ISSN 0100-2945 DOI: http://dx.doi.org /10.1590/0100-29452022875

Revista Brasileira de Fruticultura

Economy

Description of the peach fruit growth curve by diphasic sigmoidal nonlinear models

Jaqueline Gonçalves Fernandes[1], Édipo Menezes da Silva[2], Thais Destefani Ribeiro[3], Edilson Marcelino Silva[4], Tales Jesus Fernandes[5], Joel Augusto Muniz[6]

Abstract-The aim of this study was to describe the growth curve of "Aurora 1" peaches using fruit height and diameter data over time through diphasic sigmoidal models constructed from eight combinations of the following models: Brody, Gompertz and Logistic. Data were obtained from an experiment carried out in 2005 in the municipality of Vista Alegre do Alto, São Paulo, Brazil. The parameters of models were adjusted by the least squares method using the Gauss-Newton algorithm implemented in the R software. Assumptions of normality, homogeneity and independence of residues were verified based on Shapiro-Wilk, Breush and Pagan and Durbin-Watson tests, respectively. The goodness of fit of models was verified according to the corrected Akaike information criterion (AICc), residual standard deviation (RSD), asymptote adjustment index (AI) and nonlinearity measures. All models adjusted for both fruit height and diameter variables met the assumptions of normality, independence and homoscedasticity of errors. In addition, all of them present good quality of fit to fruit height and diameter data, since they presented AI values close to one and low RSD values and non-linearity measures. However, the double Gompertz (GG) and the Logistic + Gompertz (LG) models presented, respectively, the best quality of fit to fruit height and diameter data in relation to the other models. It could be concluded that all diphasic sigmoidal models evaluated showed good fit to height and diameter data and can be used to describe the growth curve of "Aurora-1" peaches, according to goodness of fit criteria. However, it is important to highlight that GG and LG models presented the best quality of fit and can be selected to describe the height and diameter growth of "Aurora 1" peach fruits, respectively, with maximum expected growth close to 63 mm in height and 48 mm in diameter.

Index terms: Peach Growth, Double Gompertz Model, Logistics + Gompertz Model, Double Sigmoidal Model.

Descrição da curva de crescimento do fruto do pessegueiro via modelos não lineares sigmoidais difásicos

Resumo - Objetivou-se descrever a curva de crescimento de pêssegos "*Aurora 1*", utilizando dados de altura e diâmetro do fruto ao longo do tempo, através de modelos sigmoidais difásicos contruídos a partir de oito combinações dos modelos: Brody, Gompertz e Logístico. Os dados deste estudo foram obtidos de um experimento realizado em 2005, no município de Vista Alegre do Alto, São Paulo, Brasil. Os parâmetros dos modelos foram ajustados pelo método de mínimos quadrados, utilizando o algoritmo de Gauss-Newton, implementados no software R. Os pressupostos de normalidade, homogeneidade e independência dos resíduos foram verificados com base nos testes de Shapiro-Wilk, Breush e Pagan e Durbin-Watson, respectivamente. A comparação dos ajustes dos modelos foi verificada de acordo com o critério de informação de Akaike corrigido (AICc), desvio padrão residual (DPR), índice de ajuste da assíntota (IA) e medidas de não linearidade. Todos os modelos ajustados para ambas as variáveis altura e diâmetro do fruto atenderam às pressuposições de normalidade, independência e homocedasticidade dos erros. Além disso, todos eles apresentam boa qualidade de ajuste aos dados de altura e diâmetro do fruto, visto que apresentaram valores de IA próximos de um e baixos valores do DPR e de medidas de não linearidade. Contudo, o modelo duplo Gompertz (GG) e o modelo Logístico + Gompertz (LG) apresentaram, respectivamente, a melhor qualidade de ajuste aos dados de altura e diâmetro do fruto, em relação aos demais modelos avaliados. Conclui-se que todos os modelos sigmoidais difásicos avaliados apresentaram bom ajuste aos dados de altura e diâmetro e podem ser utilizados para a descrição da curva de crescimento de pêssegos "Aurora-1", segundo os critérios de qualidade de ajuste. No entanto, é importante destacar que os modelos GG e LG apresentaram a melhor qualidade de ajuste e podem ser preferidos para descrever o crescimento em altura e diâmetro dos frutos de pêssego "*Aurora 1*", respectivamente, com crescimento máximo esperado próximos de 63 mm de altura e 48 mm de diâmetro.

Termos para indexação: Crescimento de Pêssego, Modelo Duplo Gompertz, Modelo Logístico + Gompertz, Modelo Sigmoidal Duplo.

Corresponding author:
jaqgonfer@gmail.com

Received: December 18, 2021
Accepted: April 12, 2022

[1]PhD in Agricultural Statistics and Experimentation, Federal University of Lavras (UFLA) Lavras-MG, Brazil. Email: jaqgonfer@gmail.com (ORCID 0000-0002-7236-9718)

[2]PhD student in Agricultural Statistic and Experimentation, Federal University of Lavras (UFLA) Lavras-MG, Brazil. Email: ediposvm01@gmail.com (ORCID 0000-0002-1613-6522)

[3]PhD in Agricultural Statistics and Experimentation, Federal University of Lavras (UFLA) Lavras-MG, Brazil. Email:t.destefani.ribeiro@gmail.com (ORCID 0000-0002-6402-5202)

[4]PhD in Agricultural Statistics and Experimentation, Professor at the Federal University of Lavras (UFLA) Lavras-MG, Brazil. Email:edilsonmg3@hotmail.com (ORCID 0000-0002-2800-3495)

[5]PhD in Agricultural Statistics and Experimentation, Professor at the Federal University of Lavras (UFLA) Lavras-MG, Brazil. Email: tales.jfernandes@ufla.br (ORCID 0000-0002-1457-9653)

[6]PhD in Agricultural Statistics and Experimentation, Professor at the Federal University of Lavras (UFLA), Lavras-MG, Brazil. Email: joamuniz@ufla.br (ORCID 0000-0002-1069-4136)

Introduction

Peach tree (*Prunus persica L. Batsch*) is native to China belonging to the family Rosaceae, subfamily *Prunoideae* and genus *Prunus* (RASEIRA, et al., 2014). According to Faostat (2019), the largest peach producing countries are: China, Spain, Italy and United States, with China accounting for 58% of world production. Brazil occupies the 14th position, with insufficient production for domestic consumption, with imports occurring in some periods of the year. According to IBGE (2020), Brazil produces 201.9 thousand tons of peach and the states with the highest production are: RS, SP, SC, MG, PR and ES. Rio Grande do Sul accounts for 64% of national production.

One of the most important steps in the peach production process is harvesting. In general, when it is made for immediate consumption, it is desirable that the fruit is at appropriate maturation stage, being resistant to handling and transport, in addition to presenting characteristics that meet the expectations of the final consumer, such as color, texture and flavor.

When production is intended for processing, it is necessary to know the storage time of the fruit in order to define the best harvest time. In this case, the fruit must be firm and have started the maturation process, thus avoiding physiological disturbances, that is, abnormal appearance or flavors. The way of handling post-harvest peach is also very important to ensure fruit quality, which is highly perishable. Even after being harvested, they remain alive, maintaining their normal physiological functions (RASEIRA et al., 2014). Thus, it is essential to know the peach development process to help producers make decisions regarding management in the field and harvest.

The harvest time is still subjectively determined, evaluating the external fruit color and/or size, which is a procedure not standardized among producers (CAVALINI et al., 2006). However, the fruit development stage at harvest will directly influence its quality and post-harvest losses. When harvested unripe or immature, they may not ripen, wrinkle or be of poor quality over time. In addition, when harvested too ripe, the storage and marketing process is impaired and numerous losses can occur. In this sense, a way of describing the fruit development process is through the construction of models based on the study of growth curves, and in this way, obtaining estimates of the parameters of these models that indicate the appropriate harvest point depending on the purpose for which the fruit is intended.

According to Medeiros and Raseira (1998), peach development is characterized by a double sigmoidal growth curve, with three different stages: accelerated seed and endocarp growth; slow growth due to physiological and anatomical changes and, finally, increase in cell volume along with the maturation process. In fact, several authors have already characterized the growth curve of this fruit through graphic description; however, without adjusting models to describe this phenomenon.

The nonlinear models most widely used to describe growth curves with sigmoidal behavior are: Gompertz, Logistic, Richards and Von Bertanlaffy. Silva et. al. (2021) reported that the main difficulty in adjusting such models is linked to the estimates of parameters, which depend on choosing initial values to start the iterative process. In the same work, the authors described all steps of the nonlinear regression analysis, detailing the biological interpretation of parameters applied to fruit growth.

One of the ways to parameterize typical double sigmoidal models is by adding two simple sigmoid functions, called two-phase models (ASCHONITIS et al., 2015; HAU et al., 1993). Several studies have shown satisfactory results when adjusting two-phase models to describe the growth behavior of different fruits, such as nectarine with double Logistic model (ALVAREZ and BOCHE, 1999), coffee using the double Logistic model (FERNANDES et al., 2017) and the double Logistic and double Gompertz models for blackberry fruits (SILVA et al., 2020).

Génard et al. (1991) and Martínez et al. (2017) adjusted some nonlinear double sigmoidal models to peach diameter data; however, without direct biological interpretation of parameters. Garre et al. (2016) adjusted simple nonlinear models to describe peach growth using fruit weight data. Pinzón-Sandoval et. al. (2021) concluded that the Logistic model was the most suitable to describe growth curves using fresh or dry weight and the Gompertz model was the most suitable to describe growth curves using the polar diameter of ‘Dorado’ fruits.

Furthermore, the authors are not aware of any work that has adjusted two-phase models for the study of peach development with estimation of parameters that present biological interpretation. Thus, the aim of this study was to describe the growth curve of “Aurora 1” peaches based on the height and diameter of fruits over time, adjusting nonlinear double sigmoidal models constructed from the combination of Brody, Gompertz and Logistic models.

Material and methods

Data used in this work were obtained from Cunha Júnior (2007) and correspond to measurements of height and diameter of “Aurora 1” peach fruits produced in tropical climate. The experiment was carried out in 2005, in the municipality of Vista Alegre do Alto, near the municipality of Jaboticabal, São Paulo, Brazil. Briefly, 200 branches containing flowers in the stage that precedes, between one or two days, the total flower opening (anthesis), were marked in 15 different plants. Twenty days after this procedure, fruits were collected and immediately taken to the Laboratory of Agricultural Products Technology at FCAV/UNESP, Jaboticabal, São Paulo, Brazil. Every seven days, 30 different fruits were harvested and randomly chosen. Then, their respective height and diameter (mm) were measured, which were performed with the aid of Mebo caliper. Fruit collections lasted until the period of total maturation, being concluded in 118 days after the marking of branches. Thus, height and diameter of peaches were measured in 14 different measurements throughout the fruit development (harvested on days 27, 37, 41, 48, 55, 62, 69, 76, 83 90, 97, 104, 111 and 118 after the marking of branches; Figure 1).

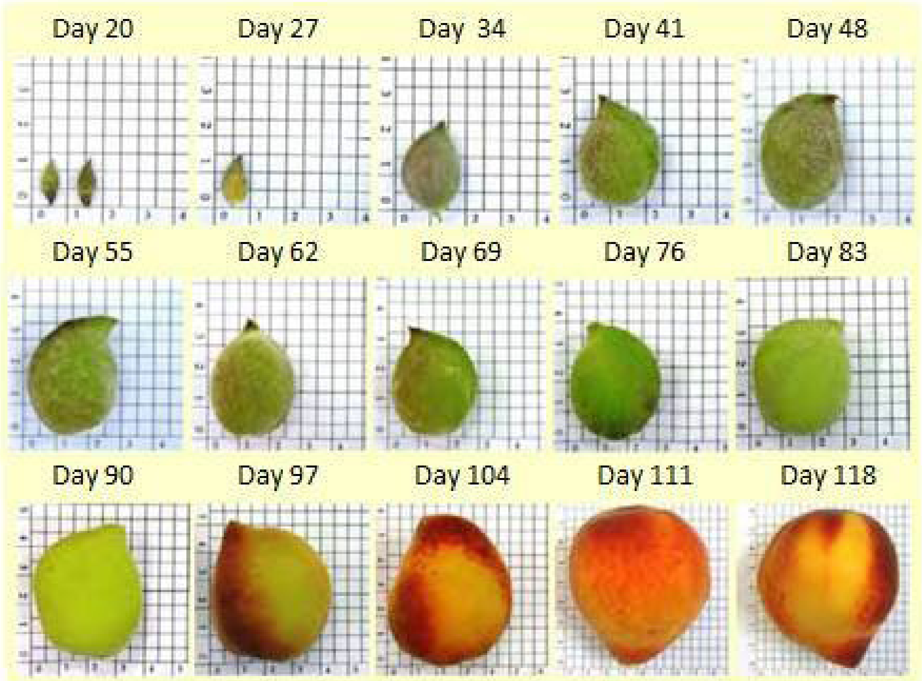

Figure 1. Images of the development over time of "Aurora-1" peaches cultivated in the region of Jaboticabal, São Paulo (adapted from Cunha Junior, 2007).

Two-phase nonlinear models were adjusted: Brody + Gompertz (BG), Brody + Logistic (BL), Gompertz + Gompertz (GG), Gompertz + Brody (GB), Gompertz + Logistic (GL), Logistic + Logistic (LL), Logistic + Brody (LB) and Logistic + Gompertz (LG), described by the following expressions:

$$y_{i\_BG} = A_1[1 - e^{K_1(B_1 - x_i)}] + (A_2 - A_1)e^{-e^{K_2(B_2 - x_i)}} + \varepsilon_i;$$

$$y_{i\_BL} = A_1[1 - e^{K_1(B_1 - x_i)}] + {(A_2 - A_1)}/{1 + e^{K_2(B_2 - x_i)}} + \varepsilon_i;$$

$$y_{i\_GG} = A_1 e^{-e^{K_1(B_1 - x_i)}} + (A_2 - A_1)e^{-e^{K_2(B_2 - x_i)}} + \varepsilon_i;$$

$$y_{i\_GB} = A_1 e^{-e^{K_1(B_1 - x_i)}} + (A_2 - A_1)[1 - e^{K_2(B_2 - x_i)}] + \varepsilon_i;$$

$$y_{i\_GL} = A_1 e^{-e^{K_1(B_1 - x_i)}} + {(A_2 - A_1)}/{1 + e^{K_2(B_2 - x_i)}} + \varepsilon_i;$$

$$y_{i\_LL} = {A_1}/{1 + e^{K_1(B_1 - x_i)}} + {(A_2 - A_1)}/{1 + e^{K_2(B_2 - x_i)}} + \varepsilon_i;$$

$$y_{i\_LB} = {A_1}/{1 + e^{K_1(B_1 - x_i)}} + (A_2 - A_1)e^{-e^{K_2(B_2 - x_i)}} + \varepsilon_i;$$

$$y_{i\_LG} = {A_1}/{1 + e^{K_1(B_1 - x_i)}} + (A_2 - A_1)e^{-e^{K_2(B_2 - x_i)}} + \varepsilon_i$$

where i = each of the observations over time; y_i = i-th observation to be studied; A_1 = maximum response expected in the first growth phase; A_2 = maximum response expected in the second and last growth phase; K_1 and K_2 = maturity indices of the respective growth stages, where higher K_1 and K_2 values indicate need for less time for the fruit to reach its final size; B_1 and B_2 are the abscissa of the inflection point of the curves of each phase (with the exception of the Brody model, which does not present this characteristic), that is, it indicates the maximum growth point; ε_i = random error associated with the model, which is assumed to be independently and identically distributed under Normal distribution with zero mean and constant variance $\varepsilon_j \sim N(0, \sigma^2)$.

To verify assumptions of normality, independence and homoscedasticity of residues, the Shapiro-Wilk (SHAPIRO and WILK, 1965), Durbin-Watson (MORETTIN and TOLOI, 2006) and Breusch and Pagan (BREUSCH and PAGAN, 1979) tests were used, respectively. The selection of the model that best fitted data was performed based on the analysis of the highest asymptote adjustment index value (AI), the lowest residual standard deviation values (RSD) and corrected Akaike information criterion (AICc), in addition to the lowest nonlinearity measure values (K^T= nonlinearity measure of the tangential component and K^N = nonlinearity measures of the normal component).

The estimation of parameters to adjust models was performed using the least squares method, which requires the use of iterative algorithms to solve the system of nonlinear normal equations. Among the algorithms most used in studies on growth curves is the Gauss-Newton algorithm (OLIVEIRA et al., 2013, RIBEIRO et al., 2018). Models were adjusted based on the Gauss-Newton algorithm implemented in the R software (R Core Team, 2020). For this, the *nls* function was used. The AICc value was obtained from the AICc function of the AICcmodavg package (MARC, 2020). Nonlinearity measure values were obtained through the rms.curv function of the *MASS* package (VENABLES and RIPLEY, 2002). The initial values were iteratively found by the *rpanel* package (BOWMAN et al., 2010).

Results and discussion

The smallest height and diameter values observed were 9.53 and 4.83 mm, respectively. The maximum height and diameter values were 57.36 and 50.31 mm, respectively (Table 1). The maximum fruit height and diameter values are important and useful both for producers (BEBBINGTON et al., 2009), and for adjusting nonlinear models. These values were used as the initial value to estimate the upper asymptote of the fruit growth curve (A_2), which presents the height or diameter values of fruits at maturity as a biological interpretation.

Other descriptive measures, such as central tendency of data, which help to describe the variables under study, were also presented in Table 1. The mean fruit height value was 38.57 mm, while the median was 37.89 mm. Regarding fruit diameter, the mean and median values were equal to 29.50 and 26.85 mm, respectively.

The estimates of parameters obtained for each of the models are presented in Table 2. BG, BL, GG, GB, GL, LL, LB and LG models were satisfactorily adjusted to data for both variables under study. However, all adjusted models overestimated fruit height at maturity; that is, all estimates related to parameter A_2 of the evaluated models were higher than the maximum observed height value (57.36 mm). However, BL and LB models were those that presented A_2 values closest to the maximum observed height value (A_2= 59.26mm).

On the other hand, models adjusted for variable fruit diameter showed estimates of parameter A_2 lower than the maximum observed value (50.31 mm). Such results indicate underestimation of the final diameter of fruits using the models under study. Similar results were observed by Fernandes et al. (2017) when evaluating the goodness of fit of two-phase nonlinear models to describe coffee growth. According to Muianga et al. (2016), this fruit diameter underestimation can be attributed to the dehydration that occurs after maturation, contributing to dimension losses. Thus, the diameter at maturity (A_2) is naturally lower than its maximum observed value. However, the LG model was the one that presented the A_2 value closest to the maximum observed diameter value (48.12 mm).

The estimates of parameters B_1 and B_2 indicate the ages (days) at which the fruit reaches the maximum growth rate in each of the phases. In general, it was observed that the ages at which the fruit reached the maximum growth rate were between 16 and 29 days after flowering for the first phase (B_1) and between 81 and 87 days for the second phase (B_2). However, when the two-phase model is composed of the Brody model in the second phase (GB and LB models), it was not possible to identify a clear biological interpretation of the estimates of parameters B_1 and B_2, since it presented B_2 values (GB = 16.82; LB = 17.00) smaller than B_1 values (GB = 82.73; LB = 86.02). In this case, the very characteristic of the Brody model, which differs from the others because it does not present sigmoidal behavior, may be the main justification for estimating parameters B_1 and B_2 without a plausible biological interpretation.

Table 1. Descriptive statistics of variables height and diameter of "Aurora-1" peaches

Variables	Number of collections	Minimum	Maximum	Mean	Median
Height (mm)	14	9.53	57.36	38.57	37.89
Diameter (mm)	14	4.83	50.31	29.50	26.85

Table 2. Estimates of parameters of two-phase nonlinear Brody (B), Gompertz (G) and Logistic (L) models adjusted to height and diameter data of "Aurora-1" peaches

Variable	Model[1]	Parameters					
		A_1	A_2	B_1	B_2	K_1	K_2
Height	BG	36.32	61.55	16.82	82.73	0.0943	0.0529
	BL	34.68	59.26	17.00	86.02	0.1036	0.0819
	GG	35.03	62.43	21.81	81.79	0.1444	0.0485
	GB	25.24	61.55	82.73	16.82	0.0529	0.0943
	GL	33.35	59.76	21.57	85.12	0.1559	0.0754
	LL	32.35	60.37	24.09	84.65	0.2170	0.0690
	LB	24.58	59.26	86.02	17.00	0.0819	0.1036
	LG	34.10	63.79	24.43	81.56	0.2041	0.0436
Diameter	BG	27.78	48.06	17.90	81.69	0.0728	0.1448
	BL	27.53	47.55	17.93	84.55	0.0743	0.2217
	GG	26.70	48.08	25.07	81.20	0.1263	0.1397
	GB	20.28	48.06	81.69	17.90	0.1448	0.0728
	GL	26.42	47.57	24.97	84.12	0.1294	0.2103
	LL	25.91	47.62	28.17	83.85	0.1923	0.2023
	LB	20.02	47.55	84.55	17.93	0.2217	0.0743
	LG	26.22	48.12	28.35	80.90	0.1868	0.1367

[1]BG = Brody + Gompertz; BL = Brody + Logistic; GG = Gompertz + Gompertz; GB = Gompertz + Brody; GL = Gompertz + Logistic; LL = Logistic + Logistic; LB = Logistic + Brody; LG = Logistic + Gompertz.

Parameters K_1 and K_2 can also be biologically interpreted as a maturity index for each of the curves. For variable fruit height, this growth index is slightly higher in the first phase compared to the second phase for most of adjusted models. Fernandes et al. (2017) found result similar to that observed in the present study, where higher coffee fresh matter accumulation rate was observed in the first growth phase compared to the second growth phase.

However, different behavior was observed for most estimates of parameters K_1 and K_2 of adjusted models for variable fruit diameter. In this case, the maturity index was higher in the second growth phase. Furthermore, models composed of the Brody model in the second phase (GB and LB) presented K_1 and K_2 values equal to K_1 and K_2 estimates, respectively, of their model constructed in the inverse form (BG and BL); that is, the K_1 estimate of the GB model is equal to the K_2 estimate of the BG model.

Table 3 describes p-values for normality (Shapiro-Wilk), independence (Durbin-Watson) and homogeneity of variances (Breusch-Pagan) tests for the analysis of residues of all adjusted models. These tests were also used by Muniz et al. (2017) and Ribeiro et al. (2018) to verify assumptions of residues obtained from the adjustment of nonlinear models.

It was observed that all models adjusted for both fruit height and diameter presented p-value greater than 0.05 (Table 3), that is, all adjusted models met the assumptions of normality, independence and homoscedasticity of errors at 5% significance level. In this way, it was possible to compare the adjusted models in order to determine which one best describes the growth of "Aurora-1" peaches.

Height and diameter observations were measured in 14 different collections (fruit development times), that is, in this study, a small sample was collected for each of the variables (Table 1). Thus, the most appropriate would be to use AICc instead of the Akaike information criterion (AIC) as a criterion for selecting the growth curve (BURNHAM and ANDERSON, 2002).

In this sense, the goodness of fit measures of models are presented in Table 4. In general, all models present appropriate adjustment to fruit height and diameter data, since they presented AI values close to one and low RSD, AICc and nonlinearity measure values (K^T and K^N). Similar results were obtained by Fernandes et al. (2017), who adjusted GG and LL models to coffee growth data and observed RSD and AIC values close to those observed in the present study.

Furthermore, the RSD values of adjusted models did not exceed 1.98 mm, which is lower than the RSD value of 2.5 mm observed by Génard et al. (1991) when adjusting the BL model to peach diameter data. In addition, the same authors considered that the BL model presented satisfactory adjustment.

Table 3. p-values for the Shapiro-Wilk normality, Durbin-Watson independence, and Breusch-Pagan homogeneity of variances tests for the analysis of residues of the two-phase Brody (B), Gompertz (G) and Logistic (L) nonlinear models adjusted to height and diameter data of "Aurora-1" peaches

Variable	Model [1]	Shapiro–Wilk	Durbin–Watson	Breusch–Pagan
Height	BG	0.26	0.88	0.17
	BL	0.45	0.66	0.15
	GG	0.14	0.95	0.18
	GB	0.26	0.95	0.17
	GL	0.25	0.88	0.15
	LL	0.38	0.93	0.16
	LB	0.45	0.68	0.15
	LG	0.33	0.85	0.21
Diameter	BG	0.17	0.47	0.28
	BL	0.20	0.22	0.19
	GG	0.45	0.77	0.09
	GB	0.17	0.65	0.21
	GL	0.45	0.75	0.16
	LL	0.48	0.71	0.12
	LB	0.20	0.59	0.36
	LG	0.23	0.67	0.08

1BG = Brody + Gompertz; BL = Brody + Logistic; GG = Gompertz + Gompertz; GB = Gompertz + Brody; GL = Gompertz + Logistic; LL = Logistic + Logistic; LB = Logistic + Brody; LG = Logistic + Gompertz

Table 4. Goodness of fit measures of the two-phase nonlinear Brody (B), Gompertz (G) and Logistic (L) models adjusted to height and diameter data of "Aurora-1" peaches.

Variable	Model [1]	Quality measures [2]				
		AICc	RSD	AI	K^T	K^N
Height	BG	56.39	1.46	0.88	4.7	0.61
	BL	57.26	1.5	0.92	5.04	0.45
	GG	55.85	1.43	0.87	4.46	0.52
	GB	56.39	1.46	0.88	5.04	0.45
	GL	56.37	1.45	0.91	4.77	0.39
	LL	75.13	1.46	0.9	5.05	0.38
	LB	57.26	1.5	0.92	5.04	0.45
	LG	56.44	1.46	0.85	5.03	0.48
Diameter	BG	64.09	1.92	0.98	2.13	0.5
	BL	65.04	1.98	0.99	2.23	0.59
	GG	60.07	1.66	0.98	1.31	0.46
	GB	64.09	1.92	0.98	2.23	0.59
	GL	61.09	1.72	0.99	1.28	0.47
	LL	78.22	1.63	0.99	1.12	0.44
	LB	65.04	1.98	0.99	2.23	0.59
	LG	58.82	1.59	0.98	1.18	0.48

[1]BG = Brody + Gompertz; BL = Brody + Logistic; GG = Gompertz + Gompertz; GB = Gompertz + Brody; GL = Gompertz + Logistic; LL = Logistic + Logistic; LB = Logistic + Brody; LG = Logistic + Gompertz. [2]AICc = corrected Akaike information criterion; RSD = residual standard deviation; AI = asymptote adjustment index; K^T= nonlinearity measure of the tangential component and K^N = nonlinearity measures of the normal component.

The GG model presented the lowest AICc, RSD and K^T values. The same model was also adjusted to describe the pear growth curve by Hurwitz et al. (1991). However, the LG model was the one that best adjusted the diameter data of this fruit. In this case, the LG model presented the lowest AICc, RSD and K^T values.

From the adjustment of these models, it was possible to affirm that the fruit height and diameter measures at the end of the first stage of the growth process were 35.03 mm and 26.22 mm, respectively; while at the end of the second growth stage, values were 62.43 mm and 48.12 mm, respectively. In addition, times after flowering of 22 and 82 days for height and 29 and 81 days for diameter corresponded to the times when fruits reached the maximum growth rate in the first and second stages of the growth process, respectively. Furthermore, the development during the first growth stage was faster for both variables under study, corresponding to 0.14 mm per day for height and 0.19 mm per day for diameter, while the index associated with development in the second stage was 0.05 mm per day for height and 0.14 mm for diameter.

The graphic representation of data together with the illustration of the optimal adjustment of two-phase models can be observed in Figures 2 and 3 for variables fruit height and diameter, respectively. These representations confirm the growth behavior with double sigmoid character described in previous studies (ÁLVARES et al., 2004; DELA BRUNA, 2007; DONOSO et al., 2007). However, these studies only graphically described the growth of peaches and did not adjust models.

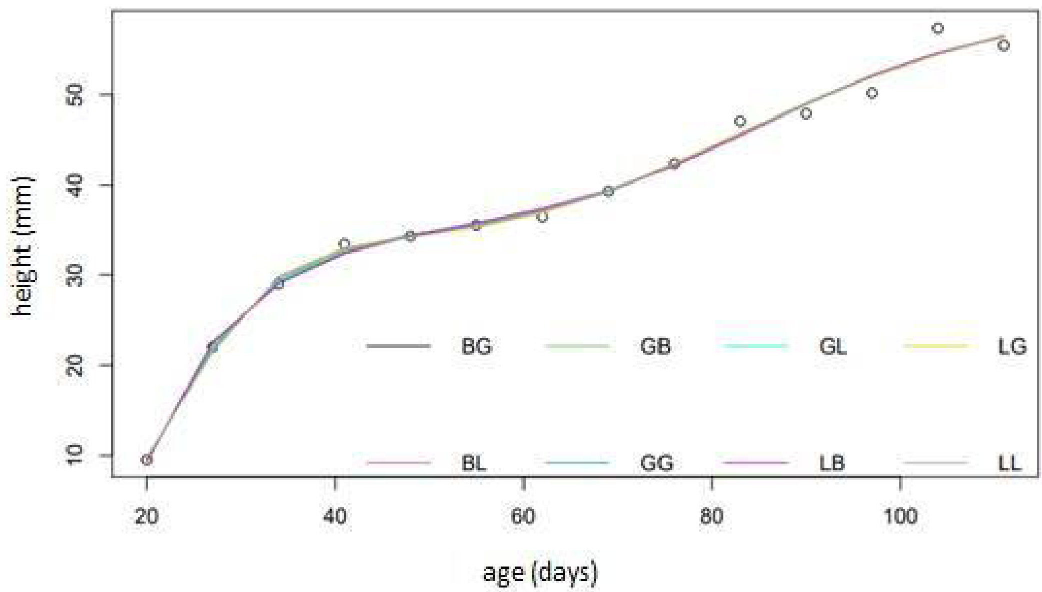

Figure 2. Adjustment of two-phase nonlinear models for the height data of "Aurora-1" peaches. BG = Brody + Gompertz, BL = Brody + Logistic, GB = Gompertz + Brody, GG = Gompertz + Gompertz, GL = Gompertz + Logistic, LB = Logistic + Brody, LG = Logistic + Gompertz, LL = Logistic + Logistic.

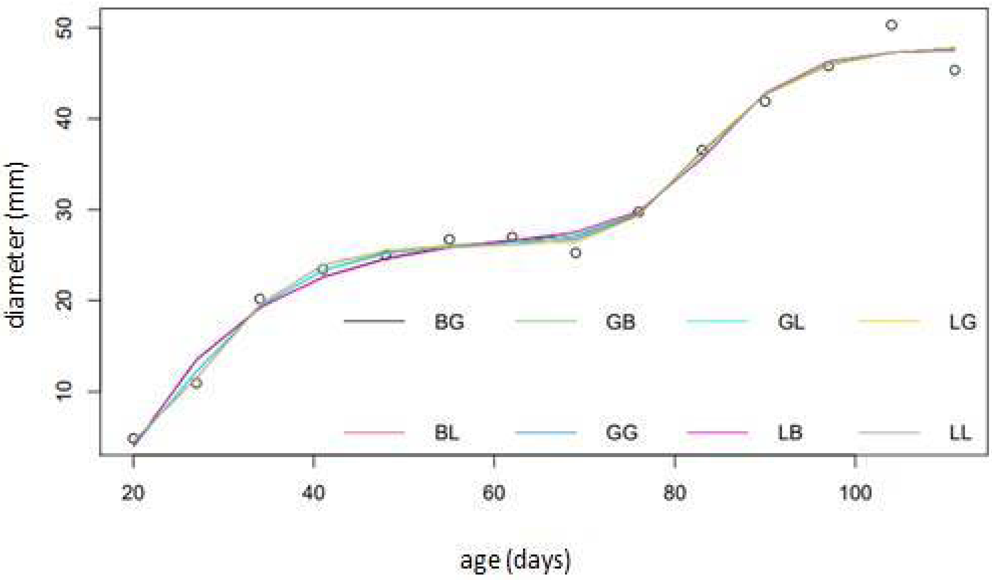

Figure 3. Adjustment of two-phase nonlinear models for the diameter data of "Aurora-1" peaches. BG = Brody + Gompertz, BL = Brody + Logistic, GB = Gompertz + Brody, GG = Gompertz + Gompertz, GL = Gompertz + Logistic, LB = Logistic + Brody, LG = Logistic + Gompertz, LL = Logistic + Logistic.

Conclusion

To describe the growth curve of "Aurora 1" peaches using fruit height data, the double Gompertz model (GG) must be adjusted, while, when using polar diameter data, the Logistic + Gompertz (LG) model must be used. It could be concluded, from the adjustment of these models, that the expected fruit height and diameter measures at the end of growth phase are equal to 62.43 mm and 48.12 mm, respectively.

Acknowledgments

The authors would like to thank CAPES and CNPq for their financial support.

References

ÁLVARES, V.S.; BRAGA, L.R.; MAIA, V.M.; SALOMÃO, L.C.C.; BRUCKNER, C.H.; RUIZ, G.A.C. Desenvolvimento do pêssego "Rei da Conserva" em Viçosa, MG. **Revista Ceres**, Viçosa, MG, v.51, n.294, p.275–283, 2004.

ALVAREZ, A.; BOCHE, S. Modelos matemáticos para describir crecimientos doble sigmoideos en frutos de un nectarin tardio (c.v.Sun Grand). **Agro Sur**, Cassila, v.27, p.21–28, 1999.

ASCHONITIS, V.G.; CASTALDELLI, G.; BARTOLI, M.; FANO, E.A. A Review and synthesis of bivariate non-linear models to describe the relative variation of ecological, biological and environmental parameters. **Environmental Modeling and Assessment**, Bussum, v.20, n.2, p.169–182, 2015.

BEBBINGTON, M.; HALL, A.J.; LAI, C.D.; ZITIKIS, R. Dynamics and phases of kiwifruit (*Actinidia deliciosa*) growth curves. **New Zealand Journal of Crop and Horticultural Science**, Abingdon, v.37, n.3, p.179–188, 2009.

BOWMAN, A.W.; GIBSON, I.; SCOTT, E.M.; CRAWFORD, E. Interactive teaching tools for spatial sampling. **Journal of Statistical Software**, Los Angeles, v.36, n.13, p.1–17, 2010.

BREUSCH, T.S.; PAGAN, A.R. A simple test for heteroscedasticity and random coefficient variation. **Econometrica**, Chicago, v.47, n.5, p.1287- 1294, 1979.

BURNHAM, K.P.; ANDERSON, D.R. **Model selection and multimodel inference**: a practical information-theoretic approach. 2nd ed. New York: Springer, 2002. 518 p.

CAVALINI, F.C.; JACOMINO, A.P.; LOCHOSKI, M.A.; KLUGE, R.A.; ORTEGA, E.M.M. Maturity indexes for "Kumagai" and "Paluma" guavas. **Revista Brasileira de Fruticultura**, Jaboticabal, v.28, n.2, p.176–179, 2006.

CUNHA JÚNIOR, L.C. **Caracterização do desenvolvimento de pêssegos 'Aurora-1' e sua conservação pós-colheita em dois estádios de maturação**. 2007. Dissertação (Mestrado em Agronomia) - Faculdade de Ciências Agrárias e Veterinárias, Universidade Estadual Paulista, Jaboticabal, 2007.

DELA BRUNA, E. Curva de crescimento de frutos de pêssego em regiões subtropicais. **Revista Brasileira de Fruticultura**, Jaboticabal, v.29, n.3, p.685–689, 2007.

DONOSO, J.M.; BASTIAS, R.; LEMUS, G.; SILVA, L. Comportamiento fenológico del duraznero (prunus pérsica l.) en tres localidades de la VI región. **Informativo INIA RAYENTUÉ**, Rengo, v.13, p.1-8, 2007.

FAOSTAT - Food and Agriculture Organization Statistics. **Crops and trade**: Crops and livestok products. 2019. Disponível em: https://www.fao.org/faostat/en/#data/QCL/visualize. Acesso em: 16 nov. 2021.

FERNANDES, T.J.; PEREIRA, A.A.; MUNIZ, J.A. Double sigmoidal models describing the growth of coffee berries. **Ciência Rural**, Santa Maria, v.47, n.8, p.1–7, 2017.

GARRE, P.A.; EGEA L.J.; A.;ESCAMEZ, F.P. Modelos matemáticos para la descripción del crecimiento de microorganismos patógenos en alimentos. **Anuario de Jóvenes Investigadores,** Cartagena, v.9, p.160–163, 2016.

GÉNARD, M.; BRUCHOU, C.; SOUTY, M. Variabilité de la croissance et de la qualité chez la pêche (*Prunus persica* L Batsch) et liaison entre croissance et qualité. **Agronomie**, Paris, v.11, n.10, p.829–845, 1991.

HAU, B.; AMORIM, L.; FILHO, A.B. Mathematical functions to describe disease progress curves of double sigmoid pattern. **Phytopathology**, Palo Alto, v.83, p.928-932, 1993.

HURWITZ, S.; TALPAZ, H.; BARTOV, I.; PLAVNIK, I. Characterization of growth and development of male British United turkeys. **Poultry Science**, Savoy, v.70, n.12, p.2419–2424, 1991.

IBGE - Instituto Brasileiro de Geografia e Estatística. **Produção agrícola municipal 1974 – 2020**. Disponível em: https://sidra.ibge.gov.br/tabela/1613#resultado. Acesso em: 16 nov. 2021.

MARC J.M. **AICcmodavg**: model selection and multimodel inference based on (Q)AIC(c).R package version 2.3-1, 2020. Disponível em: https://cran.r- project.org/package=AICcmodavg

MARTÍNEZ, J.D.; HERNÁNDEZ, I.C.; REYES, J.N.G.; NÁJERA, J.B.P.; GÜERECA, M.C.G.; PÉREZ, E.C. Growth models of peach fruit *Prunus persica* (L) in three handling systems. **Interciencia**, Caracas, v.42, n.9, p.597–602, 2017.

MEDEIROS, C.A.B.; RASEIRA, M.D.C. **A cultura do pessegueiro**. Brasilia: Embrapa-SPI, 1998. 350 p.

MORETTIN, P.A.; TOLOI, C.M.C. **Análise de séries temporais**. 2.ed. São Paulo: Blucher, 2006. 564 p.

MUIANGA, C.A.; MUNIZ, J.A.; NASCIMENTO, M.S.; FERNANDES, T.J.; SAVIAN, T.V. Descrição da curva de crescimento de frutos do cajueiro por modelos não lineares. **Revista Brasileira de Fruticultura**, Jaboticabal, v.38, n.1, p.22–32, 2016.

MUNIZ, J.A.; NASCIMENTO, M.S.; FERNANDES, T.J. Nonlinear models for description of cacao fruit growth with assumption violations. **Revista Caatinga**, Mossoró, v.30, n.1, p.250–257, 2017.

OLIVEIRA, W.S.J. de; SILVA, C.A. ; MUNIZ, J.A.; SAVIAN, T.V. Nitrogen mineralization in latosols fertilized with organic residues. **Revista Brasileira de Ciência do Solo**, Viçosa, MG, v.37, p.715-725, 2013.

PINZÓN-SANDOVAL, H.H.; PINEDA-RÍOS, W.; SERRANO-CELY, P. Mathematical models for describing growth in peach (*Prunus persica* [L.] Batsch.) fruit cv. Dorado. **Revista Colombiana de Ciencias Hortícolas**, Tunja, v.15, n.3, p.e13259-e13259, 2021.

R Core Team. **R**: a language and environment for statistical computing. Vienna: R Foundation for Statistical Computing, 2020. Disponível em.URL https://www.R-project.org/

RIBEIRO, T.D.; MATTOS, R.W.P.; MORAIS, A.R.de ; MUNIZ, J.A. Description of the growth of pequi fruits by nonlinear models. **Revista Brasileira de Fruticultura**, Jaboticabal, v.40, p.e-949, 2018

RASEIRA, M.C.B.; PEREIRA, J.F.M.; CARVALHO, F.L.C. P**essegueiro**. Brasília: Embrapa, 2014. 776 p.

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**, Santa Maria, v.48, n.1, p.1–7, 2018.

SHAPIRO, S.S.; WILK, M.B. An analysis of variance test for normality (complete samples). **Biometrika**, v.52, p.591–611, 1965.

SILVA, E.M. da.; SILVA, E.M.; TADEU, M.H.; SILVA, V.F.; PIO, R.; FERNANDES, T.J.; MUNIZ, J.A. Description of black berry fruit growth by nonlinear regression models. **Revista Brasileira de Fruticultura**, Jaboticabal, v.42, n.2, p.1-8, 2020.

SILVA, E.M. da.; FRUHAUF, A.C., SILVA, E.M., MUNIZ, J.A., FERNANDES, T.J.; SILVA, V.F.D. Evaluation of the critical points of the most adequate nonlinear model in adjusting growth data of ‘green dwarf’coconut fruits. **Revista Brasileira de Fruticultura**, Jaboticabal, v.43, n.1, 2021.

VENABLES, W.N.; RIPLEY, B.D. **Modern applied statistics with S**. 4th ed. New York: Springer, 2002.