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A new perspective on plant growth analysis - a computational tool for resource-constrained environments. Uma nova perspectiva sobre a análise do crescimento de plantas - uma ferramenta computacional para recursos limitados.

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Abstract

Plant growth, a complex interplay of physiological processes, is fundamentally driven by photosynthetic carbon assimilation. While technological advancements have enabled the quantification of numerous plant growth variables, including carbon gain and associated metrics, the high cost of specialized equipment often limits their accessibility to researchers. To address this challenge, we developed a user-friendly computer program that assists in plant growth analysis by fitting mathematical models to experimental data on leaf area, total dry mass and leaf dry mass. The program estimates key growth variables such as Crop Growth Rate (CGR), Relative Growth Rate (RGR), Net Assimilation Rate (NAR), Specific Leaf Area (SLA), Leaf Area Ratio (LAR) and Leaf Area Duration (LAD).
Keywords: Fit equation to data. Mathematical models. Plant growth indicators. Partition and allocation of photosynthates. Photosynthesis.

Resumo

O crescimento das plantas, uma interação complexa de processos fisiológicos, é fundamentalmente impulsionado pela assimilação fotossintética de carbono. Embora os avanços tecnológicos tenham permitido a quantificação de inúmeras variáveis de crescimento das plantas, ainda há carência de ferramentas que facilitem os estudos em certas áreas. Para enfrentar esse desafio, desenvolvemos um programa de computador de fácil utilização que auxilia na análise do crescimento das plantas. O programa estima os indicadores fisiológicos do crescimento, como a Taxa de Crescimento da Cultura (CGR), Taxa de Crescimento Relativo (RGR), Taxa de Assimilação Líquida (NAR), Área Foliar Específica (SLA), Razão de Área Foliar (LAR) e Duração da Área Foliar (LAD.
Palavras-chave: Ajuste de equações a dados. Modelos matemáticos. Indicadores do crescimento de plantas. Partição e alocação de fotossintatos. Fotossíntese.

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Introduction

The difference between CO_2 fixed photosynthetically and that lost through respiration and photorespiration represents a net gain in plant mass, driving growth. This accumulated mass is distributed among various plant organs such as leaves, stems, branches, roots, inflorescences and fruits. These plant parts are utilized in human and animal nutrition, provide energy sources and enrich and protect the soil with organic matter. When positive, this difference signifies carbon sequestration, contributing to the reduction of atmospheric CO_2 excess and mitigating the impact of the concerning global warming (BEJAGAM et al., 2024; WESTHOFF; WEBER, 2024; IPCC, 2023; IPCC, 2014; COX et al., 2000; HALL et al., 1985).

Therefore, quantifying this mass gain is of significant economic and ecological importance. The growth analysis technique offers a cost-effective method for quantifying the net gain of CO_2 by measuring the difference between CO_2 fixed during photosynthesis and that lost through respiration and photorespiration. This approach enables researchers to efficiently track carbon assimilation, providing valuable insights into plant growth dynamics without the need for expensive equipment. Its affordability and practicality make it an ideal option for research in resource-limited settings, supporting efforts to enhance productivity and sustainability in developing regions (PORTES et al., 2022; HUNT, 1978; KVET et al., 1971).

Growth can be analyzed from various perspectives. For example, one can measure plant height growth, diameter growth, or even the growth of specific plant parts or organs (allometric growth). However, the most common approach involves measuring the phytomass growth of plant communities, both in greenhouses and field conditions.

Despite being a classic technique (BLACKMAN, 1919), plant growth analysis remains and will continue to be highly valuable for quantifying growth and determining the partitioning of photosynthates among various plant organs. This technique supports researchers working towards grain or forage production by aiding in the selection of optimal genotypes. Furthermore, it quantifies carbon sequestration and assesses plant responses to the application of soil or foliar treatments (PORTES et al., 2022; PORTES, 2020; PORTES; CARVALHO, 2009; PORTES et al., 2000; MORGAN, 1988; KVET et al., 1971).

The analysis involves fitting mathematical equations to data on leaf area (LA), total dry matter (TDM) and leaf dry matter (LDM), collected throughout the plants' life cycle. The best-fitting equations (those with the highest correlation coefficient and significant F-test adjustment) are then used to estimate instantaneous values of physiological growth indicators: Crop Growth Rate (CGR), Relative Growth Rate (RGR), Net Assimilation Rate (NAR), Leaf Area Ratio (LAR), Specific Leaf Area (SLA) and Leaf Area Duration (LAD).

As an additional option in growth analysis, this program was developed to facilitate and expedite the analysis of different genotypes or the study of genotype-environment interactions.

This study aimed to describe the development of a computer program and its usage procedures, utilizing data collected from a greenhouse experiment. To perform growth analysis with the proposed program, data on leaf area, total and leaf dry matter and their corresponding collection dates or plant age are required.

Material and methods

Calculation of instantaneous growth indicators using equations fitted to data. In this work, the main equations that best fit plant growth data were used. The development of the work encompassed**:** fitting equations to the collected data**,** determining correlation coefficients (r) and conducting F-tests (ANOVA). With the calculated F-value available, the significance of the fit is assessed by comparing it to the tabulated F-value, usually found as annexes in statistical books (LARSON; FARBER, 2009). The fit is significant when the calculated F-value exceeds the tabulated F-value. To locate the tabulated F-value, input the regression degrees of freedom (DF) value in the horizontal line of the table and the residual degrees of freedom in the column.

The analysis is based on fitting equations to the data using the least squares method (SPIEGEL, 1984). Equations were fitted to data on leaf area (LA), total dry matter (TDM) and leaf dry matter (LDM) as a function of plant age (X) in days after emergence (DAE). The equations used included lineal, sigmoid or logistic, quadratic, cubic, quadratic exponential and cubic exponential models (Table 1).

Table 1 - Equations fitted to LA, TDM and LDM data (y) as a function of sample collection dates - DAE (X) and their versions for fitting

	Equation	**Version for fitting the equation**
Lineal	$y = a_0 + a_1X$	$y = a_0 + a_1X$
Logistic	$y = C/(1+A*\exp(-a1*X))$	$Ln((C/y)-1) = LnA - a1X$ for $y > 0$, $y < C$
Quadratic	$y = a_0 + a_1X + a_2X^2$	$y = a_0 + a_1X + a_2X^2$
Cubic	$y = a_0 + a_1X + a_2X^2 + a_3X^3$	$y = a_0 + a_1X + a_2X^2 + a_3X^3$
Quadratic Exponential	$y = c*\exp*(a_1X + a_2X^2)$	$\ln y = \ln c + a_1X + a_2X^2$ make $\ln y = Z$ and $\ln c = a_0$
Cubic Exponential	$y = c*\exp*(a_1X + a_2X^2 + a_3X^3)$	$\ln Y = \ln c + a_1X + a_2X^2 + a_3X^3$ make $\ln y = Z$ and $\ln c = a_0$

The resulting systems of lineal equations were solved using various methods, including determinants (Kramer, Sarrus and Leibniz) (LARSON; FARBER, 2009; MILONE, 2004; RUGGIERO; LOPES, 1988; PEREIRA; ARRUDA 1987; SPIEGEL, 1984; DORN; MCCRACKEN 1978; LANDSBERG, 1977; HUNT; PARSONS, 1974).

The equation that best fits the analyzed data is determined by two criteria: Highest correlation or determination coefficient: This indicates the strength of the relationship between the independent variable (plant age) and the dependent variable (LA, TDM, or LDM). Significant fit by the F-test: This statistical test assesses whether the regression model provides a significant improvement in predicting the dependent variable compared to a simple mean model.

By considering both the coefficient of determination and the F-test, the most suitable equation for describing the growth trends of the plant characteristics can be identified.

Once the best-fitting equation for the TDM data was determined, it was used to calculate the Crop Growth Rate (CGR). CGR was obtained by applying the derivative of the TDM equation with respect to plant age (X), expressed in days after emergence (DAE) (Table 2). Crop Growth Rate (CGR) = dTDM/dX. where dTDM/dX represents the derivative of the TDM equation.

The other instantaneous growth indicators were calculated using the CGR equation and the best-fitting equations for leaf area and leaf dry matter (Table 3). These include: Relative Growth Rate (RGR): RGR = (dTDM/dx) / TDM, defined as the rate of increase in biomass per unit of biomass present at any given instant. Net Assimilation Rate (NAR): NAR = (dTDM/dx) / LA, representing the rate of dry matter accumulation per unit leaf area. Specific Leaf Area (SLA): SLA = LA / LDM, indicating the leaf area per unit of leaf dry mass. Leaf Area Ratio (LAR): LAR = LA / TDM,

representing the leaf area per unit of total plant dry mass. Leaf Area Duration (LAD): $\int_{x0}^{xn} f(x)dx = \frac{h}{2}\{f(x_0) + 2[f_{(x_1)} + f(x_2) + .. + f(x_n)]\}$.$CO_2$ fluxes (Pn = Net Photosynthesis): Pn was calculated according to Portes et al. (2022).

Table 2 - Equations fitted to total dry mass (TDM = y) data and their respective derivatives. X = collection dates in the Julian calendar (days after plant emergence)

	Equation	***d*Y/dx; y = LA or TDM or LDM**
Lineal	$y = a_0 + a_1X$	$dY/dx = a_1$
Logistic	$y = C/(1+A*\exp(-a_1*X))$	$dY/dx = C*A*a_1*Exp^{(-a1*X)} / (1 + A*Exp^{(-a1.X)2})$
Quadratic	$Y = a_0 + a_1X + a_2X^2$	$dY/dx = a_1 + 2a_2X$
Cubic	$Y = a_0 + a_1X + a_2X^2 + a_3X^3$	$dY/dx = a_1 + 2a_2*X + 3a_3*X^2$
Quadratic Exponential	$Y = c*exp*(a_1X + a_2X^2)$	$dY/dx = c*(Exp^{(a1X + a2X2)}) *(a_1 + 2a_2X)$
Cubic Exponential	$Y = c*exp*(a_1X + a_2X^2 + a_3X^3)$	$dY/dx = c*Exp^{(a1X + a2X2 + a3X3)} *(a_1 + 2a_2*X + 3a_3*X^2)$

Table 3 - Plant growth indicators estimated from the equations fitted to the data

CGR	**RGR**	**NAR**	**LAR**	**SLA**	**CO_2 flow =TFL = Pn**
*d*TDM/dx	CGR/TDM	CGR/LA	LA/TDM	LA/ADM	$P_n = \text{NAR} * \left(\frac{C}{100}\right) * \left(\frac{44}{12}\right) * \left(\frac{1}{44}\right) * \left(\frac{1}{86400}\right) * (10^6)$
$P_n = \text{NAR} * 0.434027778$ para C = 45%					

Calculation of average growth indicators using classical equations

The classic equations used to calculate average growth indicators are found in the literature (KVET et al., 1971; RADFORD, 1967).

Average Crop Growth Rate (*TCC*). The dash over the acronym signifies an average value. The average dry matter production rate or average growth rate (Crop Growth Rate) in a time interval T1 to T2 is given by the equation:

$$\overline{CGR} = {(TDM2 - TDM1)}\Big/{(T2 - T1)}$$

Where:

TDM1 = Total Dry Matter at time T1; TDM2 = Total dry matter at time T2; and T2 - T1 = Time interval.

The mean Relative Crop Growth Rate (*TCR*) is defined as the rate of increase in biomass per unit of biomass present and is given by the equation (FISHER, 1921):

This equation calculates the average relative growth rate over the time interval between T1 and T2.

$$\overline{RGR} = {(lnTDM2 - lnTDM1)}\Big/{(T2 - T1)}$$

Where:

ln = logarithm natural

This equation calculates the average relative growth rate over the time interval between T1 and T2.

The Net Assimilation Rate (*NAR*) expresses the rate of increase in dry matter between two dates (T1, T2) in relation to the leaf area. The Leaf Area (LA) represents an estimate of the size of the assimilatory apparatus.

$$(\overline{NAR} = \frac{(TDM2 - TDM1)}{(LA2 - LA1)} * \frac{(lnLA2 - lnLA1)}{(T2 - T1)} = (weight.area^{-1}.time^{-1})$$

Leaf area duration

LAD (Leaf area duration) = $\int_{x0}^{xn} f(x)dx = \frac{h}{2}\{f(x_0) + 2[f_{(x_1)} + f(x_2)+..+f(x_n)]\}$

The integration was carried out using the trapezoidal summation method, with h representing the height and f(x) being the result of the equation for each value of X (DAE).

Program testing

To test the program, we analyzed the data presented in Table 4. The table contains data on leaf area (LA) in $m^2\ m^{-2}$, total dry matter (TDM) and leaf dry matter (LDM) in $g\ m^{-2}$. These data were collected from an experiment conducted in a greenhouse at the Institute of Biological Sciences (ICB) at the Federal University of Goias (UFG). The experiment was conducted in 10 L pots of soil fertilized according to soil chemical analysis.

Table 4 - Values of Leaf Area (LA), Total Dry Matter (TDM) and Leaf Dry Matter (LDM) at different collection dates (DAE =X) of bean plants (pl). Average of 4 repetitions

DAE – (X)		**26**	**33**	**41**	**47**	**56**	**68**
LA(Y)	$m^2\ m^{-2}$	0.75	1.88	2.51	2.81	2.51	0.37
TDM (Y1)	$g\ m^{-2}$	38.30	102.00	164.20	203.70	289.60	207.20
LDM (Y2)	$g\ m^{-2}$	25.50	60.60	89.30	86.00	64.00	14.70

In this experiment we have 6 observations or data pairs (n).

The first step in the program is to enter data in Form 1. All data collected on each date must be entered into this form.

After entering and saving the data, the next step involves fitting equations to the LA, TDM and LDM data as a function of collection dates (DAE = X) (Table 1). Subsequently, the physiological growth indicators are calculated from these best-fitting equations (Tables 2 and 3).

The coefficients or parameters for the linear, logistic, quadratic and quadratic exponential equations were calculated using determinants. This involved constructing a matrix and applying the Kramer rule and the Sarrus rule (PEREIRA; ARRUDA, 1987; SPIEGEL, 1984). For the cubic and cubic exponential equations, the coefficients were calculated using the Leibniz rule (https://matrixcalc.org/).

The correlation coefficient (r) is calculated as the square root of the ratio between the explained variation and the total variation (LARSON; FARBER, 2009; SPIEGEL,1984).

$$Explained\ variation = \sum(\hat{Y} - \bar{Y})^2$$

$$Unexplained\ variation = \sum(Y - \hat{Y})^2$$

$$r = \pm\sqrt{\frac{explained\ variation}{total\ variation}}$$

Total variation = explained variation + unexplained variation.

Where:

$\hat{Y}$ is the Y estimated or calculated by the fitted equation, $\bar{Y}$ is the average value of the Y values observed either in the laboratory or field.

This equation for r can be applied to both lineal (such as lineal regression) and non-linear (quadratic, cubic, quadratic exponential, cubic exponential) functions (SPIEGEL, 1984). The analysis of variance was carried out according to Table 5.

Table 5 - ANOVA for regressions

Source of Variation - SV	Degrees of freedom - DF	Sum of Squares -SS	Medium square - MS	F =
Regression Reg	Degree eq.	$\sum_{j=1}^{n}\left(\hat{Y}j - \bar{Y}\right)^2$	$\sum_{j=1}^{n}\frac{\left(\hat{Y}j - \bar{Y}\right)^2}{GL}$	MSReg/ MSRes
Residue Res	n - k	$\sum_{j=1}^{n}\left(\hat{Y}j - Yj\right)^2$	$\frac{\sum_{j=1}^{n}\left(\hat{Y}j - Yj\right)^2}{n-k}$	
Total	n - 1	$\sum_{j=1}^{n}(Yj - \bar{Y})^2$		

n = number of data pairs. In the example (table 1), n = 6;
k is the number of coefficients, including the constant term (for example c in the quadratic exponential equation), in the regression formula. Ex: k would be 2 for the lineal equation $Y = a0 + a_1X$, as it has the two coefficients a_0 and a_1. It would be 3 for the quadratic: $Y = a_0 + a_1X + a_2X^2$ and quadratic exponential ($Y = c*Exp(a_1*X + a_2*(X**^2))$;
It would be 4 for the cubic exponential equation. Degree of freedom (DF) of regression corresponds to the degree of the equation (Degree eq), first degree would be 1, second 2 and so on.

By fitting equations to growth data and calculating r and F values, researchers can develop robust models that accurately predict plant growth. These models then serve as the foundation for estimating crucial physiological growth indicators, providing valuable insights into plant performance and resource utilization (Tables 2 and 3).

Results and discussion

The equations that best fit the data on Leaf Area, Total and Leaf Dry Matter were quadratic, cubic, quadratic exponential and cubic exponential, based on their correlation coefficients (r) and significance levels (p) (Table 6).

Table 6 - The best-fitting equations for LA, TDM and ADM data, determined by correlation coefficients and significance using the F-test

Equation	**Leaf área**	**r**	**F**	**p**
Quadratic	y = -8.12327487 + (0.47108674 X) + (-0.00507602 X^2)	0.99	129.3	≤ 0.01
Cubic	y = -4.06317818 + (0.17819644 X) + (0.0015283 X^2) + (-0.00004689 X^3)	0.99	242.9	≤ 0.01
Quadratic Exponential	y = 0.00101187765110373 * Exp ((0.35598118 X) + (-0.00394095 X^2))	0.98	48.2	≤ 0.01
Exponential Cubic	y = 0.04564117 * Exp(+ (0.08115142 X) + (0.00225613 X^2) + (-0.00004399 X^3))	0.99	35.9	≤ 0.05
Equation	**Total Dry Mass**	**r**	**F**	**p**
Quadratic	y = -478,30540864 + (24.92636353 X) + (-0.21470086 X^2)	0.96	16.9	≤ 0.05
Cubic	y = 451.39233206 + (-42.14087082 X) + (1.29758451 X^2) + (-0.01073603 X^3)	0.97	31.8	≤ 0.01
Quadratic Exponential	y = 0.40535 * Exp ((0.23062018 X) + (-0.00204173 X^2))	0.99	96.3	≤ 0.01

Cubic Exponential	y = 0.14546306 * Exp (+ (0.30454982 X) + (- 0.00370875 X^2) + (0.00001183 X^3))	0.95	17.8	≤ 0.01
Equation	**Leaf Dry Mass**	**r**	**F**	**p**
Quadratic	y = -230.38631237 + (13.8216298 X) + (-0.15081952 X^2)	0.99	71.8	≤ 0.01
Cubic	y = -375.0570393 + (24.2579955 X) + (-0.38614699 X^2) + (0.00167064 X^3)	0.99	79.5	≤ 0.01
Quadratic Exponential	y = 0.07664 * Exp ((0.31588983 X) + (-0.0035079 X^2))	0.99	304.7	≤ 0.01
Cubic Exponential	y = 0.0452461 * Exp (+ (0.35390774 X) + (- 0.00436516 X^2) + (0.00000609 X^3))	0.99	51.3	≤ 0.01

The observed and calculated values for LA, TDM and LDM using the fitted equations are presented below (Figures 1,2,3):

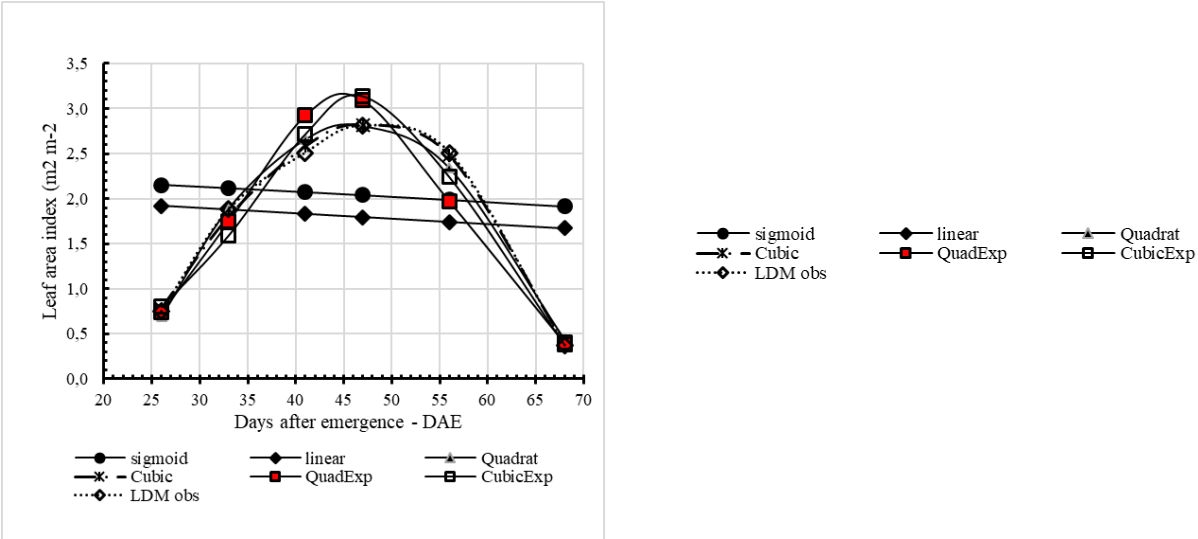


Figure 1 - Curves showing the calculated and observed values of leaf area index using the equations fitted to the data.

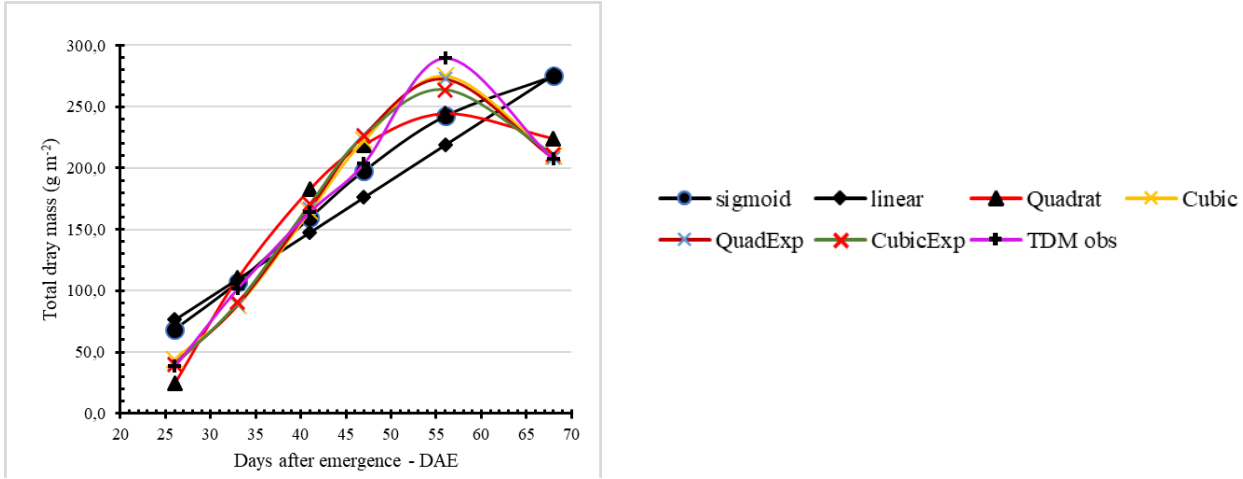


Figure 2 - Curves showing the calculated and observed values of total dry matter using the equations fitted to the data.

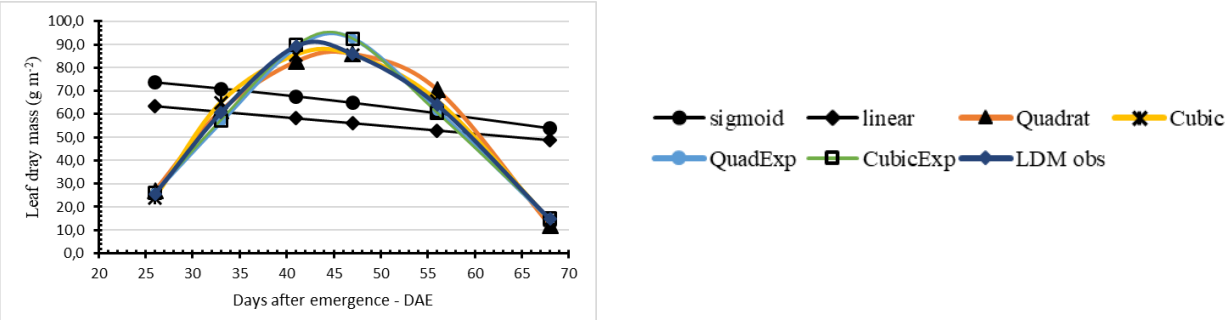


Figure 3 - Curves showing the calculated and observed values of leaf dry matter using the equations fitted to the data.

Growth indicators

The values of instantaneous growth indicators (CGR, RGR, NAR, LAR, SLA and pn) (Table 7) were obtained using the equations presented in Table 2 and 3.

Table 7 - Instantaneous growth indicators CGR, RGR, NAR, LAR, SLA, LAD and Pn estimated from the fitted equations.

dates	**26**	**33**	**41**	**47**	**56**	**68**
	CGR (g $m^{-2}dia^{-1}$)					
Quadratic	13.800	10.800	7.300	4.700	0.900	-4.300
Cubic	3.560	8.425	10.119	8.684	2.184	-14.599
Quadratic Exponential	5.099	8.493	10.578	8.793	0.531	-9.794
Cubic Exponential	5.441	8.939	10.261	7.776	0.134	-7.539
	RGR (g $g^{-2}dia^{-1}$)					
Quadratic	0.5600	0.100	0.040	0.0020	0.0036	-0.019
Cubic	0.0810	0.096	0.061	0.0390	0.0079	-0.069
Quadratic Exponential	0.1245	0.096	0.063	0.0387	0.0019	-0.047
Cubic Exponential	0.1357	0.098	0.060	0.0343	0.0006	-0.036
	NAR (g $m^{-2}dia^{-1}$)					
Quadratic	19.840	5.680	2.750	1.690	0.380	-9.730
Cubic	4.571	4.689	3.921	3.079	0.883	-38.547
Exponential Quadratic	6.919	4.860	3.615	2.844	0.269	-24.402
Exponential Cubic	6.815	5.604	3.772	2.479	0.060	-19.877
	LAR ($m^{-2}g^{-1}$					
Quadratic	0.0280	0.0170	0.0150	0.0130	0.0010	0.0020
Cubic	0.0176	0.0204	0.0156	0.0126	0.0090	0.0018
Quadratic Exponential	0.0180	0.0197	0.0175	0.0136	0.0072	0.0019
Cubic Exponential	0.0199	0.0180	0.0159	0.0139	0.0085	0.0018
	SLA (m^2 g^{-1})					
Quadratic	0.0260	0.0310	0.0320	0.0330	0.0330	0.0360
Cubic	0.0325	0.0276	0.0301	0.0330	0.0376	0.0265
Quadratic Exponential	0.0279	0.0309	0.0330	0.0334	0.0320	0.0270
Cubic Exponential	0.0306	0.0280	0.0303	0.0339	0.0370	0.0260
	pn (µmol m^{-2} s^{-1})					
Quadratic	8.994	2.573	1.248	0.767	0.170	-4.411
Cubic	2.072	2.126	1.778	1.396	0.400	-17.474
Quadratic Exponential	3.137	2.201	1.639	1.289	0.122	-11.061
Cubic Exponential	3.089	2.541	1.710	1.124	0.027	-9.010
	LAD total					
Quadratic	87.000					
Cubic	87.610					
Quadratic Exponential	83.211					
Cubic Exponential	83.910					
Classic method	83.945					

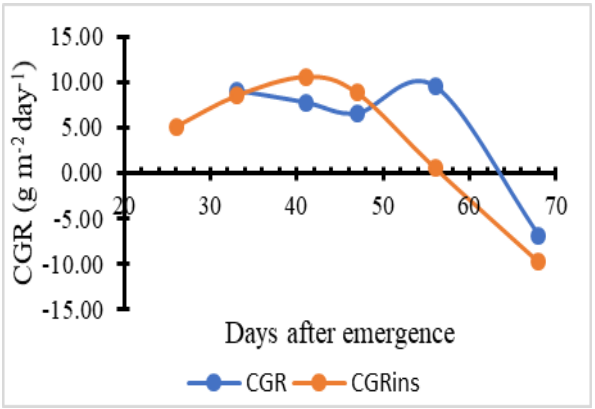
Table 8 contains the values of the mean growth indicators *CGR*, *RGR*, *NAR*, *LAR*, *SLA*, *LAD* estimated from classical equations.

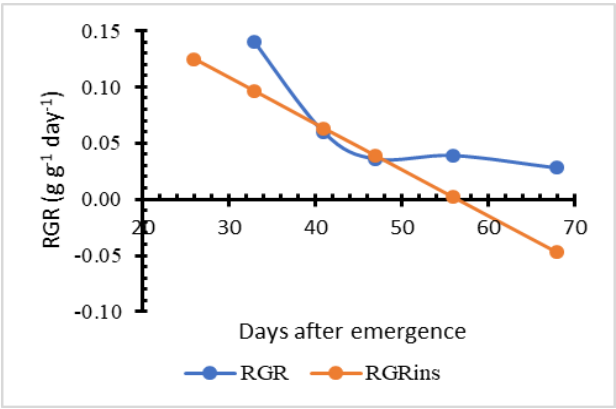
It is interesting to compare the results obtained for the growth indicators in instantaneous values and those estimated by classical equations (Table 8).

Table 8 – Average growth indicators *CGR*, *RGR*, *NAR*, *LAR*, *SLA*, *LAD* and Pn estimates from classical equations.

dates	**26**	**33**	**41**	**47**	**56**	**68**
	CGR (g $m^{-2}day^{-1}$)					
	x	9.1000	7.7750	6.5833	9.5444	-6.8667
	RGR (g $g^{-1}day$)					
	x	0.1399	0.0595	0.0359	0.0391	-0.0279
	NAR (g $m^{-2}day^{-1}$)					
	x	7.4004	3.5668	2.4776	3.5919	-6.1432
	LAR (m^2 g^{-1})					
	0.0196	0.0184	0.0153	0.0138	0.0087	0.0018
	SLA (m^2 g^{-1})					
	0.0294	0.0310	0.0281	0.0327	0.0390	0.0252
	LAD (m^2 day^{-1})					
	x	9.205	17.560	15.960	23.940	17.280
	LAD total =					
	83.945					

To facilitate visualization, the graphs are presented in Figure 4. The observed differences indicate that the values obtained from the equations fitted to the LA, TDM and LDM data are more reliable due to the high correlation coefficients and significance found for the aforementioned equations.





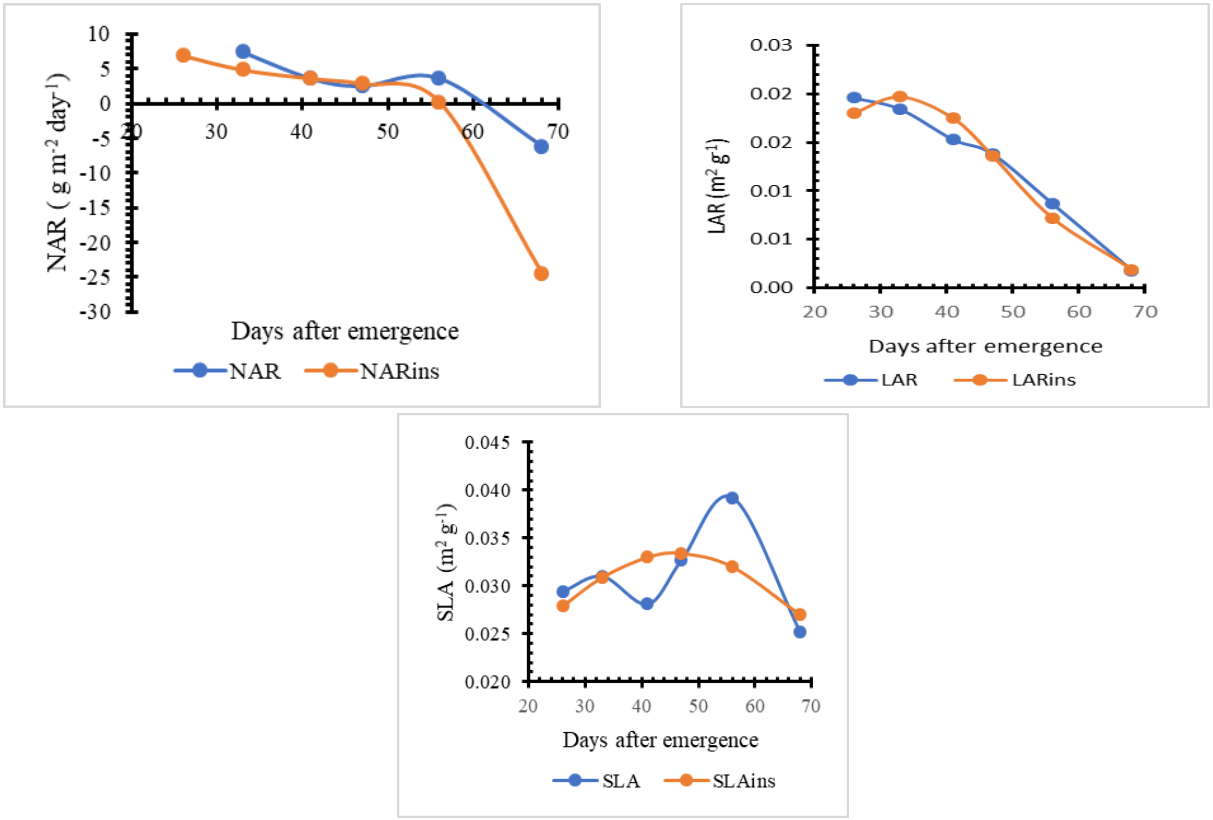


Figure 4 - Comparisons between growth indicators calculated using classical formulas (mean values) and those estimated from equations fitted to data from TDM, LA, LDM (instantaneous values). Crop Growth Rate (CGR), Relative Growth Rate (RGR), Net Assimilate Rate (NAR), Leaf Area Rate (LAR), Specific Leaf Area Rate (SLR). (ins = instantaneous values).

Growth analysis is a classic technique that remains important due to the need to measure plant growth when subjected to some treatment, both biotic or abiotic. It is through photosynthesis that all organic matter is produced, leading to plant development and growth (BRAZ et al., 2005; PORTES et al., 2020).

Conclusions

This work presents an auxiliary computer program that is highly useful for performing growth analysis calculations. It was observed that equations such as quadratic exponential and cubic exponential, when fitted to data on leaf area, total dry matter and leaf dry matter, exhibited high correlation coefficients and demonstrated significant F-test results. Consequently, the estimated growth indicators derived from these fitted equations are highly realistic and reliable. The program significantly enhances the researcher's workflow by facilitating rapid data processing and enabling the simultaneous analysis of multiple treatments. While the program offers the option of calculating growth indicators using classic equations from the literature, it is evident that these methods can introduce substantial errors. Therefore, employing equations fitted to the specific dataset is preferable for obtaining more accurate and precise results. While measuring photosynthesis is a widely used technique to estimate the productive efficiency of plants in carbon assimilation, its measurements are limited to quantifying CO_2 flow to a restricted leaf area. When extrapolated to larger areas, significant errors can occur. Growth analysis, on the other hand, involves collecting several plants from the

experimental area and calculating average values for analyzed variables, typically resulting in low errors or coefficients of variation

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