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CROP PRODUCTION

Nonlinear models for describing lettuce growth in autumn-winter

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ABSTRACT: *The objectives of this study were to fit the Gompertz and Logistic models for the fresh and dry matter of leaves and the fresh and dry matter of shoots of three lettuce cultivars and indicate the best model to describe their growth in autumn-winter. The lettuce cultivars Gloriosa, Pira Verde, and Stella were evaluated in the autumn-winter of 2016 and 2017, in soilless in a protected environment. After transplantation, the fresh and dry matter of leaves and shoots were weighed every seven days. These dependent variables were fit using the accumulated thermal sum. The parameters of the Gompertz and Logistic models were estimated, the assumptions of the models were verified, the indicators of fit quality and critical points were calculated and the parametric and intrinsic curvature measures quantified. The Logistic and Gompertz models presented a satisfactory adjustment for the fresh and dry matter of leaves and the fresh and dry matter of shoots, for the lettuce cultivars Gloriosa, Pira Verde and Stella, in autumn-winter. The Logistic model best describes the growth of the lettuce cultivars.*
Key words: *dry matter, fresh matter, Gompertz, Lactuca sativa L., Logistic.*

Modelos não lineares para descrição do crescimento de cultivares de alface em condições de outono-inverno

RESUMO: *Os objetivos deste trabalho foram ajustar os modelos Gompertz e Logístico para as massas de matéria fresca e seca de folhas, e as massas de matéria fresca e seca de parte aérea de três cultivares de alface e indicar o modelo que melhor descreve o crescimento no outono-inverno. As cultivares de alface Gloriosa, Pira Verde e Stella, foram avaliadas no outono-inverno de 2016 e outono-inverno de 2017, em cultivo sem solo em ambiente protegido. Após o transplante, a cada sete dias, foram pesadas as massas de matéria fresca e seca de folhas e as massas de matéria fresca e seca de parte aérea. Essas variáveis dependentes foram ajustadas em função da soma térmica acumulada. Foram estimados os parâmetros dos modelos Gompertz e Logístico, verificados os pressupostos dos modelos, calculados os indicadores de qualidade do ajuste e os pontos críticos e quantificadas as medidas de curvatura intrínseca e de parametrização. Os modelos Logístico e Gompertz apresentam ajuste satisfatório para as massas de matéria fresca e seca de folhas e para as massas de matéria fresca e seca de parte aérea, para as cultivares de alface Gloriosa, Pira Verde e Stella, no outono-inverno. O modelo Logístico é o que melhor descreve o crescimento das cultivares de alface.*
Palavras-chave: *Gompertz, Lactuca sativa L., Logístico, massa de matéria fresca, massa de matéria seca.*

INTRODUCTION

Lettuce (*Lactuca sativa* L.) is a temperate leafy green vegetable (SALA & COSTA, 2012). Its leaves are consumed as raw salads, soups, and creams, and is a source of dietary fibers, vitamins, and minerals (NTSOANE et al., 2016). It is the main leafy green vegetable sold and consumed in Brazil, mainly because of its ease of production and acquisition.

Lettuce cultivars are classified as crisphead, iceberg, or butterhead and other types ('mimosa', romaine, baby, and purple), corresponding to 43.3%, 41.2%, 5.0% and 10.5%, respectively, of the lettuce traded at the General Warehousing Company of São Paulo (CEAGESP, 2017). Thus, different genetic materials exist for the leaf morphological characteristics or head shape and also the growing seasons. In Rio Grande do Sul, the most favorable

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season to the growth of the crop is winter, because in this period temperatures vary between -3 to 18 ºC (ALVARES et al., 2013).

One way to characterize plant growth is via modeling (STRECK et al., 2008). Adjusting growth models to plant species helps in the evaluation of plant response to environmental conditions, as well as understanding its growth pattern (LYRA et al., 2003). Growth models using the accumulated thermal sum allow to make inferences on precocity, velocity and stabilization of the plant growth through the interpretation of parameters and critical points of the adjusted model curve (MISCHAN & PINHO, 2014).

The accumulated thermal sum is a biological time measure in plants, being more accurate than days in the civil calendar or days after sowing/transplant (GILMORE & ROGERS, 1958; MCMASTER & SMIKA, 1988). The use of accumulated thermal sum as elapsed time of the crop cycle assumes a linear relation between growth or plant development and temperature (BONHOMME, 2000). However, this would not be realistic from the biological point of view, since the plant growth in response to the thermal accumulation is nonlinear. Therefore, nonlinear models are more often used to describe the growth of plants, generally, faster in its initial phase, then decreasing its speed and, finally, tending to a stability in the adult phase (PAINE et al., 2012; MISCHAN & PINHO, 2014).

Mathematical models must be able to reproduce the plants behavior as closest as possible to the real. The adjustment of nonlinear models have been applied to describe the growth of *Allium sativum* L. (PUIATTI et al., 2013; REIS et al., 2014) and production of the *Cucurbita pepo* and *Capisicum annuum* (LÚCIO et al., 2015), cherry tomatoes (LÚCIO et al., 2016) and strawberry (DIEL et al., 2018). According to TERRA et al. (2010), models allow condensing information from a series of data, taken over time, into a small set of biologically interpretable parameters.

It has been shown that for lettuce, the models Gompertz, Logistic, and Expolinear fit well the cultivars Grand Rapids, Regina, and Great Lakes, in a hydroponic system during the summer (LYRA et al., 2003). However, no report has been reported describing growth using nonlinear models in other seasons or with different cultivars in protected environment.

Suppose that the Gompertz and Logistic models are suitable to describe the growth of three lettuce cultivars during the autumn-winter season and that it is possible to select the most appropriate model. The objectives of this research were to adjust the Gompertz and Logistic models for the fresh and dry matter of leaves and shoots of three lettuce cultivars (Gloriosa, Pira Verde, and Stella) and indicated the model that best describes the growth in autumn-winter.

MATERIALS AND METHODS

Two experiments were carried out with lettuce cultivars, one in the autumn-winter of 2016 (experiment 1) and other in the autumn-winter of 2017 (experiment 2). The plants were grown using a closed soilles system, in a protected environment of umbrella type, with 115 m² (5×23 m) environment covered with 150 µm anti-UV polyethylene. The location is between coordinates 29º42'S, 53º49'W and 95 m altitude. According to Köppen's classification, the climate of the region is humid subtropical Cfa, with hot summers and no defined dry season (ALVARES et al., 2013).

The lettuce cultivars evaluated were: Gloriosa (iceberg - light green leaves, crisp, consistent, prominent ribs, compact head), Pira Verde (crisp green - consistent and loose leaves that do not form head), and Stella (butterhead - delicate and smooth leaves with loosely formed head). These cultivars were recommended by the seed companies for autumn-winter conditions. The seedlings were produced in the floating system in 200-cell expanded polystyrene trays filled with commercial Plantmax® substrate. Transplanting was carried out when the plants developed four to five leaves, on 30/Jun/2016 (experiment 1) and 04/Jun/2017 (experiment 2).

Plants were grown in six benches of corrugated fiber cement sheets, 3.66 m long, 1.10 m wide, 6 mm thick, with six troughs of 5 cm in depth. The troughs were covered with clear 100-µm-thick plastic film and filled with washed gravel number two. The benches were raised (0.85 m) on fixed masonry blocks at the two end portions, with slope of 2%. This slope allowed the nutrient solution to return to the 500 L plastic storage tank. The solution was pumped by a low-power submersible motor pump (with a timer) to a PVC pipe (25 mm diameter). From this pipe derived four drip hoses with pots placed under the drippers at a distance of 30 cm between the plants in the row, to a density of 11.11 m^{-2} plants. Each bench consisted of four rows, totaling 44 three-liter volume pots (11 pots per row), filled with washed sieved coarse sand, with 0 dS m^{-1} electrical conductivity.

The nutrient solution consisted of the following macronutrient composition (in mmol L^{-1}): 10.36 NO_3^-; 1.0 $H_2PO_4^-$; 3.36 NH_4; 1.0 SO_4; 4.0 de K^+; 2.0 Ca^{2+}; 1.0 Mg^{2+}; and micronutrients (mg L^{-1}): 1.0 Fe; 0.50 Mn; 0.22 Zn; 0.26 B; 0.06 Cu, and 0.03 de Mo, for lettuce, with 1.33 dS m^{-1} electrical conductivity (EC) and pH 5.5 to 6.5. The EC and pH were monitored throughout the growing cycle and corrected if there was variation of 20%, higher or lower than the standard.

All cultivars were grown in the same environment, according to the information mentioned above. Seven days after transplantation, seven to twelve plants per cultivar were evaluated (nine times) in experiment 1 (total of 172 plants) and in experiment 2 six plants per cultivar were used and 10 support points (total of 180 plants) until the beginning of flowering. The variables fresh leaf matter (FLM, as g plant^{-1}), dry leaf matter (DLM, as g plant^{-1}), sum fresh stem matter and fresh leaf matter = fresh shoot matter (FSM, as g plant^{-1}), and sum dry stem matter and dry leaf matter = dry shoot matter (DSM, as g plant^{-1}) were weighed with a digital scale. For dry matter, the samples were packed in paper bags and incubated in a forced air circulation oven (60 ± 5 °C) until obtaining constant mass.

The indoor air temperature data were recorded every three hours by a digital data logger (0.1 °C resolution and 0.5 °C accuracy) installed in a weather-proof shelter located inside the umbrella greenhouse. These data were used to calculate the daily thermal sum by the method of GILMORE & ROGERS (1958) and ARNOLD (1959), using equations 1 and 2:

$$STd = (Tmax + Tmin)/2 - Tb \quad (1)$$

Where:
Tmax: maximum daily temperature as ºC;
Tmin: minimum daily temperature as ºC;
Tb: lettuce base temperature = 10ºC (BRUNINI, 1976)

$$STa = \sum STd \quad (2)$$

Where:
STa: accumulated thermal sum;
$\sum$ STd: sum of the daily thermal sum.

The fit of the Gompertz (WINDSOR, 1932) and Logistic (NELDER, 1961) models for each character (dependent variable) was performed using the repetitions of each evaluation (for each cultivar x experiment separately), using the raw data, as a function of the accumulated thermal sum (independent variable). The equation used for the Gompertz model was: $y_i = a\,exp[-exp(b - cx_i)] + \varepsilon_i$, and for the Logistic: $y_i = a/[1 + exp(-b - cx_i)] + \varepsilon_i$ y_i is the i-th observation of the dependent variable with i = 1, 2, ..., n; x_i is the i-th observation of the independent variable; *a* is the asymptotic value; *b* is a location parameter, important for maintaining the sigmoidal shape of the model; *c* is associated with growth, indicating the precocity index. The higher the value of *c* the less time will be required for the plant to reach the asymptotic value (*a*).

The assumptions of normality, independence, and homogeneity of the model residuals were tested using the Shapiro-Wilk (SHAPIRO & WILK, 1965), Durbin-Watson (DURBIN & WATSON, 1950), and Breusch-Pagan tests (BREUSCH & PAGAN, 1979) respectively.

The estimates of the parameters (*a*, *b* e *c*) for each response were compared between the experiments for each cultivar, and between the cultivars in each experiment, by overlapping confidence intervals (CI) of the parameter estimates in each model. For this purpose, we calculated the lower and upper limits of the 95% confidence interval.

The coefficient of determination ($R^2 = 1 - \frac{SQR}{SQT}$) was used to assess the quality of fit of the models, and the best fit was considered the model with the coefficient closest to 1 or 100%. The Akaike Information Criterion ($AIC = \ln(\sigma^2) + 2(p+1)/n$) in which the lower its value the better the model (that is, the more suitable the model is to describe the study), and the Residual Standard Deviation ($RSD = \sqrt{\frac{SQR}{n-p}}$) , define the best fit of the model with values closer to zero. The intrinsic curvature measures (ICM) and curvature measures of the parameter effect (PE) were quantified using the geometric concept of curvature (BATES & WATTS, 1998). The selection of the best model to describe plant growth, is based on the one that provides the lowest values of intrinsic or parametric curvature measures. Were calculated according to the equations described in MISCHAN & PINHO (2014), the inflection point (IP) to Gompertz ($IPx = \frac{b}{c}$ and $IPy = \frac{a}{e}$) and and to Logistc ($IPx = \frac{-b}{c}$ and $IPy = \frac{a}{2}$), the maximum acceleration point (MAP) to Gompertz ($MAPx = \frac{b - ln\left(\frac{3+\sqrt{5}}{2}\right)}{c}$ and $MAPy = a\,exp\left(-\frac{3+\sqrt{5}}{2}\right)$) to Logistc ($MAPx = \frac{1}{c}[-b - ln(2+\sqrt{3})]$ and $MAPy = \frac{a}{3+\sqrt{3}}$) the maximum deceleration point (MDP) to Gompertz ($MDPx = \frac{b - ln\left(\frac{3-\sqrt{5}}{2}\right)}{c}$ and $MDPy = a\,exp\left(-\frac{3-\sqrt{5}}{2}\right)$) and to Logistc ($MDPx = \frac{1}{c}[-b - ln(2-\sqrt{3})]$ and $MDPy = \frac{a}{3-\sqrt{3}}$).

Inferences about plant growth were made from these critical points. The calculations were performed using the Microsoft Office Excel® applications and the R software, with the *nls* function (R DEVELOPMENT CORE TEAM, 2018).

RESULTS AND DISCUSSION

The assumptions of normality, homogeneity, and independence of errors were met in both the Gompertz and Logistic models for fresh and dry matter of leaves and fresh and dry matter of shoots of lettuce cultivars in both experiments, as the Shapiro-Wilk, Durbin-Watson, and Breusch-Pagan tests had p-values equal to or greater than 0.05. Similar results were reported by RIBEIRO et al. (2018), in which the assumptions were taken to nonlinear models.

The estimates of *a* are the asymptotic values, that is, in the case of lettuce, represent the maximum mass achieved. For all the characters of the cultivars, the *a* values for the Gompertz model were higher than for the Logistic model (Tables 1 and 2). The estimation of *b*, in theory, provides a concept of the ratio between the initial values and the missing amount to reach the asymptote. The estimate of parameter *c*, represents the growth speed, which was higher in the Logistic model (Tables 1 and 2).

The estimates of the parameters (*a*, *b* and *c*) of each character for the Gompertz and Logistic models were compared between each experiment (Tables 1 and 2) and between the each cultivars (Tables 3), by the criterion of overlapping confidence intervals. This comparison criterion was used by WHEELERN et al. (2006) and by BEM et al. (2018), to verify if the growth curves have differed according to the treatments.

To clarify the comparison by the criterion of overlapping 95% confidence intervals (CI), the FLM of cv. Pira Verde will be used as an example to compare the estimate of the parameter *a* of the Logistic model between experiments 1 and 2 (Table 2). The following results were reported: the estimate of parameter *a* (354.7561) in experiment 1 is within the confidence interval of the estimate of parameter *a* in experiment 2 (329.5156 to 385.3911). Also, the estimate of parameter *a* (357.4533) in experiment 2 is within the confidence interval of the estimate of parameter *a* of experiment 1 (225.9895 to 483.5227). Therefore, the estimates of the parameter *a* are not different between the experiments. When at least one of the estimates is within the CI of the other, it can be concluded that the effect is not significant. If the two parameter estimates are outside the CI of the other, it can be concluded that the effect is significant.

In the Gompertz model, the parameters *b* and *c* for FLM and FSM of cv. Gloriosa were not different between the experiments (Table 1). However, the parameter a differed in all the characters, with higher values of FLM and FSM in experiment 1, which indicates higher matter production in relation to experiment 2. Opposite behavior was observed for DLM and DSM. For cv. Pira Verde, the estimates were not different for the characters except for DLM in relation to parameter *c*. These results indicated that, for this cultivar, there was no difference of the Gompertz models between the experiments. However, for cv. Stella, no differences were observed for FLM and FSM between the experiments. The DLM and DSM were not different asymptotically.

The Logistic model of cv. Gloriosa showed that DLM and DSM differed between experiments for parameters *a*, *b* and *c* (Table 2). FLM and FSM showed differences only in the asymptotic values and were higher in the experiment 1 than in the experiment 2, which indicated that the plants had higher production of green matter in experiment 1. Characters differed of cultivar Pira Verde with respect to the parameters *b* and *c*, and did not differ for parameter *a*. Asymptotic values of cultivar Stella were not different between experiments for the all the characters, the estimate of *b* was similar for FLM and FSM. However, all characters differed for growth rate.

These results suggested that the growth models had different behaviors between experiments 1 and 2. Similar results were reported for genotype tomato in two years, in the Cordillera and Ellen genotypes were more premature in 2015/2016 crop, and the Gaucho genotype was more premature in the 2016/2017 crop (SARI et al. 2019).

Comparing the cultivars in each experiment, we found that cvs. Gloriosa and Pira Verde, in the Gompertz model, experiment 1, showed no difference between the characters (Table 3). This means that the Gompertz model makes no difference between these cultivars. Conversely, Gompertz model differed for all the characters of cvs. Pira Verde and Stella, since at least one of the three parameters (*a*, *b* and *c*) was significant. This same behavior was observed between cvs. Gloriosa and Stella. In experiment 2, the cultivars Gloriosa and Pira Verde were not different for FLM, while Pira Verde and Stella did not differ for DLM and DSM.

The estimates of the Logistic model parameters, for FSM of cvs. Pira Verde and Stella in experiment 1, for FSM of cvs. Gloriosa and Pira Verde in experiment 2, and for DLM and DSM of cvs. Pira Verde and Stella in experiment 2, were not different (Table 3). All other comparisons differed in at least one of the three parameters of the Logistic model. For the Gompertz and Logistic models there was a predominance of differences, which indicated the need of specific models per character and cultivar. Different models were also required in groups of garlic accesses (REIS et al., 2014).

Goodness-of-fit indicators are used to define the most suitable model. The Logistic and Gompertz models presented acceptable goodness-of-fit values (high R^2, low AIC and RSD) and close

Table 1 - Estimates of the parameters *a*, *b*, and *c*, lower limit (LL) and upper limit (UL) of the confidence interval (CI 95%) of the Gompertz model for the characters as a function of accumulated thermal sum (in °C) of lettuce cultivars (Gloriosa, Pira Verde, and Stella) in two experiments.

Character[1]	Parameter	Estimates	CI 95%		Estimates	CI 95%	
			LL	UL		LL	UL
		Experiment 1			Experiment 2		
Gloriosa							
FLM	$a^{*(2)}$	929.8712	597.8730	1261.8694	455.6514	370.6086	540.6942
	b^{ns}	2.3061	1.8969	2.7154	2.4371	2.0036	2.8707
	c^{ns}	0.0076	0.0049	0.0102	0.0082	0.0061	0.0102
DLM	a^{*}	16.7031	15.3232	18.0831	25.3207	17.9166	32.7249
	b^{*}	4.2032	2.9665	5.4398	2.3264	1.8240	2.8288
	c^{*}	0.0198	0.0138	0.0258	0.0073	0.0048	0.0098
FSM	a^{*}	984.0988	617.5294	1350.6682	535.0355	420.6123	649.4587
	b^{ns}	2.2898	1.8898	2.6897	2.3731	1.9682	2.7780
	c^{ns}	0.0074	0.0048	0.0100	0.0076	0.0056	0.0095
DSM	a^{*}	17.8364	16.2972	19.3755	30.4005	19.9823	40.8187
	b^{*}	4.0599	2.8834	5.2364	2.2844	1.8061	2.7627
	c^{*}	0.0189	0.0132	0.0246	0.0068	0.0043	0.0092
Pira Verde							
FLM	a^{ns}	1234.9167	-921.8006	3391.6340	396.8462	344.1902	449.5022
	b^{ns}	2.4801	1.9083	3.0518	2.8152	2.2292	3.4012
	c^{*}	0.0072	0.0013	0.0130	0.0105	0.0079	0.0132
DLM	a^{ns}	16.1548	10.3930	21.9166	14.3685	12.1452	16.5917
	b^{ns}	3.9116	2.2996	5.5236	2.9788	2.0259	3.9317
	c^{ns}	0.0179	0.0088	0.0271	0.0120	0.0076	0.0164
FSM	a^{ns}	1334.4813	-1078.0040	3746.9667	417.3858	359.6425	475.1292
	b^{ns}	2.4846	1.9148	3.0543	2.7758	2.2012	3.3503
	c^{ns}	0.0071	0.0012	0.0130	0.0103	0.0077	0.0129
DSM	a^{ns}	17.0319	10.9575	23.1063	15.3914	12.8463	17.9365
	b^{ns}	3.9517	2.3272	5.5762	2.8810	1.9750	3.7870
	c^{ns}	0.0181	0.0089	0.0273	0.0114	0.0073	0.0156
Stella							
FLM	a^{ns}	331.9249	222.8545	440.9954	302.7635	242.6119	362.9151
	b^{ns}	4.5969	2.7416	6.4522	3.9793	2.0114	5.9472
	c^{ns}	0.0207	0.0107	0.0306	0.0151	0.0072	0.0231
DLM	a^{ns}	11.4854	9.7928	13.1781	12.6652	9.4969	15.8334
	b^{*}	6.3329	4.1776	8.4882	3.4840	1.5131	5.4548
	c^{*}	0.0306	0.0197	0.0416	0.0136	0.0051	0.0221
FSM	a^{ns}	350.0046	228.7424	471.2668	329.2424	258.0313	400.4536
	b^{ns}	4.5261	2.6718	6.3805	3.8011	1.9389	5.6633
	c^{ns}	0.0202	0.0102	0.0302	0.0142	0.0067	0.0217
DSM	a^{ns}	12.2469	10.3352	14.1586	14.1283	10.1332	18.1234
	b^{*}	6.2374	4.0542	8.4205	3.3240	1.4419	5.2061
	c^{*}	0.0300	0.0189	0.0411	0.0127	0.0046	0.0207

[1]FLM: fresh leaf matter, as g plant^{-1}; DLM: dry leaf matter, as g plant^{-1}; FSM: fresh shoot matter, as g plant^{-1}; and DSM: dry shoot matter, as g plant^{-1}.
[2]Comparison of the parameters estimates (*a*, *b* and *c*) between the experiments: *Significant effect at 0.05 probability of error. ^{ns}Non-significant.

to each other (Tables 4 and 5). The R^2 indicator was used by LIRA et al. (2003) to study the growth curve of lettuce cultivars. However, it is recommended to use more than one fit quality indicator to increase the reliability of the model choice.

The Gompertz and Logistic models satisfactorily described the growth curve of lettuce cultivars, with R^2 values equal to or higher than 0.913, except for cv. Stella, which showed lower Goodness-of-fit in experiment 2 ($0.769 \leq R^2 \leq 0.826$), of both

Table 2 - Estimation of the parameters *a*, *b*, and *c*, lower limit (LL) and upper limit (UL) of the confidence interval (CI 95%) of the Logistic model for the characters as a function of accumulated thermal sum (in °C) of lettuce cultivars (Gloriosa, Pira Verde, and Stella) in two experiments.

Character[(1)]	Parameter	Estimates	CI 95%		Estimates	CI 95%	
			LL	UL		LL	UL
		Experiment 1			Experiment 2		
Gloriosa							
FLM	$a^{*(2)}$	644.5429	548.4506	740.6351	374.9478	336.2122	413.6834
	b^{ns}	-5.1549	-5.8057	-4.5041	-5.0146	-5.7298	-4.2994
	c^{ns}	0.0174	0.0140	0.0208	0.0159	0.0131	0.0187
DLM	a^{*}	16.1507	15.1791	17.1223	19.8721	16.8842	22.8600
	b^{*}	-6.9451	-8.6093	-5.2809	-4.9363	-5.7612	-4.1114
	c^{*}	0.0301	0.0224	0.0378	0.0149	0.0117	0.0182
FSM	a^{*}	671.9417	568.1495	775.7339	423.4933	375.6487	471.3380
	b^{ns}	-5.1427	-5.7829	-4.5026	-5.0110	-5.6958	-4.3261
	c^{ns}	0.0172	0.0139	0.0206	0.0154	0.0127	0.0181
DSM	a^{*}	17.1579	16.1129	18.2030	22.6678	18.9117	26.4239
	b^{*}	-6.7920	-8.3663	-5.2178	-4.9890	-5.7998	-4.1783
	c^{*}	0.0291	0.0219	0.0364	0.0146	0.0114	0.0179
Pira Verde							
FLM	a^{ns}	354.7561	225.9895	483.5227	357.4533	329.5156	385.3911
	b^{*}	-6.9162	-8.2985	-5.5339	-5.4368	-6.3065	-4.5671
	c^{*}	0.0275	0.0189	0.0361	0.0185	0.0151	0.0219
DLM	a^{ns}	12.9143	10.9345	14.8941	13.4350	12.0807	14.7892
	b^{*}	-8.1440	-10.4198	-5.8683	-5.3736	-6.7002	-4.0469
	c^{*}	0.0366	0.0249	0.0483	0.0194	0.0141	0.0248
FSM	a^{ns}	371.9859	233.7199	510.2519	373.1430	343.2436	403.0423
	b^{*}	-6.9521	-8.3426	-5.5615	-5.4148	-6.2733	-4.5563
	c^{*}	0.0276	0.0189	0.0362	0.0183	0.0150	0.0216
DSM	a^{ns}	13.5725	11.5050	15.6401	14.2652	12.7645	15.7659
	b^{*}	-8.2774	-10.6061	-5.9486	-5.2873	-6.5615	-4.0131
	c^{*}	0.0371	0.0252	0.0490	0.0189	0.0137	0.0240
Stella							
FLM	a^{ns}	267.4332	225.5213	309.3451	284.7468	246.6736	322.8200
	b^{ns}	-9.5607	-12.5727	-6.5486	-7.2670	-10.4551	-4.0790
	c^{*}	0.0421	0.0273	0.0570	0.0253	0.0138	0.0367
DLM	a^{ns}	10.4087	9.5845	11.2329	11.9094	9.8986	13.9203
	b^{*}	-12.9179	-16.8192	-9.0166	-6.2848	-9.2759	-3.2937
	c^{*}	0.0599	0.0415	0.0783	0.0222	0.0109	0.0335
FSM	a^{ns}	279.2195	233.6137	324.8253	305.9605	262.6841	349.2370
	b^{ns}	-9.4826	-12.4910	-6.4743	-7.0754	-10.1261	-4.0247
	c^{*}	0.0417	0.0268	0.0566	0.0243	0.0133	0.0352
DSM	a^{ns}	11.0147	10.1213	11.9081	13.0975	10.6849	15.5101
	b^{*}	-12.9199	-16.9054	-8.9345	-6.1507	-9.0592	-3.2421
	c^{*}	0.0597	0.0409	0.0785	0.0213	0.0104	0.0321

[(1)]FLM: fresh leaf matter, as g $plant^{-1}$; DLM: dry leaf matter, as g $plant^{-1}$; FSM: fresh shoot matter, as g $plant^{-1}$; and DSM: dry shoot matter, as g $plant^{-1}$.
[(2)]Comparison of the parameters estimates (*a*, *b* and *c*) between the experiments: *Significant effect at 0.05 probability of error. ^{ns}Non-significant.

models. LYRA et al. (2003) adjusted growth models for dry leaf matter in lettuce cultivars in the summer in Viçosa, Minas Gerais, Brazil, and obtained results partially similar to the present study, with a coefficient of determination equal to or greater than 0.98.

Although, the models presented satisfactory Goodness-of-fit for FLM and FSM of cv. Gloriosa in experiment 1, the Gompertz model overestimated the parameter *a* with 929.8712 for FLM and 984.0988 for FSM (Table 1), that is, these estimates were higher

Table 3 - Comparison of estimates of parameters (*a*, *b* and *c*) in the Gompertz and Logistic models for characters as a function of cumulative thermal sum based on the confidence interval (CI 95%), between lettuce cultivars Gloriosa, Pira Verde, and Stella in two experiments.

Cultivars	Cultivars	FLM[1]	DLM	FSM	DSM	FLM	DLM	FSM	DSM
		--------Experiment 1--------				--------Experiment 2--------			
--------Gompertz--------									
--------*a*--------									
Gloriosa	Pira Verde	ns[2]	ns	ns	ns	ns	*	*	*
Gloriosa	Stella	*	*	*	*	*	*	*	*
Pira Verde	Stella	ns	ns	ns	*	*	ns	*	ns
--------*b*--------									
Gloriosa	Pira Verde	ns	ns	ns	ns	ns	ns	ns	ns
Gloriosa	Stella	*	ns	*	ns	ns	ns	ns	ns
Pira Verde	Stella	*	*	*	*	ns	ns	ns	ns
--------*c*--------									
Gloriosa	Pira Verde	ns	ns	ns	ns	ns	*	*	*
Gloriosa	Stella	*	ns	*	ns	ns	ns	ns	*
Pira Verde	Stella	*	*	*	*	ns	ns	ns	ns
--------Logistic--------									
--------*a*--------									
Gloriosa	Pira Verde	*	*	*	*	ns	*	*	*
Gloriosa	Stella	*	*	*	*	*	*	*	*
Pira Verde	Stella	*	*	ns	*	*	ns	*	ns
--------*b*--------									
Gloriosa	Pira Verde	*	ns	*	*	ns	ns	ns	ns
Gloriosa	Stella	*	*	*	*	*	ns	ns	ns
Pira Verde	Stella	ns	*	ns	ns	ns	ns	ns	ns
--------*c*--------									
Gloriosa	Pira Verde	*	ns	*	ns	ns	ns	ns	ns
Gloriosa	Stella	*	*	*	*	ns	ns	ns	ns
Pira Verde	Stella	ns	*	ns	ns	ns	ns	ns	ns

[1]FLM = fresh leaf matter, as g plant^{-1}; DLM = dry leaf matter, as g plant^{-1}; FSM = fresh shoot matter, as g plant^{-1}; and DSM = dry shoot matter, as g plant^{-1}. [2]Comparison of the parameters estimates (*a*, *b* and c) between the cultivars: * = Significant effect at 0.05 probability of error. ns = Non-significant.

than the maximum values observed in the data set, which were 647.4 g plant^{-1} of FLM and 665.77 g plant^{-1} of FSM. A greater overestimation was found for FLM and FSM of cv. Pira Verde in experiment 1, where the Gompertz model estimated the parameter *a* as 1234.9167 for FLM and as 1334.4813 for FSM, while the maximum value observed was 276.16 g plant^{-1} for FLM and 288.02 g plant^{-1} for FSM. Cases of overestimation of parameters in the Gompertz model were also described for the dry matter of bulbs of garlic accesses (REIS et al., 2014).

Intrinsic curvature measures (ICM) and curvature measures of the parameter effect (PE) help us choose the best model. We found that the Logistic model had lower ICM for most of the characters of the cultivars in the two experiments and the PE was always smaller than in the Gompertz model (Tables 4 and 5). The lower ICM and, especially, the lower PE indicate better suitability of the Logistic model, when compared to the Gompertz model.

Considering the five Goodness-of-fit indicators (R^2, AIC, RSD, ICM, and PE), we can infer that the Logistic model had suitable behavior regardless of cultivar, character, and experiment and is the best indicated to describe the growth of the lettuce cultivars. To exemplify the growth curve shape of the Logistic model for each character, with the respective critical points, we selected cv. Gloriosa of experiment 2 (Figure 1). The other growth curves can be constructed with the respective estimates of the parameters (Table 2).

Inflection points, maximum acceleration and maximum deceleration are used to infer the crop growth, having as a base the general behavior to the cultivars Gloriosa, Pira Verde and Stella (Tables 4

Table 4 - Coefficient of determination (R^2), Akaike information criterion (AIC), residual standard deviation (RSD), intrinsic curvature measures (ICM), curvature measures of the parameter effect (PE), inflection point (IP), maximum acceleration point (MAP), and maximum deceleration point (MDP) of the Gompertz model for characters [(1)] as a function of the accumulated thermal sum (in °C) of lettuce cultivars (Gloriosa, Pira Verde, and Stella) in two experiments.

Statistic		FLM	DLM	FSM	DSM	FLM	DLM	FSM	DSM
		Experiment 1				Experiment 2			
Gloriosa									
R²		0.968	0.918	0.968	0.922	0.969	0.952	0.970	0.952
AIC		7.243	1.309	7.296	1.371	6.334	0.786	6.453	0.953
RSD		35.802	1.851	36.758	1.909	22.596	1.410	23.982	1.533
ICM		0.165	0.128	0.164	0.134	0.147	0.191	0.146	0.192
PE		6.975	0.787	7.448	0.851	2.575	4.373	3.111	5.477
IP	x	305.065	212.742	309.348	214.657	298.835	319.371	314.040	337.689
	y	342.080	6.145	362.030	6.562	167.625	9.315	196.829	11.184
MAP	x	177.750	164.029	179.324	163.771	180.824	187.248	186.681	195.418
	y	67.831	1.218	71.786	1.301	33.238	1.847	39.029	2.218
MDP	x	432.380	261.455	439.372	265.543	416.846	451.494	441.398	479.961
	y	634.654	11.400	671.665	12.174	310.990	17.282	365.171	20.749
Pira Verde									
R²		0.964	0.935	0.964	0.935	0.960	0.913	0.961	0.915
AIC		5.769	0.335	5.846	0.442	6.665	0.998	6.727	1.066
RSD		16.940	1.126	17.608	1.188	26.674	1.569	27.519	1.623
ICM		0.324	0.229	0.327	0.207	0.141	0.213	0.143	0.220
PE		87.261	5.582	92.807	5.552	1.627	1.904	1.708	2.043
IP	x	345.989	217.964	349.716	218.552	266.933	247.837	269.886	251.721
	y	454.300	5.943	490.928	6.266	145.992	5.286	153.548	5.662
MAP	x	211.724	164.335	214.251	165.325	175.678	167.763	176.310	167.631
	y	90.082	1.178	97.345	1.242	28.948	1.048	30.447	1.123
MDP	x	480.254	271.592	485.181	271.780	358.189	327.910	363.462	335.811
	y	842.853	11.026	910.808	11.625	270.855	9.807	284.873	10.505
Stella									
R²		0.935	0.925	0.935	0.923	0.821	0.769	0.824	0.769
AIC		6.474	0.359	6.552	0.489	8.090	1.997	8.185	2.151
RSD		24.130	1.139	25.093	1.215	54.362	2.583	57.029	2.791
ICM		0.057	0.065	0.060	0.067	0.360	0.311	0.340	0.312
PE		4.705	1.388	5.087	1.506	2.182	2.860	2.371	3.232
IP	x	222.486	206.749	223.651	207.711	262.976	255.899	267.333	262.513
	y	122.108	4.225	128.759	4.505	111.380	4.659	121.122	5.198
MAP	x	175.906	175.329	176.094	175.661	199.373	185.208	199.646	186.506
	y	24.213	0.838	25.531	0.893	22.085	0.924	24.017	1.031
MDP	x	269.067	238.169	271.208	239.760	326.578	326.589	335.020	338.519
	y	226.545	7.839	238.885	8.359	206.642	8.644	224.714	9.643

(1) FLM: fresh leaf matter, as g $plant^{-1}$; DLM: dry leaf matter, as g $plant^{-1}$; FSM: fresh shoot matter, as g $plant^{-1}$; and DSM: dry shoot matter, as g $plant^{-1}$.

and 5). The maximum acceleration point occurred at the beginning of the curve, when the plants showed slow growth, which is related to smaller plants and still young leaves. For most cultivars, in both experiments, the inflection point (IP) coincided with the phase close to harvest point, with the appearance of senescent basal leaves, which in practice is one of the criteria to classify the produce commercially. In general, independent of the experiment, in the Gompertz model, the cultivars reached the IP with lower STa than in the Logistic model. Among the cultivars, Gloriosa required the greatest accumulation of thermal sum and had the highest dry and fresh matter compared with cvs. Stella and Pira Verde. The results showed that

Table 5 - Coefficient of determination (R^2), Akaike information criterion (AIC), residual standard deviation (RSD), intrinsic curvature measures (ICM), curvature measures of the parameter effect (PE), inflection point (IP), maximum acceleration point (MAP), and maximum deceleration point (MDP) of the Logistc model for characters (1) as a function of the accumulated thermal sum (in °C) of lettuce cultivars (Gloriosa, Pira Verde, and Stella) in two experiments.

Statistic		FLM	DLM	FSM	DMS	FLM	DLM	FSM	DMS
		--Experiment 1--				--Experiment 2--			
--Gloriosa--									
R²		0.966	0.924	0.966	0.928	0.966	0.950	0.967	0.951
AIC		7.287	1.234	7.342	1.301	6.427	0.825	6.546	0.984
RSD		36.621	1.777	37.635	1.838	23.708	1.439	25.157	1.558
ICM		0.109	0.163	0.108	0.158	0.109	0.129	0.105	0.127
PE		1.817	0.479	1.901	0.494	0.985	1.461	1.085	1.634
IP	x	296.197	230.903	298.366	233.091	315.854	330.376	325.917	340.785
	y	322.271	8.075	335.971	8.579	187.474	9.936	211.747	11.334
MAP	x	220.526	187.118	221.960	187.895	232.902	242.235	240.261	250.828
	y	136.208	3.413	141.998	3.626	79.236	4.199	89.495	4.790
MDP	x	371.869	274.688	374.773	278.287	398.806	418.517	411.573	430.742
	y	508.335	12.738	529.944	13.532	295.712	15.673	333.999	17.878
--Pira Verde--									
R²		0.965	0.940	0.966	0.940	0.962	0.916	0.963	0.918
AIC		5.731	0.264	5.809	0.372	6.614	0.971	6.674	1.039
RSD		16.605	1.083	17.267	1.144	25.990	1.546	26.785	1.600
ICM		0.197	0.188	0.198	0.184	0.121	0.192	0.119	0.187
PE		6.247	1.674	6.484	1.665	0.742	1.004	0.758	1.036
IP	x	251.318	222.612	252.083	222.943	293.726	276.446	296.137	280.373
	y	177.378	6.457	185.993	6.786	178.727	6.717	186.571	7.133
MAP	x	203.463	186.614	204.330	187.472	222.577	208.694	224.112	210.537
	y	74.969	2.729	78.610	2.868	75.539	2.839	78.854	3.015
MDP	x	299.173	258.610	299.836	258.414	364.876	344.198	368.162	350.208
	y	279.787	10.185	293.376	10.704	281.915	10.596	294.289	11.251
--Stella--									
R²		0.936	0.930	0.936	0.929	0.824	0.772	0.826	0.771
AIC		6.467	0.279	6.546	0.409	8.072	1.987	8.171	2.143
RSD		24.014	1.096	24.968	1.170	53.860	2.570	56.593	2.778
ICM		0.169	0.153	0.172	0.160	0.316	0.354	0.310	0.349
PE		1.810	0.596	1.918	0.624	1.284	1.623	1.342	1.741
IP	x	226.871	215.800	227.530	216.468	287.776	282.866	291.759	289.191
	y	133.717	5.204	139.610	5.507	142.373	5.955	152.980	6.549
MAP	x	195.620	193.800	195.930	194.403	235.624	223.593	237.453	227.270
	y	56.515	2.200	59.006	2.328	60.174	2.517	64.657	2.768
MDP	x	258.122	237.801	259.129	238.533	339.928	342.140	346.065	351.112
	y	210.918	8.209	220.213	8.687	224.573	9.393	241.303	10.330

(1) FLM: fresh leaf matter, as g $plant^{-1}$; DLM: dry leaf matter, as g $plant^{-1}$; FSM: fresh shoot matter, as g $plant^{-1}$; and DSM: dry shoot matter, as g $plant^{-1}$.

iceberg cultivars need higher thermal sum during the autumn-winter period, due to the process of formation of a compact commercial head (YURI et al., 2017).

The characters fresh leaf matter and fresh shoot matter represent the edible part of the lettuce, that is, the part of major commercial interest. Thus, the fresh mass has greater relevance than the dry matter. Accordingly, the inflection points of the fresh leaf mass and aerial part can be used in a practical way, since the accumulated thermal sum (IPx) reflects the amount of mass accumulated (IPy) near the harvest point. Therefore, this information is useful for producers and researchers that work with this crop.

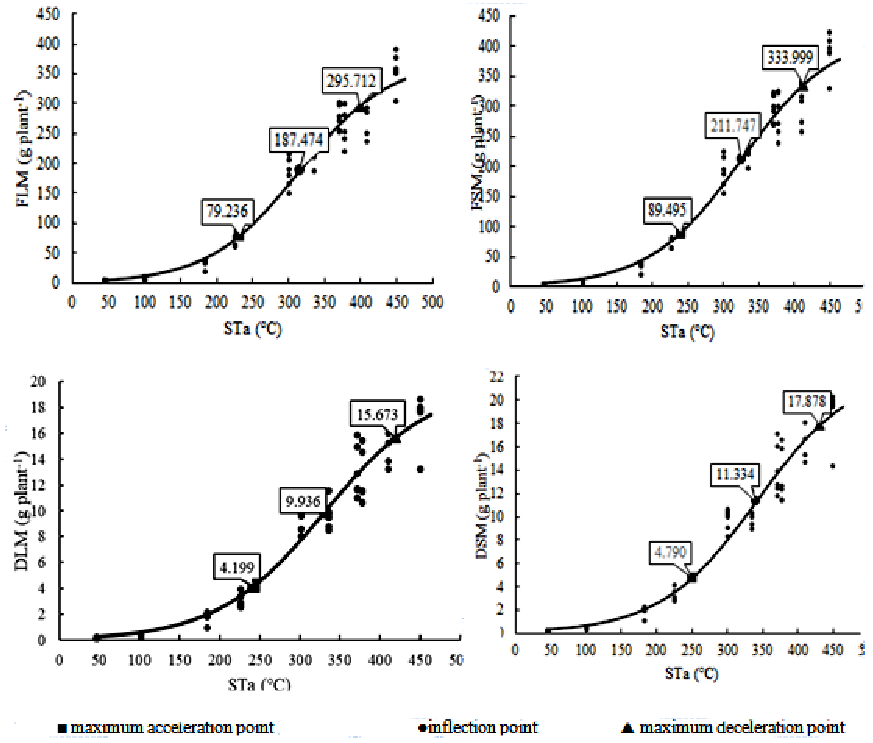

Figure 1 - Logistic model plot for fresh leaf matter (FLM, as g plant-1), dry leaf matter (DLM as g plant-1), fresh shoot matter (FSM, as g plant-1), and dry shoot matter (DSM, as g plant-1) as a function of the accumulated thermal sum (STa, in °C), for the cultivar Gloriosa, in experiment 2.

The results of this study showed that the Logistic nonlinear growth model and its critical points are relevant to help the selection of promising lettuce cultivars. The Logistic model was also used to describe the growth curve of dry matter of the aerial part, the bulb and the whole plant of the onion culture (PÔRTO et al., 2006), the production of genotype tomato (SARI et al., 2019) and to describe the production of strawberry cultivars from different seedling origins grown on organic substrates (DIEL et al., 2018).

The parameters of the Logistic model were estimated as a function of the relations between the productive characters and the accumulated thermal sum. The parameters (*a*, *b* and *c*) estimated in this study can be used for simulation and prediction of growth of cvs. Gloriosa, Pira Verde, and Stella in the autumn-winter period, for research or production. However, we recommend the use of the thermal sum from the crop site, because the lettuce crop is more influenced by temperature during its vegetative phase (LOPES et al., 2004). Thus, this prediction can be used, but the values obtained will be approximated to those reported in this study and should follow its growth curve pattern. In addition, because we found no studies focusing on growing these cultivars in autumn-winter, the models developed here can become a reference for further research.

CONCLUSION

The growth models developed show differences between the experiments (years) and among the cultivars. The Logistic and Gompertz growth models showed a satisfactory Goodness-of-fit for the fresh and dry matter of leaves and fresh and dry matter of shoots of the lettuce cultivars Gloriosa, Pira Verde, and Stella, in autumn and winter. The Logistic model best describes the growth of the lettuce cultivars.

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DECLARATION OF CONFLICT OF INTERESTS

The authors declare no conflict of interest. The founding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results.

AUTHORS' CONTRIBUTIONS

The authors contributed equally to the manuscript.

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