PAB
Pesquisa Agropecuária Brasileira

ISSN 1678-3921

Journal homepage: www.embrapa.br/pab

For manuscript submission and journal contents, access: www.scielo.br/pab

Crop Science/ Original Article

Study of dry matter accumulation in maize hybrids using nonlinear models

Abstract – The objective of this work was to study the growth curves of total dry matter (TDM) accumulation of the P30F33 and GNZ2004 maize hybrids using nonlinear models. The used models were: Brody, Gompertz, logistic, Meloun I, Meloun II, Michaelis-Menten, modified Michaelis-Menten, Mitscherlich, Richards, Schnute, von Bertalanffy, and Weibull. To estimate the parameters, the least squares method and the Gauss-Newton convergence algorithm were used. The adjusted coefficient of determination, the residual standard deviation, and the Akaike information criterion were used as criteria to evaluate the goodness of fit of the models. The Gauss-Newton method did not converge for 8 out of the 12 models studied. The Gompertz, logistic, von Bertalanffy, and Weibull models were considered appropriate for fitting the dry matter accumulation of the evaluated maize hybrids. The estimated TDM was 34,700 and 31,980 kg ha^{-1} for GNZ2004 and P30F33, respectively. The maximum daily gain in TDM was 483 and 381 kg ha^{-1}, respectively, reached at 83 days after emergence, with TDM stabilization at 121 and 129 days after emergence. The logistic model is the best one to describe the TDM accumulation of the GNZ2004 and P30F33 maize hybrids.

Index terms: *Zea mays*, modelling, plant growth, regression analysis.

Estudo do acúmulo de matéria seca em híbridos de milho por meio de modelos não lineares

Resumo – O objetivo deste trabalho foi estudar as curvas de crescimento de acúmulo de matéria seca total (MST) dos híbridos de milho P30F33 e GNZ2004, por meio de modelos não lineares. Os modelos utilizados foram: Brody, Gompertz, logístico, Meloun I, Meloun II, Michaelis-Menten, Michaelis-Menten modificado, Mitscherlich, Richards, Schnute, von Bertalanffy e Weibull. Para estimar os parâmetros, foram utilizados o método de mínimos quadrados e o algoritmo de convergência de Gauss-Newton. O coeficiente de determinação ajustado, o desvio-padrão residual e o critério de informação de Akaike foram utilizados como critérios para avaliar a qualidade de ajuste dos modelos. O método de Gauss-Newton não convergiu para 8 dos 12 modelos estudados. Já os modelos Gompertz, logístico, von Bertalanffy e Weibull foram considerados adequados para ajustar o acúmulo de matéria seca dos híbridos de milho avaliados. A MST estimada foi 34.700 e 31.980 kg ha^{-1} para GNZ2004 e P30F33, respectivamente. O ganho diário máximo de MST foi 483 e 381 kg ha^{-1}, respectivamente, tendo sido atingido aos 83 dias após emergência, com estabilização da MST aos 121 e 129 dias após emergência. O modelo logístico é o melhor para descrever a MST acumulada dos híbridos de milho GNZ20004 e P30F33.

Termos para indexação: *Zea mays*, modelagem, crescimento de plantas, análise de regressão.

Isolina Aparecida Vilas Bôas[1 ✉],
Felipe Augusto Fernandes[1]
Tales Jesus Fernandes[1] and
Joel Augusto Muniz[1]

[1] Universidade Federal de Lavras, Instituto de Ciências Exatas e Tecnológicas, Departamento de Estatística, Campus Universitário, Caixa Postal 3037, CEP 37200-900 Lavras, MG, Brazil. E-mail: linavilasboas@gmail.com, fernandesfelipest@gmail.com, tales.jfernandes@ufla.br, joamuniz@ufla.br

✉ Corresponding author

Received
August 07, 2022

Accepted
July 04, 2023

How to cite
VILAS BÔAS, I.A.; FERNANDES, F.A.; FERNANDES, T.J.; MUNIZ, J.A. Study of dry matter accumulation in maize hybrids using nonlinear models. **Pesquisa Agropecuária Brasileira**, v.58, e03077, 2023. DOI: https://doi.org/10.1590/S1678-3921.pab2023.v58.03077.

Introduction

Maize (*Zea mays* L.) is one of the most produced grains worldwide (Duarte et al., 2021). In Brazil, it is the second most produced (Milho, 2022), representing a crop of great importance to agribusiness since it is used as human and animal feed and as raw material for industrial production (Souza et al., 2018). In this scenario, it is essential to develop strategies to increase grain yield by studying yield-related factors such as the production, accumulation, and nutrient transport of dry matter (Hou et al., 2020; Liu et al., 2020a, 2020b), which is obtained after the plant's moisture is removed and contains fiber, protein, minerals, carbohydrates, and nutrients (Embrapa Gado de Corte, 2016).

Several growth models have been used to analyze crops in terms of development, nutrient accumulation, dry matter production, and yield, assisting in their management and improvement (Lacasa et al., 2021). According to Fernandes et al. (2015), in studies of the growth patterns of agricultural crops, linear models are the most commonly used. However, Jane et al. (2020) concluded that plant growth and associated factors generally follow a sigmoidal curve, which is in alignment with Vitti & Mira (2020), who found that dry matter accumulation is well characterized by this type of curve.

Therefore, due to their sigmoid functions, nonlinear models may be more suitable for growth evaluations, standing out for their parsimony and practical interpretation of parameters, which facilitate the understanding of the phenomenon under study (Fernandes et al., 2017, 2019; Ribeiro et al., 2018). In the literature, nonlinear growth curves have been shown to provide biological information on plants, such as growth rates and biomass accumulation (Prado et al., 2013). In addition, some authors have reported satisfactory results when using nonlinear models to study dry matter accumulation (Lima et al., 2019; Cunha et al., 2020). Woli et al. (2017) found significant differences in dry matter accumulation when comparing two popular hybrids of each of the five era-decades from 1960 to 2000, showing how these hybrids have changed morphologically over the last 60 years (Elmore et al., 2019).

The objective of this work was to study the growth curves of total dry matter (TDM) accumulation of the P30F33 and GNZ2004 maize hybrids using nonlinear models.

Materials and Methods

The maize hybrids evaluated for TDM accumulation were P30F33 and GNZ2004, with a high grain yield and a high forage production, respectively, according to the data of Borges (2006).

The experiment was conducted in a randomized complete block design, with four replicates, in a 2x11 split-plot factorial arrangement, with the two hybrids and 11 phenological stages, as plots and sublots, respectively. The subplots consisted of four rows of 5.0 m each spaced at 0.8 m, and the data were collected from the two central rows. The total number of experimental units was 88. More details on the experimental area are found in Borges (2006).

For sample collection, plants in the 11 phenological stages, based on the phenotypic aspects that reflect the physiological processes that occur during plant development (Vitti & Mira, 2020), were cut close to the ground and transported to the laboratory as soon as possible. Each whole plant was divided into stem, leaves, straw, cobs, and grains, which were dried, at 70°C, until reaching a constant mass. To calculate TDM, the dry matter of these five parts was summed and expressed in kg ha^{-1}.

TDM accumulation data were described using nonlinear models, whose equations are shown in Table 1. Some models present an inflection point represented by the β_4 parameter, others have a fixed inflection point, while others do not, such as the Brody and Michaelis-Menten models. Overall, the β_2 parameter had no biological interpretation, being considered an integration constant, but represented the moment when half of the maximum accumulation was reached by the Michaelis-Menten model.

The model parameters were estimated by the least squares method. In case of a non-explicit solution of normal equations, the iterative process was used (Fernandes et al., 2017), specifically that of Gauss-Newton. The initial values adopted in the execution of the iterative process were chosen based on exploratory data analysis.

After fitting the models, the assumptions of normality of the residuals, homoscedasticity, and the independence of residuals were checked using the tests of Shapiro-Wilk, Breusch-Pagan, and Durbin-Watson, respectively, at 5% probability.

The criteria used to determine the best model were the adjusted coefficient of determination (R^2_{adj}), the residual standard deviation (RSD), and the Akaike information criterion (AIC) according to the following equations:

$$R^2_{adj} = 1 - \left[\frac{(1-R^2)(n-i)}{(n-p)}\right]$$

$$RSD = \sqrt{MSE}$$

$$AIC = -2\ln L(\hat{\theta}) + 2p$$

Table 1. Nonlinear equation adjusted to the total dry matter accumulation data of the GNZ2004 and P30F33 maize (*Zea mays*) hybrids.

Model	Equation[(1)]
Brody	$y_i = \beta_1\left(1-\beta_2 e^{(-\beta_3 x_i)}\right) + \varepsilon_i$
Gompertz	$y_i = \beta_1 e^{\left(-e^{\beta_3(\beta_2 - x_i)}\right)} + \varepsilon_i$
Logistic	$y_i = \dfrac{\beta_1}{\left(1+e^{\beta_2(\beta_3 - x_i)}\right)} + \varepsilon_i$
Melon I	$y_i = \beta_1 - \beta_2 e^{(-\beta_3 x_i)} + \varepsilon_i$
Melon II	$y_i = \beta_1 - e^{(-\beta_2 - \beta_3 x_i)} + \varepsilon_i$
Michaelis-Menten	$y_i = \dfrac{\beta_2 {\beta_3}^{\beta_4} + \beta_1 {x_i}^{\beta_4}}{{\beta_3}^{\beta_4} + {x_i}^{\beta_4}} + \varepsilon_i$
Modified Michaelis-Menten	$y_i = \dfrac{\beta_1 x_i}{x_i + \beta_2} + \varepsilon_i$
Mitscherich	$y_i = \beta_1\left(1 - e^{(\beta_3\beta_2 - \beta_3 x_i)}\right) + \varepsilon_i$
Richards	$y_i = \dfrac{\beta_1}{\left(1+e^{(\beta_2 - \beta_3 x_i)}\right)^{\frac{1}{\beta_4}}} + \varepsilon_i$
Schnut	$y_i = \dfrac{\beta_1}{\left(1+\beta_4 e^{(\beta_3\beta_2 - x_i)}\right)^{\frac{1}{\beta_4}}} + \varepsilon_i$
von Bertalanffy	$y_i = \beta_1\left(\dfrac{1-e^{\beta_3(\beta_2 - x_i)}}{3}\right)^3 + \varepsilon_i$
Weibull	$y_i = \beta_1 - \beta_2 e^{\left(-e^{\beta_3} {x_i}^{\beta_4}\right)} + \varepsilon_i$

[(1)]The variables used in the equations were: y_i, the i-th observed value of dry matter content (kg ha^{-1}); β_1, the asymptotic value or maximum dry matter content of maize, i.e., dry matter maximum weight; β_3, the point when the dry matter accumulation growth curve reaches maximum acceleration; x_i, the day after emergence; and ε_i, the random error associated with the i-th observation, assumed to have a normal distribution, constant variance, and to be independent, i.e., $\varepsilon_i \sim N(0, \sigma^2)$.

where R^2 is the square root of the correlation between the predicted and the observed values; p is the number of parameters of the model; i is equal to 1 or 0, representing the presence or absence of an intercept of the regression curve, respectively; MSE is the mean square of the residuals; and $\ln L(\hat{\theta})$ is the natural log of the likelihood function of the estimated parameters.

The best model was considered the one with the lowest RSD and AIC values and the highest R^2_{adj}.

The statistical analysis was carried using the following packages of the R software, version 4.0.5 (R Core Team, 2021): car, version 3.1-1; lmtest, version 0.9-39; nlme, version 3.1-152; nls, version 2.0-0; qpcR, version 1.4-1; and rsq, version 2.5.

Results and Discussion

Twelve models were adjusted to the TDM accumulation data of the two maize hybrids, totaling 24 equations. The Gauss-Newton method did not converge for the Brody, Meloun I, Meloun II, Michaelis-Menten, modified Michaelis-Menten, Mitscherlich, Richards, and Schnute models. The Gompertz, logistic, von Bertalanffy, and Weibull models were checked for assumptions, meeting those of the normality of residuals, homoscedasticity, and the independence of residuals (p>0.05) (Table 2). Therefore, for these four models, the obtained parameter estimates were reliable (Table 3), meaning that the inferences made from them were valid.

The β_1 estimates of the von Bertalanffy model resulted in the highest maximum TDM accumulation of the GNZ2004 and P30F33 hybrids. In addition, the β_1 estimates of the Gompertz, logistic, von Bertalanffy,

Table 2. P-values of the Shapiro-Wilk, Durbin-Watson, and Breusch-Pagan tests used to check the assumptions of the fitted nonlinear models for total dry matter accumulation of the GNZ2004 and P30F33 maize (*Zea mays*) hybrids.

Hybrid	Model	Shapiro-Wilk	Durbin-Watson	Breusch-Pagan
GNZ2004	Gompertz	0.728	0.764	0.642
	logistic	0.192	0.760	0.685
	von Bertalanffy	0.817	0.456	0.400
	Weibull	0.178	0.644	0.588
P30F33	Gompertz	0.825	0.398	0.123
	logistic	0.665	0.298	0.133
	von Bertalanffy	0.438	0.580	0.128
	Weibull	0.803	0.576	0.283

and Weibull models were significantly higher than those reported in the literature for other maize hybrids, overestimating the maximum TDM accumulation. Azevedo et al. (2020), Klein et al. (2018), Menezes et al. (2018), and Silva et al. (2018), for example, found lower values of 13,840, 16,421.60, 19,666.56, and 27,095 kg ha^{-1} TDM accumulation, respectively. This difference could be attributed to the fact that the hybrids studied here are early and have a shorter height, which allow of a greater number of plants per hectare, increasing their dry matter (Borges, 2006). Vitti & Mira (2020) added that closer planting rows increase TDM accumulation because of a better use of light and of water and nutrients, as well as of a better distribution of the plants in the area.

However, caution is necessary when using TDM data as a function of days after emergence (DAE) since the time of occurrence of physiological events in plants may vary among different hybrids, mainly due to genetic and environmental factors.

The results of the R^2_{adj}, RSD, and AIC of the Gompertz, logistic, von Bertalanffy, and Weibull models, which showed a good fit, are presented in Table 3. The logistic model was considered the best one due to its lower values of RSD and AIC and higher values of R^2_{adj}. According to Soares et al. (2014), the logistic model adequately described the growth curve of TDM accumulation of the CSVW80007 and CSVW80147 maize hybrids, whereas the exponential model better represented their growth cycle, which was shorter than that of hybrids CSVW82028 and CSVW82158. In the literature, the logistic model was indicated as the most appropriate for describing the development of other crops such as coffee (*Coffea arabica* L.) by Fernandes et al. (2017), sugarcane (*Saccharum officinarum* L.) by Jane et al. (2020), green dwarf coconut (*Cocos nucifera* L.) by Silva et al. (2021), and garlic (*Allium sativum* L.) by Macedo et al. (2017).

The graphs of the Gompertz, logistic, von Bertalanffy, and Weibull models are presented in the

Table 3. Parameter estimates and respective results of the coefficient of determination (R^2_{adj}), residual standard deviation (RSD), and the Akaike information criterion (AIC) of the fitted nonlinear models for dry matter accumulation of the P30F33 and GNZ2004 maize (*Zea mays*) hybrids.

Hybrid	Model	Parameter	Estimate	R^2_{adj}	RSD	AIC
GNZ2004	Gompertz	β_1	39,800	0.975	1,710.343	202.041
		β_2	76.08			
		β_3	0.03			
	Logistic	β_1	34,700	0.980	1,487.181	198.874
		β_2	82.84			
		β_3	0.06			
	von Bertalanffy	β_1	45,340	0.969	1,874.035	204.060
		β_2	72.74			
		β_3	0.02			
	Weibull	β_1	33,570	0.979	1,531.394	201.515
		β_2	32,510			
		β_3	15.88			
		β_4	3.51			
P30F33	Gompertz	β_1	38,260	0.979	1,332.624	196.462
		β_2	77.35			
		β_3	0.02			
	Logistic	β_1	31,980	0.981	1,250.035	195.064
		β_2	83.28			
		β_3	0.05			
	von Bertalanffy	β_1	44,910	0.976	1,279.040	197.761
		β_2	74.75			
		β_3	0.02			
	Weibull	β_1	31,890	0.980	1,413.013	197.761
		β_2	31,230			
		β_3	12.70			
		β_4	2.79			

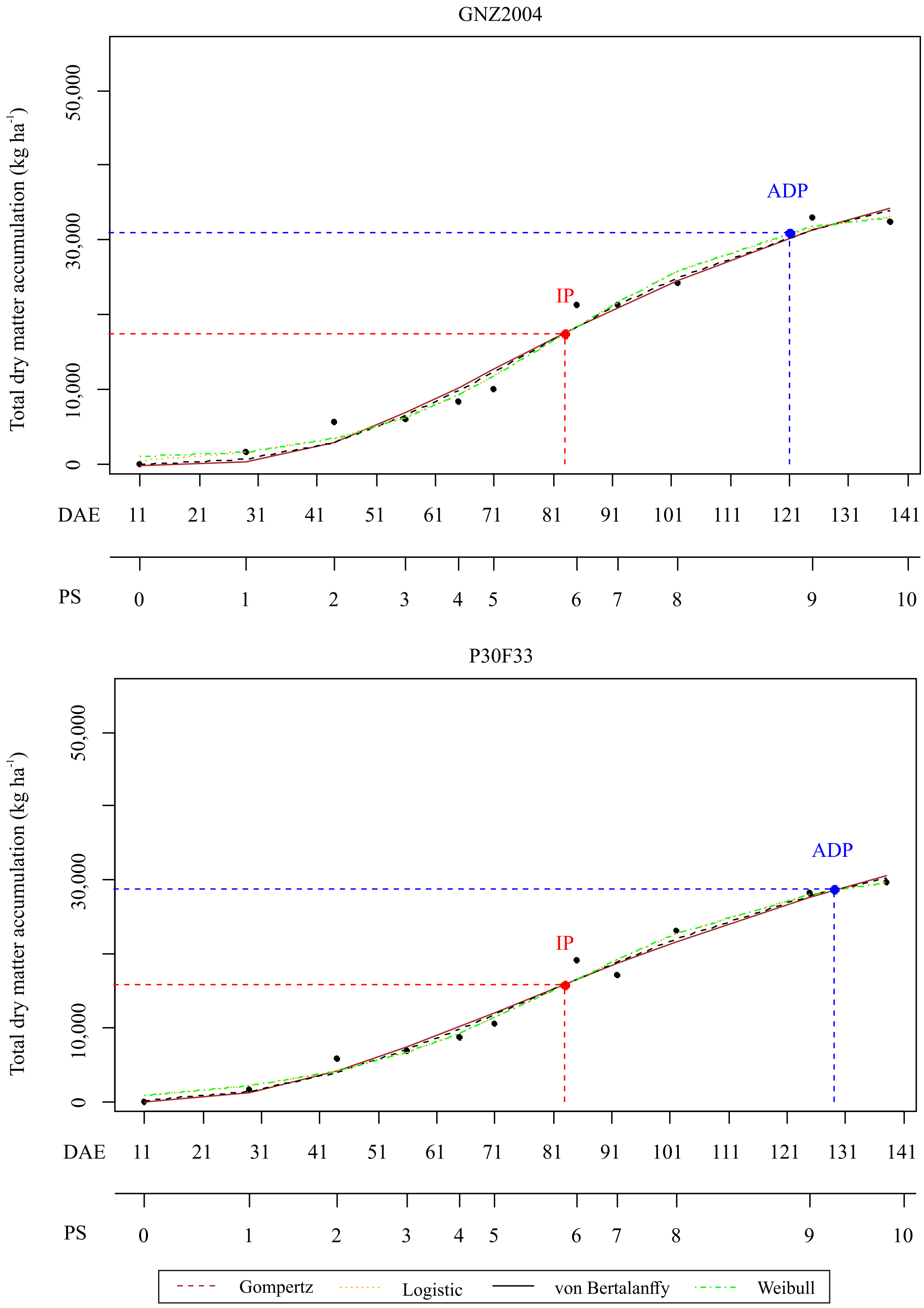

Figure 1. Graphs showing the growth curves of the Gompertz, logistic, von Bertalanffy, and Weibull models obtained for total dry matter accumulation considering days after emergence (DAE) and the respective phenological stages (PS) of the P30F33 and GNZ2004 maize (*Zea mays*) hybrids. The inflexion point (IP) and asymptotic deceleration point (ADP) were also estimated for the logistic model.

Figure 1, showing the sigmoidal shape of the TDM accumulation of GNZ2004 and P30F33.

The absolute growth rate (AGR) was also determined for the logistic model through the first derivative of the model function. AGR allows of analyzing the average growth in kg ha^{-1} of TDM, showing when TDM reaches the maximum gain, i.e., the inflection point, considered the moment of deceleration in dry matter gain (Silva et al., 2021). The maximum daily TDM gain of the GNZ2004 and P30F33 hybrids was 483 and 381 kg ha^{-1}, respectively, achieved at 83 DAE. In another study, Martins et al. (2016) observed that, for hybrid DKB390 PRO 2, daily dry matter gain increased up to 84 DAE, reaching 227 kg ha^{-1}. For the BR106 hybrid, Carvalho et al. (2014) found that the average daily dry matter accumulation rate increased until 89 DAE.

For the logistic model, the asymptotic deceleration point (ADP), defined as the day when mass gain stabilizes and can be considered minimal, can be estimated using the following equation: $ADP = (\beta_3 \times \beta_2 \times 2.2924)/\beta_3$ (Silva et al., 2021). For the GNZ2004 and P30F33 hybrids, ADP occurred at 121 and 129 DAE, respectively. Furthermore, the accumulation of dry matter was practically null. Studying hybrid DKB390 PRO 2, Martins et al. (2016) reported that daily dry matter gain became zero at 112 DAE because the plant slowed its dry matter accumulation as a result of the senescence process. For hybrid BR106, Carvalho et al. (2014) found a dry matter gain up to 122 DAE. Fiorini et al. (2017) concluded that hybrid DKB390 increased its dry matter accumulation until 95 DAE, when it reached physiological maturity, a phenomenon attributed to the constant accumulation of photoassimilates throughout the crop cycle. The highest dry matter production was observed at the maturity stage due to the increase in dry matter after flowering (Duarte et al., 2003). Considering these findings, it can be inferred that the hybrids evaluated in the present study took longer to stabilize total dry matter.

Conclusions

1. The Gompertz, logistic, von Bertalanffy, and Weibull models are suitable to describe the total dry matter (TDM) accumulation of the GNZ2004 and P30F33 maize (*Zea mays*) hybrids.
2. The logistic model is the best one to describe the TDM of the studied hybrids.
3. Both hybrids reach the inflection point approximately on the same day, but TDM daily gain is greater in GNZ2004.
4. Hybrid GNZ2004 stabilizes its TDM gain about a week before P30F33.

Acknowledgments

To Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES), for financing, in part, this study (Finance Code 001); and to Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), for financial support.

References

AZEVEDO, D.M.P. de; MACHADO, F.A.; CARDOSO, M.J.; ARAÚJO NETO, R.B. de; ANDRADE JUNIOR, A.; SÉRVULO, S.P.; SILVA, A.A. **Rendimento de biomassa em consórcio de milho e forrageiras tropicais**. Teresina: Embrapa Meio-Norte, 2020. 14p. (Embrapa Meio-Norte. Comunicado técnico, 256).

BORGES, I.D. **Marcha de absorção de nutrientes e acúmulo de matéria seca em milho**. 2006. 115p. Tese (Doutorado) – Universidade Federal de Lavras, Lavras.

CARVALHO, L.B.; BIANCO, S.; BIANCO, M.S. Estudo comparativo do acúmulo de massa seca e macronutrientes por plantas de *Zea mays* e *Ipomoea hederifolia*. **Planta Daninha**, v.32, p.99-107, 2014. DOI: https://doi.org/10.1590/S0100-83582014000100011.

CUNHA, A.L.B. da; CHAVES, F.C.M.; KANO, C.; BRAGA, Í.G.; OLIVEIRA, M.R. de. Nutrient uptake rate for yard long bean. **Horticultura Brasileira**, v.38, p.175-184, 2020. DOI: https://doi.org/10.1590/S0102-053620200210.

DUARTE, A.P.; KIEHL, J. de C.; CAMARGO, M.A.F. de; RECO, P.C. Acúmulo de matéria seca e nutrientes em cultivares de milho originárias de clima tropical e introduzidas de clima temperado. **Revista Brasileira de Milho e Sorgo**, v.2, p.1-20, 2003.

DUARTE, J. de O.; MATOZZO, M.J.; GARCIA, J.C. **Milho**: importância socioeconômica. 2021. Available at: <https://www.embrapa.br/agencia-de-informacao-tecnologica/cultivos/milho/pre-producao/socioeconomia/importancia-socioeconomica>. Accessed on: Oct. 2 2023.

ELMORE, R.W.; SAWYER, J.E.; BOYER, M.J.; WOLI, K.P. Updating an old paradigm: corn growth, development, dry matter, and nutrient accumulation and partitioning. **Crops & Soils Magazine**, v.52, p.34-58, 2019. DOI: https://doi.org/10.2134/cs2019.52.0213.

EMBRAPA GADO DE CORTE. **O que é matéria seca (MS) dos alimentos? Qual a sua importância? Como determiná-la?** 2016. Available at: <https://cloud.cnpgc.embrapa.br/sac/2016/05/24/o-que-e-materia-seca-ms-dos-alimentos-qual-a-sua-importancia-como-determina-%c2%adla/>. Accessed on: Oct. 10 2021.

FERNANDES, F.A.; FERNANDES, T.J.; PEREIRA, A.A.; MEIRELLES, S.L.C.; COSTA, A.C. Growth curves of meat-producing mammals by von Bertalanffy's model. **Pesquisa Agropecuária Brasileira**, v.54, e01162, 2019. DOI: https://doi.org/10.1590/S1678-3921.pab2019.v54.01162.

FERNANDES, T.J.; MUNIZ, J.A.; PEREIRA, A.A.; MUNIZ, F.R.; MUIANGA, C.A. Parametrization effects in nonlinear models to describe growth curves. **Acta Scientiarum. Technology**, v.37, p.397-402, 2015. DOI: https://doi.org/10.4025/actascitechnol.v37i4.27855.

FERNANDES, T.J.; PEREIRA, A.A.; MUNIZ, J.A. Double sigmoidal models describing the growth of coffee berries. **Ciência Rural**, v.47, e20160646, 2017. DOI: https://doi.org/10.1590/0103-8478cr20160646.

FIORINI, I.V.A.; VON PINHO, R.G.; PEREIRA, H.D.; PIRES, L.P.M.; FIORINI, F.V.A.; RESENDE, E.L. Acúmulo de matéria seca, clorofila e enxofre foliar em milho adubado com diferentes fontes de enxofre. **Journal Bioenergy and Food Science**, v.4, p.1-11, 2017. DOI: https://doi.org/10.18067/jbfs.v4i1.114.

HOU, P.; LIU, Y.; LIU, W.; LIU, G.; XIE, R.; WANG, K.; MING, B.; WANG, Y.; ZHAO, R.; ZHANG, W.; WANG, Y.; BIAN, S.; REN, H.; ZHAO, X.; LIU, P.; CHANG, J.; ZHANG, G.; LIU, J.; YUAN, L.; ZHAO, H.; SHI, L.; ZHANG, L.; YU, L.; GAO, J.; YU, X.; SHEN, L.; YANG, S.; ZHANG, Z.; XUE, J.; MA, X.; WANG, X.; LU, T.; DONG, B., LI, G.; MA, B.; LI, J.; DENG, X.; LIU, Y.; YANG, Q.; FU, H.; LIU, X.; CHEN, X.; HUANG, C.; LI, S. How to increase maize production without extra nitrogen input. **Resources, Conservation and Recycling**, v.160, art.104913, 2020. DOI: https://doi.org/10.1016/j.resconrec.2020.104913.

JANE, S.A.; FERNANDES, F.A.; MUNIZ, J.A.; FERNANDES, T.J. Nonlinear models to describe height and diameter of sugarcane RB92579 variety. **Revista Ciência Agronômica**, v.51, e20196660, 2020.

KLEIN, J.L.; VIANA, A.F.P.; MARTINI, P.M.; ADAMS, S.M.; GUZATTO, C.; BONA, R. do A.; RODRIGUES, M. da S.; ALVES FILHO, D.C.; BRONDANI, I.L. Desempenho produtivo de híbridos de milho para a produção de silagem da planta inteira. **Revista Brasileira de Milho e Sorgo**, v.17, p.101-110, 2018.

LACASA, J.; HEFLEY, T.J.; OTEGUI, M.E.; CIAMPITTI, I.A. A practical guide to estimating the light extinction coefficient with nonlinear models – a case study on maize. **Plant Methods**, v.17, art.60, 2021. DOI: https://doi.org/10.1186/s13007-021-00753-2.

LIMA, K.P.; SILVA, L.M.; VIEIRA, N.M.B.; MORAIS, A.R.; ANDRADE, M.J.B. Modelagem não linear da biomassa seca do feijoeiro cv. Jalo. **Sigmae**, v.8, p.359-369, 2019.

LIU, G.; YANG, Y.; LIU, W.; GUO, X.; XUE, J.; XIE, R.; MING, B.; WANG, K.; HOU, P.; LI, S. Leaf removal affects maize morphology and grain yield. **Agronomy**, v.10, art.269, 2020a. DOI: https://doi.org/10.3390/agronomy10020269.

LIU, W.; HOU, P.; LIU, G.; YANG, Y.; GUO, X.; MING, B.; XIE, R.; WANG, K.; LIU, Y.; LI, S. Contribution of total dry matter and harvest index to maize grain yield – a multisource data analysis. **Food and Energy Security**, v.9, e256, 2020b. DOI: https://doi.org/10.1002/fes3.256.

MACEDO, L.R. de.; CECON, P.R.; SILVA, F.F. e; NASCIMENTO, M.; PUIATTI, G.A.; OLIVEIRA, A.C.R. de.; PUIATTI, M. Bayesian inference for the fitting of dry matter accumulation curves in garlic plants. **Pesquisa Agropecuária Brasileira**, v.52, p.572-581, 2017. DOI: https://doi.org/10.1590/S0100-204X2017000800002.

MARTINS, K.V.; DOURADO-NETO, D.; REICHARDT, K.; FAVARIN, J.L.; SARTORI, F.F.; FELISBERTO, G.; MELLO, S.C. Maize dry matter production and macronutrient extraction model as a new approach for fertilizer rate estimation. **Anais da Academia Brasileira de Ciências**, v.89, p.705-716, 2016. Suppl. 1. DOI: https://doi.org/10.1590/0001-3765201720160525.

MENEZES, J.F.S.; BERTI, M.P. da S.; VIEIRA JUNIOR, V.D.; RIBEIRO, R. de L.; BERTI, C.L.F. Extração e exportação de nitrogênio, fósforo e potássio pelo milho adubado com dejetos suínos. **Revista de Agricultura Neotropical**, v.5, p.55-59, 2018. DOI: https://doi.org/10.32404/rean.v5i3.1645.

MILHO. **Acompanhamento da Safra Brasileira [de] Grãos**: safra 2021/22: décimo segundo levantamento, v.9, n.12, 2022, p.50-62, 2022. Available at: <https://www.conab.gov.br/info-agro/safras/graos/boletim-da-safra-de-graos?start=20>. Acessed on: Mar. 30 2022.

PRADO, T.K.L. do; MUNIZ, J.A.; SAVIAN, T.V.; SÁFADI, T. Ajuste do modelo logístico na descrição do crescimento de frutos de coqueiro anão por meio de algoritmos iterativos MCMC. **Revista Brasileira de Biometria**, v.31, p.216-232, 2013.

R CORE TEAM. **R**: a language and environment for statistical computing. Vienna: R Foundation for Statistical Computing, 2021.

RIBEIRO, T.D.; SAVIAN, T.V.; FERNANDES, T.J.; MUNIZ, J.A. The use of the nonlinear models in the growth of pears of 'Shinseiki' cultivar. **Ciência Rural**, v.48, e20161097, 2018. DOI: https://doi.org/10.1590/0103-8478cr20161097.

SILVA, C.G.M.; RESENDE, Á.V. de; MARTÍNEZ GUTIÉRREZ, A.; MOREIRA, S.G.; BORGHI, E.; ALMEIDA, G.O. Macronutrient uptake and export in transgenic corn under two levels of fertilization. **Pesquisa Agropecuária Brasileira**, v.53, p.1363-1372, 2018. DOI: https://doi.org/10.1590/S0100-204X2018001200009.

SILVA, E.M. da; FRUHAUF, A.C.; SILVA, E.M.; MUNIZ, J.A.; FERNANDES, T.J.; SILVA, V.F. da. Evaluation of the critical points of the most adequate nonlinear model in adjusting growth data of ‘green dwarf’ coconut fruits. **Revista Brasileira de Fruticultura**, v.43, e-726, 2021. DOI: https://doi.org/10.1590/0100-29452021726.

SOARES, E.R.; COUTINHO, E.L.M.; RAMOS, S.B.; SILVA, M.S. da; BARBOSA, J.C. Acúmulo de matéria seca e macronutrientes por cultivares de sorgo sacarino. **Semina: Ciências Agrárias**, v.35, p.3015-3030, 2014. DOI: https://doi.org/10.5433/1679-0359.2014v35n6p3015.

SOUZA, A.E. de; REIS, J.G.M. dos; RAYMUNDO, J.C.; PINTO, R.S. de. Estudo da produção do milho no Brasil: regiões produtoras, exportação e perspectivas. **South American Development Society Journal**, v.4, p.182-194, 2018. DOI: http://doi.org/10.24325/issn.2446-5763.v4i11p182-194.

VITTI, G.C.; MIRA, A.B. de. **Adubação do milho para qualidade e produtividade**. Israel: International Potash Institute, 2020. (Boletim IPI, nº 23).

WOLI, K.P.; SAWYER, J.E.; BOYER, M.J.; ABENDROTH, L.J.; ELMORE, R.W. Corn era hybrid dry matter and macronutrient accumulation across development stages. **Agronomy Journal**, v.109, p.751-761, 2017. DOI: https://doi.org/10.2134/agronj2016.08.0474.