

Fitting growth curves of coffee plants in the nursery stage of growth: A functional approach

Ajuste de curvas de crecimiento de plantas de café durante la etapa de crecimiento de almácigo: Un enfoque funcional

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ABSTRACT

The growth patterns of coffee plants are determined by interactions between genetic, physiological, and climate factors. The objective of this study was to evaluate the growth patterns of coffee plants in the nursery under the climatic conditions of Chinchiná, Caldas, Colombia, during the first semester of 2019. Measurements were carried out in the Cenicafe 1 variety during six months. Growth parameters such as leaf area, number of leaves, height, stem diameter, and length of the main root were evaluated every 15 d after transplanting (DAT) in 20 plants and the average of absolute growth (\hat{G}) rate of each growth variable were calculated. For the total leaf area, total number of leaves, and stem height, a sigmoidal-type growth curve was adjusted, while the growth curve was linear for the stem diameter ($R^2 = 0.97$) and main root length ($R^2 = 0.95$). Average values were obtained for 520 cm² for total leaf area, with an \hat{G} of 3.31 cm² d⁻¹, 11 for total leaves (\hat{G} 0.055 leaves d⁻¹), 30.23 cm for height (\hat{G} 0.155 cm d⁻¹), 4.87 mm for stem diameter (\hat{G} 0.199 mm d⁻¹), and 28.80 cm for main root length (\hat{G} 0.087 cm d⁻¹) at 180 DAT. These results suggest that growth curves could be a useful tool for describing the growth patterns of coffee seedlings during the nursery stage of growth.

Key words: *Coffea arabica* L., nonlinear regression, goodness of fit, leaf area, absolute growth rate.

RESUMEN

Los patrones de crecimiento de las plantas de café están determinados por las interacciones entre los factores genéticos, fisiológicos y climáticos. El objetivo de este estudio fue evaluar los patrones de crecimiento de las plantas de café en etapa de almácigo bajo condiciones climáticas de Chinchiná, Caldas, Colombia, durante el primer semestre de 2019. Las mediciones se realizaron en plantas de la variedad Cenicafe 1 durante seis meses. Se evaluaron los parámetros de crecimiento como área foliar, número de hojas, altura, diámetro del tallo y longitud de la raíz principal, cada 15 d después del trasplante (DDT) de 20 plantas y se calculó la tasa promedio de crecimiento absoluto (\hat{G}) de cada variable de crecimiento. Para el área foliar total, número total de hojas y altura del tallo, se ajustó una curva de crecimiento tipo sigmoidal, mientras que fue lineal para el diámetro del tallo ($R^2 = 0.97$) y longitud de la raíz principal ($R^2 = 0.95$). Se obtuvieron valores promedio a los 180 DDT de 520 cm² de área foliar total con \hat{G} 3.31 cm² d⁻¹, 11 hojas totales (\hat{G} 0.055 hojas d⁻¹), 30.23 cm de altura (\hat{G} 0.155 cm d⁻¹), 4.87 mm para diámetro del tallo (\hat{G} 0.199 mm d⁻¹) y 28.80 cm para longitud de la raíz principal (\hat{G} 0.087 cm d⁻¹). Estos resultados sugieren que las curvas de crecimiento pueden ser una herramienta útil para describir los patrones de crecimiento de las plantas de café durante la etapa de almácigo.

Palabras clave: *Coffea arabica* L., regresión no lineal, criterios de ajuste, área foliar, tasa absoluta de crecimiento.

Introduction

Coffee (*Coffea arabica* L.) is one of the most important tropical crops worldwide, with Colombia ranked third in production with 13,4 million bags of green beans (60 kg) and 884 thousand ha (Nab & Maslin, 2020; Ceballos-Sierra & Dall' Erba, 2021; FNC, 2021). The growth of coffee plants is a process regulated by interactions between genetics,

physiological processes, and climatic conditions, with implications for agronomic management and crop success (Paine *et al.*, 2012; Liu *et al.*, 2018; Rakocevic & Matsunaga, 2018). Factors such as solar radiation, temperature, water availability in soil, and humidity in atmosphere are key climatic conditions that influence the growth and development of the plants (DaMatta, 2007; Bote & Vos, 2017; Jaramillo, 2018; León-Burgos *et al.*, 2022). Growth patterns

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in each phenological stage could serve as an important tool for planning agronomic practices such as planting density, spatial arrangements, application of fertilizers and liming, controls of pests, diseases and weeds, and management of the crop pruning systems (Arcila, 2007; Rendón, 2020). This is necessary to ensure adequate growth and development of plants in the field and, thus, a high production potential.

Plants in the nursery constitute an early phase of growth in coffee crops that lasts from four to six months, with implications in the growth and development of plants in the field and production cycle (Arcila, 2007; Moraes *et al.*, 2010; Castillo & Andrade, 2021). Shoot growth at this phase takes place in the meristematic zones located in the apical and lateral buds of the main stem (Arcila *et al.*, 2002). The purpose of the coffee nursery stage is to select plants with appropriate growth characteristics, such as the number of leaves, height and leaf area, so that, when established in the field, they can adapt to the climate and soil conditions to avoid damages to their physiological performance that can cause plant death (Jaramillo, 2018; Castillo & Andrade, 2021). Furthermore, at the initial stages of projection in perennial crops life cycles, it is necessary to ensure good quality of the plant material from the point of view of crop health, so that, in the production cycle, it would express the highest production (Arcila, 2007; Gaitán *et al.*, 2011). Therefore, the nursery stage of growth is a determining step for planning crop management and production projection in Colombian coffee cultivation (Rendón, 2020).

Growth curves are widely used in agriculture to simulate plant growth patterns as a function of time under particular climatic conditions (Poorter & Garnier, 1996; Paine *et al.*, 2012; Liu *et al.*, 2018; Bakhshandeh *et al.*, 2020). Analyses have been developed with functions or mathematical models through linear or nonlinear regressions that are adjusted according to statistical criteria. These criteria define the degree of prediction of the changes and behavior in the magnitudes of growth, based on data measured in plants, called a functional approach (Kaufmann, 1981; Hunt *et al.*, 2002; Liu *et al.*, 2018). This technique is mainly used to evaluate the temporal variation of plant growth dynamics at phenological stages of interest, since only a few individuals are measured but with many replicates throughout the time, particularly during rapid changes in growth (Hunt, 1979; Paine *et al.*, 2012). Therefore, these methods can be used to describe changes in the magnitude of growth and to define selection criteria that may ensure good quality and growth of the plants coming from nursery stage.

Currently the coffee variety “Cenicafé 1” makes up approximately 80% of the cultivable area for coffee in Colombia (FNC, 2021). There is little information on the growth patterns and selection criteria for classifying good growth performance of the plants during the nursery stage. In this research we considered the following objectives: i) evaluation of the fit of mathematical functions that could simulate the growth from a functional approach and ii) description of the growth patterns of coffee plants during the nursery stage under the climatic conditions of Chinchiná-Caldas, located in the central coffee zone of Colombia. Mathematical functions were studied to describe plant growth patterns as a function of time using five growth measures: total leaf area (cm²), number of leaves, stem height (cm), stem diameter (mm), and length of main root (cm). With the adjusted mathematical functions and growth patterns, it is possible to predict the growth magnitude and to define selection criteria for coffee plants under nursery conditions.

Materials and methods

Study area and growth conditions

The plant material was the coffee Cenicafé 1 variety, established on the Plan alto Farm of the National Coffee Research Center-Cenicafé (04°59'34.9" N, 75°35'50.5" W), located at km 4 of the old Manizales-Chinchiná road (Caldas, Colombia), at an altitude of 1,332 m a.s.l. This material is a variety made up by eight progenies, resistant to coffee rust (*Hemileia vastatrix*) and coffee berry disease (CBD) (*Colletotrichum kahawae*) (Maldonado & Ángel-Giraldo, 2020). During the study period between January and July, 2019, the nursery was established in the area with following average climatic conditions: temperature of 21.8°C (maximum: 28.5°C and minimum: 17.4°C), relative air humidity of 82%, with an accumulated rainfall of 1,419 mm and 782 h of sunlight (Meteorological Stations of the National Federation of Coffee Growers of Colombia, Agroclima, 2019).

The plants (*chapolas*, in Spanish) were transplanted from seed germinators 75 d after sowing the seeds; at the moment of transplant the plants were at the BBCH10 phenological stage, when the cotyledonary leaves were fully expanded. Subsequently, the plants were established in a nursery with a 50% shade net in 17 × 23 cm plastic bags (Arcila, 2007). The substrate consisted of a mixture of disinfected (solarized) soil with decomposed coffee pulp at a 3:1 ratio (v/v). For the fertilization of the plants, 2 g of diammonium phosphate (DAP, 18-46-0) were applied at two and four months after transplant according to the recommendations of Sadeghian (2014). Agronomic practices reported by Gaitán *et al.* (2011) as the regulation of excess shade,

waterlogging avoidance, and applications of cyproconazole (0.7 cc L⁻¹) were carried out to manage brown eye spot disease (*Cercospora coffeicola* Berkeley & Curtis); and destructive monthly samples were performed for the monitoring of the pest known as mealybug (Pseudococcidae).

Measurements and data collection

To evaluate the growth behavior of coffee plants during their nursery stage, 400 plants were established. At 30 d after transplanting (DAT), when the first pair of leaves was developed, 20 plants were randomly selected as a sampling unit. This selection was sampled every 15 d until 180 DAT. In each sampling, the following growth measurements were recorded: total leaf area (cm²), total number of leaves, stem height (cm), stem diameter (mm), and main root length (cm). The leaf area was determined by measuring the leaf blade length, and width on the central part of the leaf blade of each leaf using a ruler without including the petiole. The data were then incorporated into Equation 1, proposed by Unigarro-Muñoz *et al.* (2015):

$$LAE = 0.99927 \times (L \times (-0.14757 + 0.60986 \times W)) \quad (1)$$

where *LAE* is the estimate of the leaf area in cm², *L* is leaf length in cm, and *W* is leaf width in cm.

The total number of leaves was determined with direct counts on the plants; height was measured from the base to the apex of the stem with a ruler; and the diameter was measured with a Vernier digital caliper (500-196-30B, Mitutoyo, Brazil) from the basal part of the stem. For the length of the main root, destructive sampling was done, measuring length from the base to the apex of this organ.

For each growth measurement, the absolute growth rate (\hat{G}) was estimated with Equation 2, proposed by Hunt (1990):

$$\hat{G} = \frac{V2 - V1}{t2 - t1} \quad (2)$$

where \hat{G} is the average absolute growth rate, *V1* (cm², cm, or mm) is the value of the growth variable for time *t1* (d), and *V2* is the value of the growth variable for time *t2* (d).

Data analysis

To describe the behavior of growth measurements over time, four mathematical functions, described in Table 1, were evaluated using linear and nonlinear regressions. For the adjustment and selection of each mathematical function, the following statistical criteria were used: coefficient of determination *R*², widely used for the adjustment of models or functions; adjusted coefficient of determination - adj *R*², a criterion with greater precision adjusted

according to the degrees of freedom. The mean square error (MSE), a criterion that measures the degree of error that a model or function can simulate. The standard error of the estimates (SEE) that refers to the normal deviation of the residuals. Finally, the Akaike (AIC) and Bayesian-Schwarz (BIC) information criteria, measuring the accuracy and complexity of the model as well as the relationship between its bias and variance and the significance of the parameters of each equation according to the t-student test at 5% significance (Torres *et al.*, 2012; Voorend *et al.*, 2014; Liu *et al.*, 2018). Subsequently, the relationship between the observed values for each growth measure and the estimated values for each adjusted and selected mathematical function was determined with a simple linear regression analysis to verify that the regression coefficient was statistically equal according to the 1% t-test.

TABLE 1. Studied functions for the fit of growth curves of coffee plants.

Mathematical functions	Function	Parameters
Linear	$Y = y_0 + a \times x$	y ₀ a
Quadratic	$Y = y_0 + a \times x + b \times x^2$	y ₀ a b
Sigmoidal	$Y = \frac{a}{1 + \exp\left(-\left(\frac{x - x_0}{b}\right)\right)}$	a x ₀ b
Exponential	$Y = a \times (1 - \exp(-b \times x))$	a b

All analyses were performed with the software R, version 3.6.0 with statistical package stats and nls2 (R Development Core Team, 2019; Grothendieck, 2022).

Results and discussion

Fitting of growth curves of coffee plants

In general, average values of 496.13 cm² ± 3.64 (mean ± standard error (SE)) for total leaf area (TLA), 12.0 ± 0.40 for total number of leaves (TNL), 30.01 cm ± 1.30 for stem height (HS), 4.91 ± 0.26 mm for stem diameter (DS) and 29.09 ± 0.83 cm for length of the main root (LMR) were recorded in the coffee plants at 180 DAT, considered a suitable age for establishment in field conditions. The linear, quadratic, sigmoidal, and exponential functions used to simulate the growth patterns of the coffee plants during the nursery stage varied in the behavior of the growth measurements. The TLA, TNL and HS were fitted to a sigmoidal growth, and for the DS and LMR, a linear type was used (Fig. 1). Similar trends in the growth of coffee plants during this stage have been reported by Silveira *et al.* (2014) and

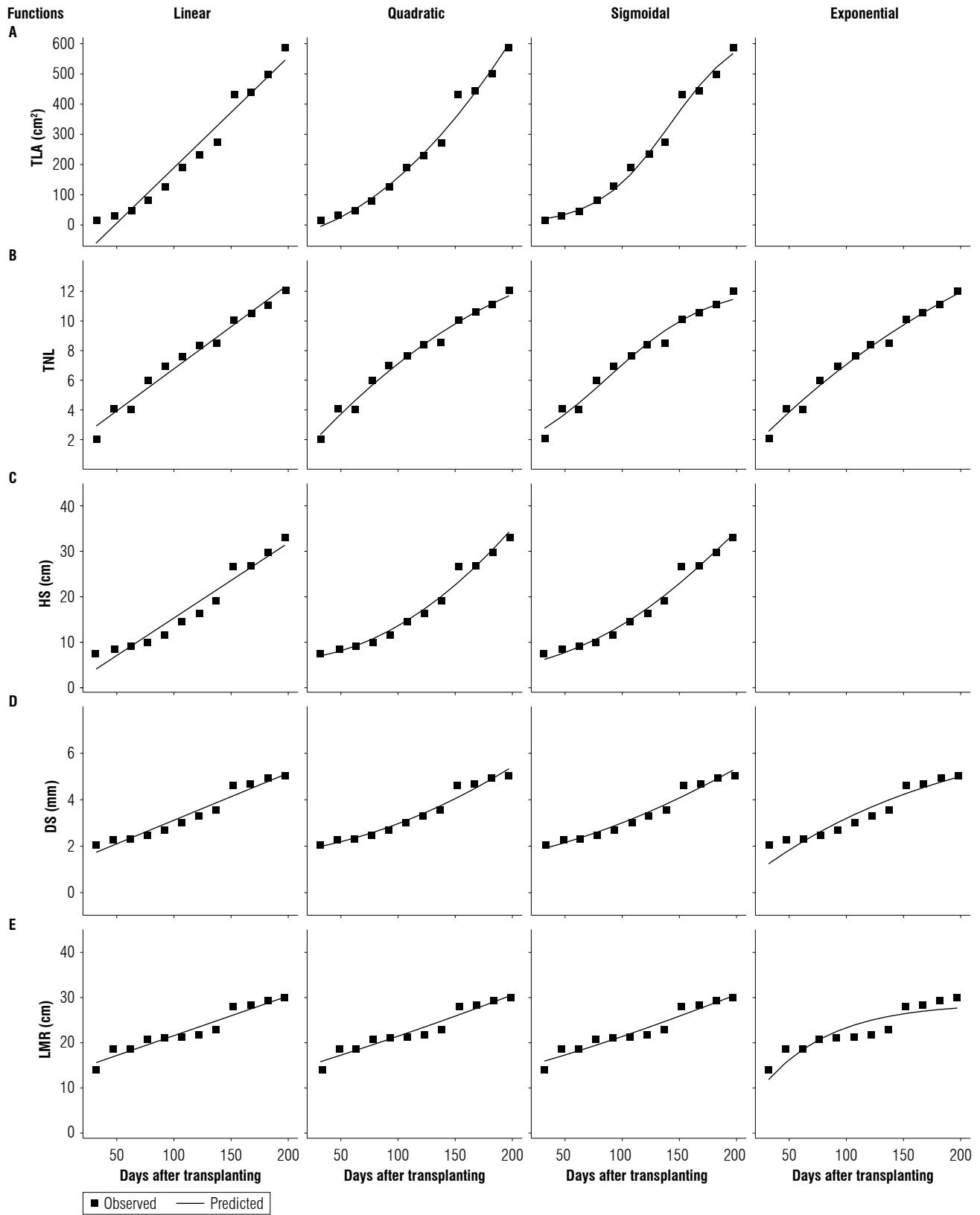


FIGURE 1. Growth curves of coffee seedlings at the nursery stage for each studied mathematical function. A) total leaf area (TLA), B) total number of leaves (TNL), C) height of the stem (HS), D) diameter of the stem (DS), E) length of the main root (LMR). Each point represents the mean ($n=20$).

Encalada *et al.* (2016). The opposite occurred in studies by Neiva *et al.* (2019) and Castillo and Andrade (2021) that describe quadratic behaviors in the growth of coffee plants during the nursery stage with contrasting results given the particular climatic conditions of the study areas.

Sigmoidal growth for the total leaf area, total leaf number and height described a growth pattern where the size of these variables increased along with the speed (Hunt, 1979; Kaufmann, 1981). However, the behavior of these growth variables was divided into two phases, a slow phase that started from 0 to 60 DAT, with average values between 19.91 to 49.13 cm² for TLA, 3 to 4 leaves and 6.21 until 8.95 cm for HS, and an accelerated phase (75 to 180 DAT) with values of 75.61 to 520.00 cm² for TLA, 6 until 12 leaves and between 10.68 to 30.16 cm for HS. DS and LMR increase linear according to DAT. Average values of 3.23 mm for DS and 22.23 cm for LMR were reported throughout the study (Fig. 1).

Once the mathematical functions were defined for each growth variable evaluated in the coffee plants, the significance of each parameter estimated by the functions was compared. In general, all parameters of the functions for TLA (sigmoidal), TNL (sigmoidal), HS (sigmoidal), DS (linear), and LMR (linear) showed significant differences ($P < 0.05$) from the other mathematical functions. Therefore, the selected functions were representative of each growth measurement evaluated in this study (Tab. 2).

The statistical criteria selected to evaluate the adjustment and selection of the mathematical functions have been used to simulate, adjust, and predict plant growth (Torres *et al.*, 2012; Voorend *et al.*, 2014; Liu *et al.*, 2018). To interpret the selection of each function, the adjustment criteria (R^2 and R^2 -adjusted) must be close to 1; and the selection criteria MSE, SEE, AIC and BIC must be the lowest values recorded by each function or model (Torres *et al.*, 2012; Liu *et al.*, 2018). The sigmoidal function of the TLA registered adjustment values with R^2 0.99 and R^2 -adjusted 0.98, along with the selection criteria MSE (694.88), SEE (26.36), AIC (117.12), and BIC (119.06). These were lower than values recorded in the linear and quadratic function, except for the exponential one, where it was not possible to adjust the total leaf area data because of the non-convergence of the function (Tab. 3). Therefore, this adjustment can simulate the growth of TLA in coffee plants during the nursery stage, this same adjustment mathematical function with R^2 values between 0.96 and 0.99 has been reported by Schmidt *et al.* (2014) and Unigarro-Muñoz *et al.* (2015).

The sigmoidal function of TNL and HS were selected and adjusted to represent the most appropriate values both fit ($R^2 = 0.97$) and selection (MSE= 0.42, SEE= 0.65) to describe the behavior of these growth measurements according to DAT. This growth pattern both TNL and HS in coffee plants were reported by the Arcila and Chaves (1995) and Silveira *et al.* (2014). For the HS measurement, it is not possible to adjust the exponential function because of the non-convergence of this function with the data measured in the plants (Tab. 3). The opposite occurred for the DS ($R^2 = 0.97$, MSE= 0.07, and SEE= 0.27) and LMR ($R^2 = 0.95$, MSE= 2.46, and SEE= 1.56). The values of the statistical criteria evaluated were adjusted to the linear function. However, for the HS and DS, the values of both the adjustment and selection criteria were similar to the quadratic function

TABLE 2. Estimates of parameters for the fitted mathematical functions of the coffee plant growth.

Functions	Y0	X0	A	b
TLA (cm²)				
Linear	-176.7118	-	3.6599*	-
Quadratic	-38.8708	-	0.6331ns	0.0132 ^{ns}
Sigmoidal	-	141.9468*	666.3588*	31.5924*
Exponential	-	-	-	-
TNL				
Linear	1.0890 ^{ns}	-	0.0564*	-
Quadratic	-0.3687 ^{ns}	-	0.0884*	-0.0001 ^{ns}
Sigmoidal	-	88.1591*	12.3858*	44.6322*
Exponential	-	-	22.7510*	0.0037*
HS (cm)				
Linear	-1.1801 ^{ns}	-	0.1654*	-
Quadratic	6.1252*	-	0.005 ^{ns}	0.007*
Sigmoidal	-	203.9372*	70.8206*	73.456*
Exponential	-	-	-	-
DS (mm)				
Linear	1.0646*	-	0.0203*	-
Quadratic	1.6960*	-	0.0065 ^{ns}	0.00006 ^{ns}
Sigmoidal	-	260.5549 ^{ns}	14.099 ^{ns}	122.0635*
Exponential	-	-	7.3769*	0.0056*
LMR (cm)				
Linear	12.8724*	-	0.0875*	-
Quadratic	13.3904*	-	0.0761 ^{ns}	0.00004 ^{ns}
Sigmoidal	-	207.0409 ^{ns}	62.6259 ^{ns}	163.7977 ^{ns}
Exponential	-	-	28.7558*	0.0168*

* Significance according to t-student test ($P < 0.05$). ^{ns} No significance.

TLA: total leaf area; TNL: total number of leaves; HS: height of the stem; DS: diameter of the stem; LMR: Length of the main root.

TABLE 3. Goodness-of-fit criteria for the studied mathematical functions.

Functions	R^2	Adjusted R^2	MSE	SEE	AIC	BIC
TLA (cm²)						
Linear	0.97	0.95	1954.47	44.20	128.8012	130.2559
Quadratic	0.99	0.97	860.14	29.32	119.6875	121.6271
Sigmoidal	0.99	0.98	694.88	26.36	117.129	119.0686
Exponential	-	-	-	-	-	-
TNL						
Linear	0.97	0.94	0.55	0.74	30.77351	32.22823
Quadratic	0.98	0.95	0.46	0.68	29.50542	31.44504
Sigmoidal	0.97	0.95	0.42	0.65	27.72089	29.17561
Exponential	0.97	0.94	0.56	0.75	31.74271	33.68234
HS (cm)						
Linear	0.97	0.94	5.08	2.25	57.3758	58.83502
Quadratic	0.99	0.97	1.96	1.40	46.69788	48.63751
Sigmoidal	0.99	0.97	2.00	1.41	46.93079	48.87041
Exponential	-	-	-	-	-	-
DS (mm)						
Linear	0.97	0.94	0.07	0.27	6.904349	8.359069
Quadratic	0.98	0.95	0.05	0.23	4.155049	6.094676
Sigmoidal	0.98	0.95	0.05	0.24	4.578776	6.518402
Exponential	0.93	0.86	0.17	0.41	16.86562	18.32034
LMR (cm)						
Linear	0.95	0.90	2.46	1.56	48.67703	50.12545
Quadratic	0.95	0.88	2.71	1.64	50.58916	52.52879
Sigmoidal	0.95	0.88	2.73	1.65	50.66634	52.60597
Exponential	0.88	0.75	5.94	2.43	59.248	60.70272

TLA = total leaf area; TNL = total number of leaves; HS = height of the stem; DS = diameter of the stem; LMR = Length of the main root.

(Tab. 3). However, the adjustment of the function was made based on the significance of the parameters of the functions (Tab. 2). The results of the growth behavior of the DS measurements were similar to those reported by Criollo *et al.* (2019) in coffee plants grown in the municipality of La Unión (Nariño, Colombia) as well as in the study by Souza *et al.* (2016). Similar descriptions were also recorded in the growth of LMR in coffee plants (Silveira *et al.*, 2014).

The results of the fitted growth curves reported in this study may be used to hold the recommendations of the agronomic management of the coffee plants during the nursery stage of growth. These particularly include the fertilization, pest, disease, and weed controls focused during the 60 DAT to guarantee suitable conditions before the start of accelerated growth, where the growth of coffee plants are increased (Rendón, 2020; Sadeghian & Ospina-Penagos, 2021).

Description of the growth of coffee plants at nursery stage

The growth curves simulated with the adjusted mathematical functions correctly described the growth behavior of coffee plants under nursery conditions. In this way, a coffee plant at the 180 DAT, according to the adjusted functions, registered average values of 520 cm² for TLA, 11.0 for TNL, 30.23 cm for HS, 4.87 mm for DS, and LMR of 28.80 cm. These results of growth variables as TLA (240 to 438 cm²), TNL (10 leaves) and HS (14 until 21 cm) have been reported for *C. arabica* cvs. Caturra and Castillo Tambo plants during the nursery stage that were established with 50% shading net under climate conditions from Cuba and Colombia (Encalada *et al.*, 2016; Castillo and Andrade, 2021). In this way, the growth variables evaluated were confirmed as adequate criteria for the selection of plant material with good growth performance for establishment under field conditions. They were associated with physiological

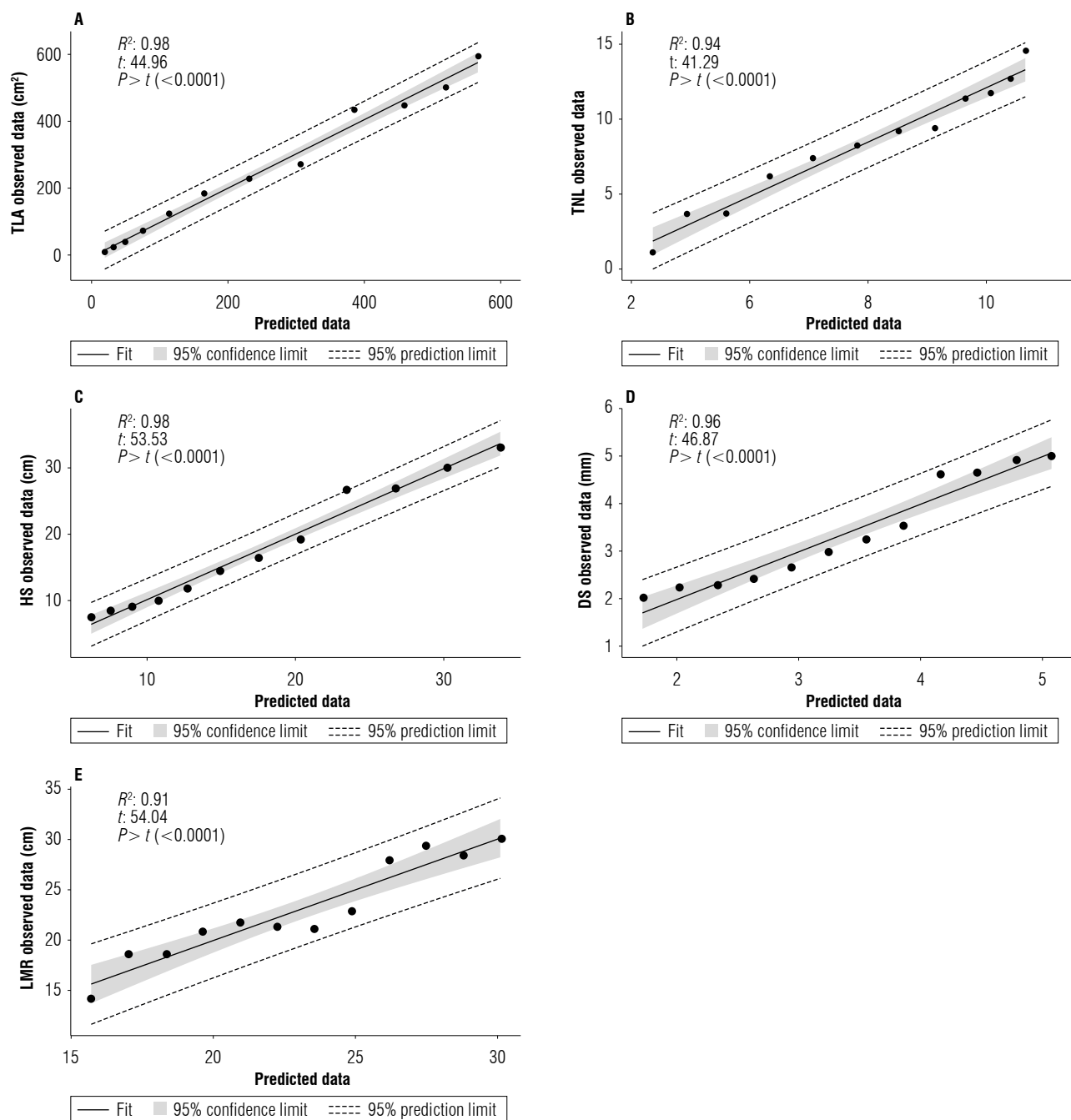


FIGURE 2. Relationships between data predicted by each fitted mathematical function and observed data for growth measurements of coffee plants. A) total leaf area (TLA), B) total number of leaves (TNL), C) height of the stem (HS), D) diameter of the stem (DS), and E) length of the main root (LMR).

processes, such as water and nutrient uptake and carbon metabolism in the plants. However, the dry mass also was a measure that allows us to understand the growth of the plants under particular climate conditions (Tatagiba *et al.*, 2010; Rodríguez-López *et al.*, 2014; Maradiaga *et al.*, 2017).

The regression coefficient was significantly different from zero, based on the 1% t-test, obtaining R^2 values between 0.91 to 0.98 (Fig. 2). These results showed that the functions

do not overestimate or underestimate the estimated data for each growth measurement evaluated in this study (Unigarro-Muñoz *et al.*, 2015). Therefore, the TLA, TNL, HS, DS, and LMR of coffee plants under the climatic conditions of this study can be simulated and predicted with these functions.

The average absolute growth rate \hat{G} , used to analyze the growth of coffee plants is shown in Figure 3 for each growth

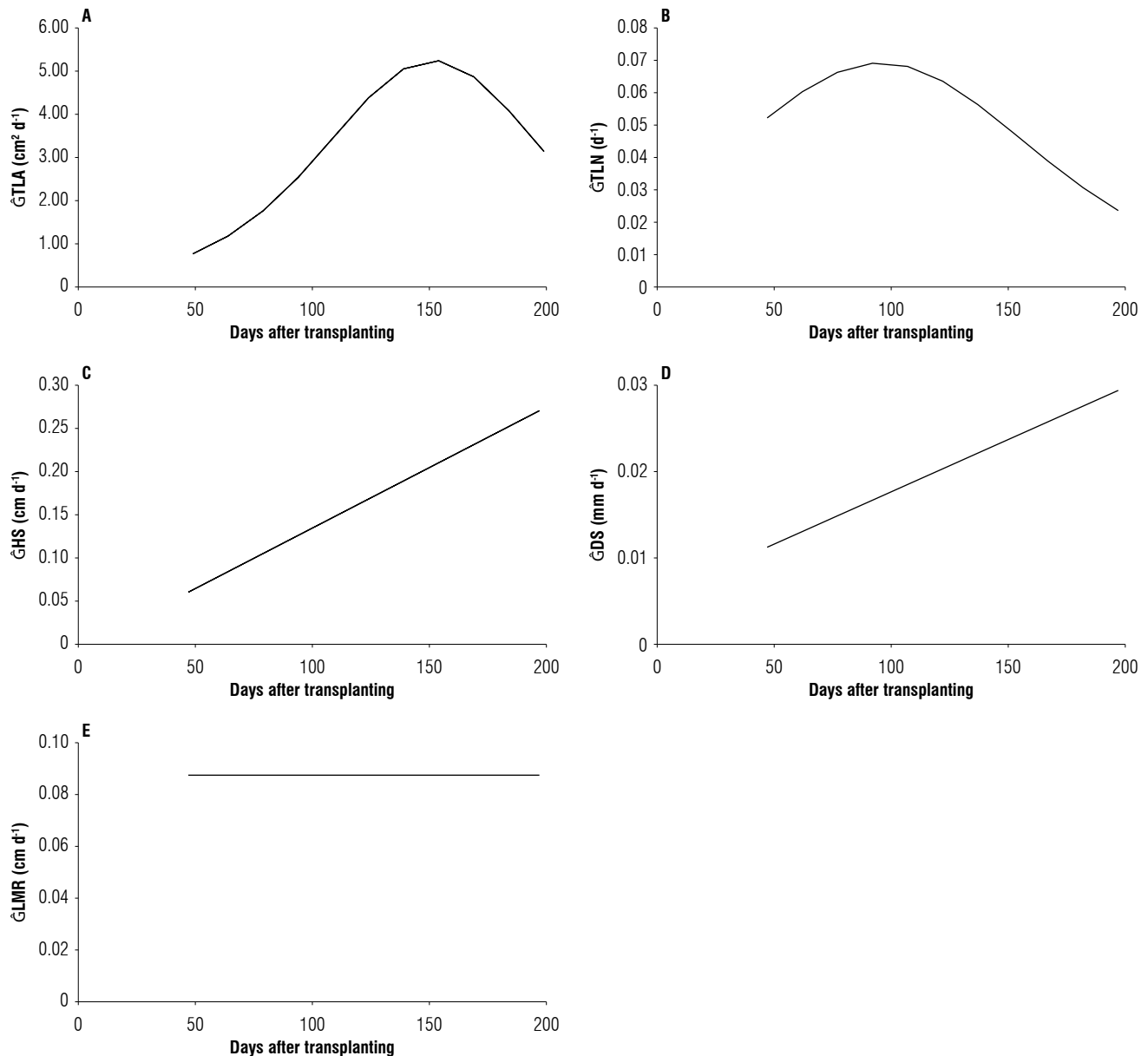


FIGURE 3. Mean absolute growth rate (\hat{G}) of coffee seedlings. A) mean absolute growth rate for the total leaf area (\hat{G}_{TLA}); B) mean absolute growth rate for the total leaf number (\hat{G}_{TLN}); C) mean absolute growth rate for the stem height (\hat{G}_{HS}); D) mean absolute growth rate for the diameter of the stem (\hat{G}_{DS}), and E) mean absolute growth rate for the length of the main root (\hat{G}_{LMR}).

measurement evaluated in this study. The average absolute growth rate of total leaf area (\hat{G}_{TLA}) throughout the study was $3.31 \text{ cm}^2 \text{ d}^{-1}$, with representative increases in size ($4.90 \text{ cm}^2 \text{ d}^{-1}$) after 120 to 150 DAT, showing a decrease from 160 DAT ($4.47 \text{ cm}^2 \text{ d}^{-1}$). The opposite occurred with the average absolute growth rate of the total number of leaves (\hat{G}_{TLN}), since its representative increases were from 30 to 90 DAT (between 0.052 and 0.069 leaves d^{-1}) with average values throughout the study of 0.055 leaves d^{-1} . The average absolute growth rates of height (\hat{G}_{HS}) and stem diameter

(\hat{G}_{DS}) increased proportionally during the study, from 0.060 to 0.25 cm d^{-1} for \hat{G}_{HS} and between 0.011 and 0.030 mm d^{-1} for \hat{G}_{DS} . While, for the average growth rate of the main root length- \hat{G}_{LMR} there was no increase over time, reporting average values throughout the study of 0.087 cm d^{-1} (Fig. 3). These trends on the increase of \hat{G} from 150 DAT, particularly on the \hat{G}_{TLA} ($5 \text{ cm}^2 \text{ d}^{-1}$) have been reported by Encalada *et al.* (2016) in coffee cultivar Caturra plants established in a nursery stage with 50% shading net under climate conditions of Cuba.

Conclusions

In general, the fitted sigmoidal growth curves for TLA, TNL and HS, and linear for the DS and LMR reported in this study, adequately describe the growth of coffee plants of the variety Cenicafé 1 in the nursery stage. The statistical criteria guaranteed a highest degree of fit and selection of each mathematical functions for simulating the growth measures evaluated in the coffee plants. Finally, the estimate of the growth parameters reported at 180 DAT with mathematical functions may be selection criteria to ensure adequate plant material for establishment under field conditions.

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Conflict of interest statement

The authors declare that there is no conflict of interests regarding the publication of this article.

Author's contributions

AFLB, CR, JRRS, LIQ and CU developed and designed the methodology. AFLB, CR and JRRS performed the field experiment. AFLB, LIQ and CU contributed to the data analysis and result description. AFLB and HBL wrote the draft. All authors reviewed and approved the manuscript.

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