J. Agric. Res. 11, 116-125. Doi: 10.3923/ijar.2016.116.125

Arévalo, L.P., P.A. Méndez, and P.R. Linares. 2011. Propuesta para desarrollar una plantación forestal de la especie *Jatropha curcas* para extracción de biodiesel en el municipio de Guaduas, Cundinamarca. Revista Gestión. Integral Ingen. Neogranadina 3, 35-50.

Bártoli, J.A.A. 2008. Manual para el cultivo de Piñon (*Jatropha curcas*) en Honduras. Centro de Comunicación Agrícola de la Fundación Hondureña de Investigación Agrícola (FHIA), Cortes, Honduras.

Campuzano, L.F. 2008. Programa Jatropha Colombia: genética, agronomía, poscosecha y desarrollo agroindustrial del piñón en Colombia (2008-2012). Rev. Innov. Cambio Tecnol. 7, 64-68.

Chhetri, A.B., M.S. Tango, S.M. Budge, K.C. Watts, and M.R. Islam. 2008. Non-edible plant oils as new sources for biodiesel production. Int. J. Molec. Sci. 9, 169-180. Doi: 10.3390/ijms9020169

Clough, B.F. and K. Scott. 1989. Allometric relationships for estimating above-ground biomass in six mangrove species. Forest Ecol. Manage. 27, 117-127. Doi: 10.1016/0378-1127(89)90034-0

Collier, L.S., D.V. Castro, J.J. Dias Neto, D.R. Brito, and P.A.D.A. Ribeiro. 2006. Nitrogen fertilization management for maize

on legume straw crop with no tillage cultivation in Gurupi, Tocantins State. Cienc. Rural 36, 1100-1105. Doi: 10.1590/S0103-84782006000400009

Cumming, G., F. Fidler, L. David, and D.L. Vaux. 2007. Error bars in experimental biology. J. Cell Biol. 177, 7-11. Doi: 10.1083/jcb.200611141

Davis, C.S. 2002. Statistical methods for the analysis of repeated measurements. Springer-Verlag, New York, USA. Doi: 10.1093/ije/dyg249

De Lima, R.D., A.R. Campos, C.A. de Azevedo, J.A. Calado, S. de Sousa Silva, and R. do Nascimento. 2016. Effects of planting density on vegetative growth and production components of jatropha (*Physic nut* L). Austral. J. Crop Sci. 10, 632-636. Doi: 10.21475/ajcs.2016.10.05.p7148

Ghosh, A., J.S. Patolia, D.R. Chaudhary, J. Chikara, S.N. Rao, D. Kumar, G. Boricha, and A. Zala. 2007. Response of *Jatropha curcas* under different spacing to Jatropha de-oiled cake, pp. 26-28. In: Expert seminar on *Jatropha curcas* L. agronomy and genetics. Wageningen, The Netherlands.

Holdridge, L.R. 1967. Life zone ecology. 1st ed. Tropical Science Center, San Jose.

IDEAM. 2017. Instituto de hidrología, meteorología y estudios ambientales, Bogota.

Kalannavar, V.N., S.S. Angadi, V.C. Patil, S.G. Angadi, A.S. Byadagi, and S.J. Patil. 2009. Effect of major nutrients on growth and yield of *Jatropha curcas*. Int. J. Agric. Sci. 5, 390-393.

Lara, W.A.R. and M.A. Souza. 2008. Ammonia volatilization, leaching of nitrogen and corn yield in response to the application of mix of urea and ammonium sulphate or gypsum. Rev. Bras. Cienc. Solo 32, 2331-2342. Doi: 10.1590/S0100-06832008000600012

Larcher, W. 2003. Carbon utilization and dry matter production. In: Physiological plant ecology: ecophysiology and plant physiology of functional groups. Springer-Verlag, New York.

Laviola, B.G., A.A. Alves, F.D.L. Gurgel, T.B. Rosado, R.D. Costa, and R.B. Rocha. 2012. Estimate of genetic parameters and predicted gains with early selection of physic nut families. Cienc. Agrotec. 36, 163-170. Doi: 10.1590/S1413-70542012000200004

Levia, D.F. 2008. A generalized allometric equation to predict foliar dry weight on the basis of trunk diameter for eastern white pine (*Pinus strobus* L.). For. Ecol. Manage. 255, 1789-1792. Doi: 10.1016/j.foreco.2007.12.001

Lott, J.E., S.B. Howard, C.R. Black, and C.K. Ong. 2000. Allometric estimation of above-ground biomass and leaf area in managed *Grevillea robusta* agroforestry systems. Agrofor. Syst. 49, 1-15. Doi: 10.1023/A:1006330830109

Makungwa, S.D., A. Chittock, D.L. Skole, G.Y. Kanyama-Phiri, and I.H. Woodhouse. 2013. Allometry for biomass estimation in *Jatropha* trees planted as boundary hedge in farmers' fields. Forests 4, 218-233. Doi: 10.3390/f4020218

Matos, F.S., V.R. Rosa, L.F.O. Borges, R.P. Ribeiro, C.K.L. Crucinel, and L.A.S. Dias. 2014. Response of *Jatropha curcas* plants to changes in the availability of nitrogen and phosphorus in Oxissol. Afric. J. Agric. Res. 9, 3581-3586. Doi: 10.5897/AJAR2014.9188

Mohapatra, S. and P.K. Panda. 2011. Effects of fertilizer application on growth and yield of *Jatropha curcas* L. in an aeric tropaquept of Eastern India. Not. Sci. Biol. 3, 95-100. Doi: 10.15835/nsb.3.1.5497

Montagu, K.D., K. Düttmer, C.V.M. Barton, and A.L. Cowie. 2005. Developing general allometric relationships for regional estimates of carbon sequestration - an example using *Eucalyptus pilularis* from seven contrasting sites. For. Ecol. Manage. 204, 113-127. Doi: 10.1016/j.foreco.2004.09.003

Montgomery, D.C. 2013. Design and analysis of experiments. 8th ed. Arizona State University, John Wiley and Sons, USA.

Nirala, D.P., P. Santosh, A. Sinha, and K. Rajneesh. 2017. Effect of pruning and fertilizer application to optimize branching and fruiting in *Jatropha curcas* L. Life Sci. Leafl. 92, 42-49.

Patil, S.J. and K. G. Parameshwarappa. 2007. Silvicultural management of jatropha (*Jatropha curcas* L.) under rainfed conditions. pp. 371-372. In: National seminar on changing global vegetable oil scenario: Issues and challenges before India. ISOR, Hyderabad, India.

Pedraza, E.A. and D.G. Cayón. 2010. Caracterización morfo-fisiológica de *Jatropha curcas* L. variedad Brasil cultivada en dos zonas de Colombia. Acta Agron. 59, 30-36. Doi: 10.15446/acag

Reis, A.D.S., T.R.B. da Silva, J. Gonçalves, D. Secco, C.Z. Alves, and R.F. Santos. 2018. Organic and mineral fertilizer on the initial development and nutrition of jatropha. J. Agric. Sci. 10, 274-281. Doi: 10.5539/jas.v10n10p274

Salis, S.M., M.A. Assis, P.P. Mattos, and A.C.S. Pião. 2006. Estimating the aboveground biomass and wood volume of savanna woodlands in Brazil's Pantanal wetlands based on allometric correlations. For. Ecol. Manag. 228, 61-68. Doi: 10.1016/j.foreco.2006.02.025

Shabanimofrad, M., M.Y. Rafii, P.M. Wahab, A.R. Biabani, and M.A. Latif. 2013. Phenotypic, genotypic and genetic divergence found in 48 newly collected Malaysian accessions of *Jatropha curcas* L. Ind. Crop. Prod. 42, 543-551. Doi: 10.1016/j.indcrop.2012.06.023

Silva, E.B., L.P. Patente, S.R. Santos, and P.S. Resende. 2009. Sintomas visuais de deficiências nutricionais em pinhão-manso. Pesq. Agropec. Bras. 44, 392-397. Doi: 10.1590/S0100-204X2009000400009

Sokal, R.R. and F.J. Rohlf. 2012. Biometry: the principles and practice of statistics in biological research. 4th ed., Freeman, USA.

Su, L., F. Qin, T. Su, T. He, Y. Zhang, Y. Zeng, L. Hie, Y. Huang, and Y. Liu. 2013. Effects of fertilization on growth and dynamic of leaf nutrients of *Jatropha curcas*. J. Southern Agric. 44, 1517-1523.

Suriharn, B., J. Sanitchon, P. Songsri, and T. Kemala. 2011. Effect of pruning levels and fertilizer rates on yield of physic nut (*Jatropha curcas* L.). Asian J. Plant Sci. 10, 52-29. Doi: 10.3923/ajps.2011.52.59

Tigere, T.A., T.C. Gatsi, I.I. Mudita, T.J. Chikuvire, S. Thamangani, and Z. Mavunganidze. 2006. Potential of *Jatropha curcas* in improving smallholder farmers' livelihoods in Zimbabwe: an exploratory study of Makosa ward, Mutoko district. J. Sust. Dev. Africa 8, 1-9.

Tjeuw, J., M. Slingerland, and K. Giller. 2015. Relationships among *Jatropha curcas* seed yield and vegetative plant components under different management and cropping systems in Indonesia. Biomass Bioenergy 80, 128-139. Doi: 10.1016/j.biombioe.2015.05.003

Wang, J.R., T. Letchford, P. Comeau, and J.P. Kimmins. 2000. Above- and below-ground biomass and nutrient distribution of a paper birch and subalpine fir mixed-species stand in the Sub-Boreal Spruce zone of British Columbia. For. Ecol. Manage. 130, 17-26. Doi: 10.1016/S0378-1127(99)00193-0

Wang, W.G., R. Li, B. Liu, L. Li, S. H. Wang, and F. Chen. 2011. Effects of low nitrogen and drought stresses on proline synthesis of *Jatropha curcas* seedling. Acta Physiol. Plant. 33, 1591-159. Doi: 10.1007/s11738-010-0692-6