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Fitting a logistic growth model to yield traits in lettuce cultivars growing in summer

Ajuste del modelo logístico para caracteres productivos de cultivares de lechuga en condiciones de verano

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Lettuce cultivars experiment view.

Photo: F. Carini

ABSTRACT

The objective of this study was to fit a logistic model to leaf fresh and dry matter and shoot fresh and dry matter in four lettuce cultivars to describe growth in summer. The cultivars Crocantela, Elisa, Rubinela, and Vera were evaluated in the summers of 2017 and 2018 in soil in a protected environment and in a soilless system. Seven days after transplanting, the leaf fresh and dry matter and shoot fresh and dry matter of 8 plants were weighed every 4 days. The model parameters were estimated using R software with the least squares method and iterative process of Gauss-Newton. This study also estimated the confidence intervals of the parameters, verified the assumptions of the models, calculated the goodness-of-fit measures and the critical points, and quantified the parametric and intrinsic nonlinearities. The logistic growth model fit well to the fresh and dry matter in the leaves and shoots in the cultivars Crocantela, Elisa, Rubinela, and Vera and described the growth of lettuce.

Additional key words: *Lactuca sativa*; plant models; crop modelling; non-linear models; vegetable crop.

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RESUMEN

El objetivo de este trabajo fue ajustar el modelo Logístico para las masas fresca y seca de hojas y las masas fresca y seca de parte aérea de cuatro cultivares de lechuga para describir el crecimiento en el verano. Se utilizaron los cultivares de lechuga Crocantela, Elisa, Rubinela y Vera, cultivados en el verano de los años 2017 y 2018, en ambiente protegido y cultivo sin suelo. Después de 7 días del trasplante, se determinó las masas fresca y seca de hojas y las masas fresca y seca de parte aérea de 8 plantas, estas evaluaciones se realizaron cada 4 días. Los parámetros del modelo fueron estimados utilizando el software R, por el método de mínimos cuadrados y proceso iterativo de Gauss-Newton. También se estimaron los intervalos de confianza de los parámetros, verificados los supuestos, calculados los indicadores de calidad del ajuste, los puntos críticos y cuantificados las no linealidades paramétrica e intrínseca. El modelo de crecimiento logístico presentó un ajuste satisfactorio para las masas fresca y seca de hojas y para las masas fresca y seca de parte aérea para las cultivares de lechuga Crocantela, Elisa, Rubinela y Vera, siendo así, indicado para describir el crecimiento de los cultivares de lechuga.

Palabras clave adicionales: *Lactuca sativa*; modelos vegetales; modelación de cultivos; modelos no lineales; cultivo de hortalizas.

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INTRODUCTION

Lettuce is a leafy green vegetable in the Asteraceae family, consumed as raw salads, broths, and soups, that has high vitamin and mineral contents and few calories (Ntsoane *et al*., 2016). In Brazil, lettuce production has economic and social importance, generating jobs and income for family agriculture (Andriolo, 2017).

Since lettuce originated from a temperate climate, temperatures above 30ºC induce flowering, reducing the vegetative phase and number of leaves and affecting the formation of compact heads. The optimum temperature for this crop varies between 15.5 and 18.3°C, with a minimum of 7.2°C and a maximum of 23.9°C (Maynard and Hochmuth, 2007). Genetic improvement techniques have developed cultivars that are tolerant to early bolting with extended cultivation in other seasons and sites.

Lettuce cultivars are classified into groups according to the morphological characteristics of the leaves, head shape, and color, such as iceberg, looseleaf (lollo and oakleaf), butterhead, romaine, and others (Sala and Costa, 2012). The selection of cultivars adapted to the climatic conditions and the crop growing system are determining factors for production success. In addition, in protected environments, during the summer (December to March) in Rio Grande do Sul, high temperatures still affect the quality and palatability of lettuce leaves.

Nonlinear models are widely used in agricultural research (Archontoulis and Miguez, 2015). To describe the growth of plants and fruits, the accumulation of matter over time must be measured. Nonlinear models are important for the proper management and improvement of research methodologies related to lettuce (Terra *et al*., 2010). These tools evaluate the growth rate, stabilization, and reduction of production at the end of the cycle (Mischan and Pinho, 2014).

Empirical models are often used to estimate plant growth and their components, including the logistic model. These model have already been applied to describe the dry matter accumulation in *Allium sativum* (Reis *et al*., 2014), production of strawberry cultivars (Diel *et al*., 2018), production of tomato genotypes (Sari *et al*., 2019), production of *Cucurbita pepo* and *Capsicum annuum* (Lúcio *et al*., 2015), growth of coffee cultivar Rubi MG 1192 (Pereira *et al*., 2014), morphological characters of *Crotalaria juncea* (Bem *et al*., 2017), and growth of green dwarf coconut (Prado *et al*., 2013), cacao (Muniz *et al*., 2017), and Asian pear (Ribeiro *et al*., 2018).

For lettuce, the Gompertz, logistic, and Expolinear models were fit to the leaf dry matter of cultivars Grand Rapids, Regina, and Great Lakes in a hydroponic system in summer (Lyra *et al*., 2003). Studies were also carried out to analyze the growth of lettuce, variety Batavia, in saline soils, using the logistic model (Carranza *et al*., 2009). However, studies that describe growth using nonlinear models for other cultivars, traits, and goodness-of-fit measures were not found.

The objectives of this study were to adjust the logistic model to fit the leaf and shoot fresh and dry matter of four lettuce cultivars (Crocantela, Elisa, Rubinela, and Vera) and to describe the growth of these cultivars in summer.

MATERIALS AND METHODS

Two experiments on the lettuce crop were carried out, one in the summer of 2017 (experiment 1) and the other in the summer of 2018 (experiment 2) in Santa Maria-RS (Brazil) (29°42'S, 53°49'W and 95 m altitude) in a protected environment, of the rain shelter type. The climate of the region is humid subtropical Cfa, with hot summers and an undefined dry season, according to the Köppen classification (Alvares *et al*., 2013).

The evaluated cultivars were: Crocantela (iceberg - green leaves, consistent, crisp, loose, prominent ribs, non-heading); Elisa (butterhead - delicate leaves – loosely-formed head); Rubinela (lollo, loose purple leaves, non-heading), and Vera (lollo - green crisp - consistent, loose leaves, and non-heading). The selection of the genetic material was based on the meteorological characteristics of the cultivation site during the crop cycle and the seed companies' recommendations. Seedlings were produced in 200-cell expanded polystyrene trays filled with commercial Plantmax® substrate in a floating system. Plants with four to five leaves were transplanted on 01/27/2017 (experiment 1) and 09/02/2018 (experiment 2).

The plants were grown on six benches made of corrugated fiber cement sheets, 3.66 m long, 1.10 m wide, 6 mm thick, with six troughs with a depth of 5 cm. The culture channels were waterproofed with 100 μm-thick, clear plastic film and filled with number two washed gravel. The troughs were covered with clear, 100-μm-thick plastic film and filled with number two.washed gravel The benches were raised (0.85 m) on fixed masonry blocks at both ends with a 2% slope. 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). This pipe had four drip hoses with pots placed under the drippers at a distance of 30 cm between plants in a row, with a plant density of 11.11 m^{-2}. Each bench had four rows, totaling 44, with 3 L volume pots (11 pots per row) filled with washed sieved coarse sand with 0 dS m^{-1} electrical conductivity.

The macronutrient composition of the nutrient solution was as follows (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+}; and 1.0 Mg^{2+}; and the micronutrients were (mg L^{-1}): 1.0 Fe; 0.50 Mn; 0.22 Zn; 0.26 B; 0.06 Cu, and 0.03 Mo. The electrical conductivity (EC) was maintained at 1.33 dS m^{-1} , and the pH was between 5.5 and 6.5 in both experiments. The EC and pH were monitored during cultivation and corrected when they presented a variation of 20%, higher or lower, in relation to the standard EC and pH.

Seven days after transplantation, evaluations started with eight plants of each cultivar. Then, the evaluations took place every 4 d until the beginning of flowering. Ten evaluations were performed for the two experiments, totaling 80 plants of each cultivar, except for cultivar Elisa in experiment 1, which had 64 plants assessed in eight evaluations. There were 624 plants analyzed in the two experiments for the four cultivars. The fresh leaf matter (FLM, in g/plant), dry leaf matter (DLM, in g/plant), fresh shoot matter (FSM, in g/plant), and dry shoot matter (DSM, in g/plant) were determined in these plants. To obtain the dry matter, the material was packed into paper bags and incubated in a forced circulation oven (60°C ±5°C) to constant matter.

The data on the indoor air temperature were recorded every three hours with a digital data logger (0.1°C resolution and 0.5°C accuracy) installed in a weatherproof shelter. With the data, the daily thermal sum was calculated with the method of Gilmore and Rogers (1958) and Arnold (1959), using equations (1) and (2)

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

where *Tmax* is maximum daily temperature, °C; *Tmin* is the daily minimum temperature, °C; and *Tb* is the lettuce base temperature = 10°C (Brunini, 1976)

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

where *ATS* is accumulated thermal sum, and $\sum STd$ is the daily thermal sum.

The fitting of the logistic model to each trait (dependent variable), with the repetitions of each evaluation, as a function of the accumulated thermal sum (ATS) (independent variable) was performed using the least squares method and the iterative process of Gauss-Newton. The equation was: $y_i = a/[1+exp(-b -cx_i)]$ where, yi 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; and c is associated with growth, indicating the growth rate.

The assumptions of normality, independence, and homogeneity of the errors were verified using the Shapiro-Wilk, Durbin-Watson, and Breusch-Pagan tests, respectively. Traits that did not meet the assumptions were Box-Cox transformed with the statistical software Action.

The lower and upper limits of the 95% confidence interval were calculated, and, using the criterion of overlapping of the confidence intervals, the estimates of the parameters (a, b and c) for each trait were compared between the experiments in each cultivar and between the cultivars in each experiment.

The goodness-of-fit of the model was assessed with an adjusted coefficient of determination (R^2 aj), in which the best fit is the one closest to 1, the Akaike Information Criterion (AIC) and the residual standard deviation (RSD), in which the best fit for both is the one closest to zero. The intrinsic nonlinearity (IN) and the parameter-effects nonlinearity (PE) were quantified based on the geometric concept of curvature (Bates and Watts, 1988). The inflection point (IP), the maximum acceleration point (MAP), and the maximum deceleration point (MDP) were calculated according to the equations described by Mischan and Pinho (2014). Inferences about plant growth were made from these critical points. The calculations were made using Microsoft Office Excel® applications and the software R (R Development Core Team, 2018).

RESULTS AND DISCUSSION

In both experiments, the Shapiro-Wilk, Durbin-Watson, and Breusch-Pagan tests had p-values greater than or equal to 0.05 (Tab. 1). Thus, the assumptions of normality, independence, and homogeneity of errors were met for the residuals of the model for the

Table 1. P-value of the Shapiro-Wilk (SW), Durbin-Watson (DW), and Breusch-Pagan (BP) tests applied to Logistic residuals for characteristics as a function of cumulative thermal sum of four lettuce cultivars in two experiments.

Character	Cultivars	SW	DW	BP	SW	DW	BP
		Experiment 1			Experiment 2		
FLM	'Crocantela'	0.92	0.10	0.12	0.17	0.69	0.57
	'Elisa'	0.16	0.35	0.07	0.08	0.47	0.18
	'Rubinela'	0.56	0.57	0.05	0.09	0.20	0.74
	'Vera'	0.22	0.14	0.06	0.90	0.65	0.05
DLM	'Crocantela'	0.42	0.30	0.07	0.28	0.57	0.07
	'Elisa'	0.69	0.22	0.06	0.09	0.16	0.28
	'Rubinela'	0.17	0.84	0.11	0.07	0.29	0.11
	'Vera'	0.14	0.10	0.08	0.08	0.27	0.06
FSM	'Crocantela'	0.89	0.24	0.14	0.19	0.72	0.89
	'Elisa'	0.82	0.47	0.10	0.88	0.33	0.21
	'Rubinela'	0.60	0.84	0.09	0.10	0.24	0.54
	'Vera'	0.42	0.08	0.80	0.96	0.91	0.12
DSM	'Crocantela'	0.30	0.16	0.06	0.19	0.36	0.07
	'Elisa'	0.28	0.18	0.11	0.51	0.10	0.49
	'Rubinela'	0.23	0.66	0.07	0.05	0.32	0.09
	'Vera'	0.06	0.11	0.05	0.07	0.57	0.05

FLM: fresh leaf matter; DLM: dry leaf matter; FSM: fresh shoot matter; and DSM: dry shoot matter.

fresh and dry matter of the leaves and shoots of the lettuce cultivars. Similar results were found for a tomato crop, indicating that the estimation of the parameters with the method of ordinary least squares is adequate (Carini *et al.*, 2019; Sari *et al*., 2019).

For each trait of the logistic model, the estimates of the parameters (*a*, *b*, and *c*) were compared between the experiments (Tab. 2) and between the cultivars (Tab. 3) with the criterion of overlapping confidence intervals. As an illustration of the use of the criterion of overlapping 95% confidence intervals (CI), the DLM of cv. Crocantela was selected to compare the estimate of parameter a with the logistic model between experiments 1 and 2 (Tab. 2). The estimate of parameter a (361.4624) in experiment 1 was found to lie outside the confidence interval of the estimate of parameter *a* in experiment 2 (375.3193 to 407.5963). However, the estimate of parameter *a* (391.4578) in experiment 2 is within the confidence interval of the estimate of parameter *a* of experiment 1 (312.2015 to 410.7332). Thus, when at least one of the estimates is within the CI of the other, the effect is non-significant. On the other hand, when two estimates lie outside the confidence interval, they differ between the experiments.

Table 2. **Estimation of the parameters *a*, *b*, and *c*, lower limit (LL) and upper limit (UL) of the confidence interval (CI95%) of the logistic model for the traits as a function of accumulated thermal sum (in ºC) of lettuce cultivars (Crocantela, Elisa, Rubinela, and Vera) in two experiments in the summer.**

Character	Parameter	Estimates	CI95%		Estimates	CI95%	
			LL	UL		LL	UL
		Experiment 1			Experiment 2		
'Crocantela'							
FLM	a^{NS}	361.4624	312.2015	410.7232	391.4578	375.3193	407.5963
	b^*	-5.2352	-6.3805	-4.0899	-6.7770	-7.6323	-5.9217
	c^*	0.0097	0.0071	0.0124	0.0160	0.0138	0.0182
DLM	a^{NS}	22.2816	12.9211	31.6422	15.2970	14.3764	16.2177
	b^*	-4.9474	-5.9063	-3.9886	-7.5154	-9.2015	-5.8292
	c^*	0.0073	0.0048	0.0099	0.0182	0.0139	0.0226
FSM	a^{NS}	476.9038	394.2911	559.5165	457.3523	436.4193	478.2853
	b^*	-5.1544	-6.1619	-4.1469	-6.6278	-7.4289	-5.8267
	c^*	0.0089	0.0066	0.0112	0.0152	0.0131	0.0172
DSM	a^{NS}	29.2298	14.6145	43.8450	18.0644	16.9789	19.1500
	b^*	-5.1348	-6.0036	-4.2660	-7.1991	-8.6089	-5.7893
	c^*	0.0072	0.0047	0.0097	0.0169	0.0133	0.0205
'Elisa'							
FLM	a^*	185.2778	169.8337	200.7219	244.3639	222.4487	266.2790
	b^{NS}	-6.6950	-8.7591	-4.6309	-8.1763	-11.2348	-5.1177
	c^{NS}	0.0179	0.0121	0.0238	0.0207	0.0128	0.0287
DLM	a^*	8.9630	7.2465	10.6795	12.6729	11.5186	13.8272
	b^*	-4.8269	-6.6855	-2.9683	-7.9188	-10.8457	-4.9919
	c^*	0.0119	0.0064	0.0173	0.0199	0.0123	0.0275
FSM	a^*	300.6402	275.2325	326.0478	376.2930	353.6540	398.9319
	b^*	-5.9503	-7.0829	-4.8177	-8.4225	-10.4071	-6.4378
	c^*	0.0139	0.0109	0.0169	0.0195	0.0146	0.0244
DSM	a^*	12.0021	9.5491	14.4550	17.3384	15.9877	18.6890
	b^*	-5.0590	-6.7237	-3.3943	-7.7846	-10.0156	-5.5535
	c^*	0.0115	0.0068	0.0161	0.0183	0.0127	0.0240

Continues...

Table 2.

Character	Parameter	Estimates	IC95%		Estimativa	IC95%	
			LL	UL		LL	UL
		Experiment 1			Experiment 2		
'Rubinela'							
FLM	*a* NS	290.3400	231.9672	348.7129	299.5631	280.2090	318.9172
	b *	-4.5073	-5.1155	-3.8992	-6.5113	-7.2516	-5.7709
	c *	0.0073	0.0057	0.0090	0.0138	0.0119	0.0157
DLM	*a* NS	24.2729	5.4084	43.1373	11.2546	10.3438	12.1655
	b *	-4.5282	-4.9548	-4.1016	-7.1432	-8.8810	-5.4055
	c *	0.0055	0.0039	0.0071	0.0164	0.0120	0.0208
FSM	*a* NS	440.1027	318.3813	561.8241	349.3106	326.0222	372.5991
	b *	-4.6709	-5.1383	-4.2035	-6.4519	-7.1002	-5.8036
	c *	0.0068	0.0054	0.0082	0.0133	0.0117	0.0150
DSM	*a* NS	33.9705	1.7778	66.1632	12.8154	11.7420	13.8889
	b *	-4.8280	-5.3390	-4.3170	-6.9138	-8.4208	-5.4068
	c *	0.0055	0.0040	0.0070	0.0155	0.0117	0.0194
'Vera'							
FLM	*a* *	418.9802	382.8992	455.0612	355.1664	323.8265	386.5064
	b *	-5.1416	-5.6644	-4.6188	-6.5101	-7.7919	-5.2284
	c *	0.0090	0.0078	0.0102	0.0144	0.0111	0.0178
DLM	*a* *	29.6956	20.5754	38.8158	14.6730	13.5342	15.8117
	b *	-4.9483	-5.4720	-4.4246	-7.2819	-9.1636	-5.4002
	c *	0.0070	0.0055	0.0085	0.0171	0.0123	0.0219
FSM	*a* *	612.9969	536.9193	689.0745	440.9334	399.6508	482.2160
	b *	-5.1509	-5.6253	-4.6766	-6.5082	-7.6124	-5.4040
	c *	0.0082	0.0070	0.0093	0.0139	0.0110	0.0167
DSM	*a* *	40.0535	25.5274	54.5796	18.0346	16.5610	19.5082
	b *	-5.1771	-5.6506	-4.7036	-7.1899	-8.8487	-5.5310
	c *	0.0070	0.0055	0.0084	0.0162	0.0120	0.0204

FLM: fresh leaf matter, as g/plant; DLM: dry leaf matter, as g/plant; FSM: fresh shoot matter, as g/plant; and DSM: dry shoot matter, as g/plant. Comparison of the estimates of the parameters (*a*, *b*, and *c*) between the experiments. *Significant effect at 0.05 probability level. NS: Non-significant.

Table 3. Comparison of the estimates of the parameters (*a*, *b*, and *c*) of the logistic model for the traits as a function of the accumulated thermal sum, based on the confidence interval (CI95%) between lettuce cultivars (Crocantela, Elisa, Rubinela and Vera) in two experiments in the summer.

Cultivars	Cultivars	FLM	DLM	FSM	DSM	FLM	DLM	FSM	DSM
		Experiment 1				Experiment 2			
a									
'Crocantela'	'Elisa'	*	*	*	*	*	*	*	NS
'Crocantela'	'Rubinela'	*	NS	NS	NS	*	*	*	*
'Crocantela'	'Vera'	*	NS	*	NS	*	NS	NS	NS
'Elisa'	'Rubinela'	*	NS	*	NS	*	*	*	*
'Elisa'	'Vera'	*	*	*	*	*	*	*	NS
'Rubinela'	'Vera'	*	NS	*	NS	*	*	*	*

Continues...

Table 3.

b									
'Crocantela'	'Elisa'	NS	NS	NS	NS	NS	NS	NS	NS
'Crocantela'	'Rubinela'	NS	NS	NS	NS	NS	NS	NS	NS
'Crocantela'	'Vera'	NS	NS	NS	NS	NS	NS	NS	NS
'Elisa'	'Rubinela'	*	NS	*	NS	NS	NS	NS	NS
'Elisa'	'Vera'	NS	NS	NS	NS	NS	NS	NS	NS
'Rubinela'	'Vera'	*	NS	*	NS	NS	NS	NS	NS
c									
'Crocantela'	'Elisa'	*	NS	*	NS	NS	NS	NS	NS
'Crocantela'	'Rubinela'	NS	NS	NS	NS	NS	NS	NS	NS
'Crocantela'	'Vera'	NS	NS	NS	NS	NS	NS	NS	NS
'Elisa'	'Rubinela'	*	*	*	*	NS	NS	*	NS
'Elisa'	'Vera'	*	NS	*	NS	NS	NS	*	NS
'Rubinela'	'Vera'	NS	NS	NS	NS	NS	NS	NS	NS

FLM: fresh leaf matter, as g/plant; DLM: dry leaf matter, as g/plant; FSM: fresh shoot matter, as g/plant; and DSM: dry shoot matter, as g/plant. Comparison of the parameters estimates (*a*, *b* and *c*) between the experiments: * Significant effect at 0.05 probability of error. NS: Non-significant.

In the logistic model, the behavior of the estimates of parameter *a* of the cultivars Crocantela and Rubinela was the same, with asymptotic values that did not differ between all traits. The opposite behavior was found for parameters *b* and *c*, which were different between the experiments (Tab. 2). The traits DLM, FSM, and DSM of cv. Elisa showed differences for all parameters, and the asymptotic values in experiment 2 were higher than those in experiment 1, indicating that the plants had a greater fresh matter production in experiment 2. All traits of cv. Vera differed in relation to the parameters *a*, *b*, and *c*. These findings showed that the growth models were different between experiments 1 and 2. Different models were also selected for different experiments for the production of tomato genotypes (Sari *et al*., 2019).

The comparison between cultivars in each experiment showed that, for the logistic model, in experiment 1, the traits DLM, FSM and DSM did not differ between 'Crocantela' and 'Rubinela', and the traits DLM and DSM did not differ between 'Crocantela' and 'Vera' or between 'Rubinela' and 'Vera' (Tab. 3). In experiment 2, the estimates of DLM, FSM and DSM did not differ between 'Crocantela' and 'Vera', and DSM did not differ between 'Crocantela' and 'Elisa' or between 'Elisa' and 'Vera'. The other comparisons showed a difference in at least one of the three parameters of the logistic model. Differences predominated for the logistic model, indicating the need for specific models for each trait and cultivar. Different models were also needed to describe production in *Cucurbita pepo* and *Capsicum annuum* (Lúcio *et al*., 2015) and fruit production estimates in *Lycopersicon esculentum* var. *cerasiforme* (Lúcio *et al.*, 2016).

Goodness-of-fit measures were used to determine the model that best fit the original data. The logistic model showed acceptable goodness-of-fit values (high R^2, low AIC, and intermediate RSD) that were close to each other (Tab. 4). Lyra *et al*. (2003) also reported high coefficients of determination but did not use other goodness-of-fit measures, which was seen as a limitation in the study.

Although the models showed satisfactory goodness-of-fit, a small overestimation occurred for the logistic model in 'Rubinela' in Experiment 1, with an asymptotic value of 440.1027 for FSM, and the maximum value of 368.30 g/plant was observed in the data set. The tendency for overestimations in the logistic model was also reported in the modeling of production during the formation of sugarcane (Batista *et al*., 2013). However the use of models to describe the accumulation of dry mass in garlic plant accessions did not present an overestimation of parameters for the Logistic model but did for the Brody, von Bertalanffy and Mitscherlich models (Puiatti *et al*., 2013).

Intrinsic nonlinearity (IN) and parameter-effects nonlinearity (PE) are used to help in the determination of the model. The logistic model presented reduced values of IN and PE for all traits, cultivars, and experiments (Tab. 4). The lower values of IN and PE indicated better suitability of the logistic model. These criteria were also adopted to indicate the most appropriate model to describe production in strawberries (Diel *et al*., 2018) and salad tomato genotypes (Sari *et al*., 2019).

Table 4. Coefficient of determination adjusted (R^2 aj), Akaike information criterion (AIC), residual standard deviation (RSD), intrinsic nonlinearity (IN), nonlinearity of the parameter effect (PE), inflection point (IP) , maximum acceleration point (MAP), and maximum deceleration point (MDP) of the Logistic model for characters as a function of the accumulated thermal sum (in °C) of lettuce cultivars (Crocantela, Elisa, Rubinela and Vera) in two experiments.

Statistic		FLM	DLM	FSM	DSM	FLM	DLM	FSM	DSM
		Experiment 1				Experiment 2			
Crocantela									
R^2 aj		0.884	0.844	0.896	0.861	0.974	0.927	0.976	0.944
AIC		7.668	1.727	7.933	1.926	6.488	1.139	6.674	1.147
RSD		44.576	2.285	50.907	2.525	24.712	1.705	27.115	1.711
PE		1.140	4.479	1.520	5.838	0.355	0.468	0.426	0.529
IN		0.169	0.173	0.154	0.166	0.101	0.175	0.098	0.157
IP	x	537.368	674.108	579.890	712.798	423.085	412.157	436.856	426.523
	y	180.731	11.141	238.452	14.615	195.729	7.649	228.676	9.032
MAP	x	402.188	494.667	431.726	529.982	340.868	339.933	350.051	348.498
	y	76.386	4.709	100.782	6.177	82.725	3.233	96.650	3.817
MDP	x	672.548	853.549	728.054	895.615	505.303	484.382	523.661	504.547
	y	285.076	17.573	376.122	23.053	308.733	12.064	360.702	14.247
Elisa									
R^2 aj		0.864	0.722	0.934	0.784	0.814	0.817	0.935	0.895
AIC		6.579	1.121	6.589	1.308	7.786	1.836	7.412	1.770
RSD		29.039	1.895	29.195	2.081	47.308	2.415	39.349	2.338
PE		0.666	1.558	0.677	1.705	0.593	0.620	0.560	0.675
IN		0.243	0.275	0.147	0.241	0.275	0.276	0.193	0.230
IP	x	373.847	405.774	429.476	441.149	394.710	397.842	431.857	424.509
	y	92.639	4.482	150.320	6.001	122.182	6.336	188.146	8.669
MAP	x	300.309	295.063	334.422	326.310	331.133	331.678	364.331	352.692
	y	39.154	1.894	63.533	2.536	51.640	2.678	79.520	3.664
MDP	x	447.386	516.485	524.530	555.989	458.286	464.007	499.383	496.326
	y	146.124	7.069	237.107	9.466	192.724	9.995	296.773	13.674
Rubinela									
R^2 aj		0.924	0.903	0.941	1.530	0.977	0.916	0.981	0.929
AIC		6.303	0.352	6.487	0.498	5.643	0.601	5.694	0.639
RSD		22.542	1.150	24.732	1.237	16.199	1.303	16.613	1.327
PE		1.954	13.526	3.135	19.553	0.665	0.755	0.696	0.816
IN		0.108	0.101	0.093	0.096	0.091	0.197	0.081	0.176

Continues...

Table 4.

IP	x	613.956	828.298	688.861	882.761	471.953	435.302	483.970	445.222
	y	145.170	12.136	220.051	16.985	149.782	5.627	174.655	6.408
MAP	x	434.570	587.400	494.637	641.966	376.497	355.047	385.182	360.414
	y	61.356	5.129	93.005	7.179	63.305	2.378	73.818	2.708
MDP	x	793.342	1069.197	883.086	1123.557	567.410	515.556	582.758	530.029
	y	228.984	19.143	347.098	26.792	236.258	8.876	275.493	10.107
Vera									
R^2 aj		0.970	0.938	0.971	0.946	0.937	0.907	0.951	0.925
AIC		6.375	1.096	6.838	1.332	7.120	1.280	7.222	1.407
RDP		23.421	1.668	29.548	1.877	33.880	1.829	35.650	1.948
PE		0.750	3.548	1.180	4.631	0.866	0.680	0.959	0.796
IN		0.080	0.102	0.076	0.098	0.159	0.208	0.136	0.187
IP	x	573.692	704.507	629.627	743.069	450.795	425.772	469.360	443.158
	y	209.490	14.848	306.498	20.027	177.583	7.336	220.467	9.017
MAP	x	426.748	517.007	468.647	554.045	359.602	348.770	374.384	361.985
	y	88.541	6.275	129.541	8.464	75.055	3.101	93.180	3.811
MDP	x	720.637	892.007	790.606	932.093	541.989	502.774	564.336	524.331
	y	330.439	23.420	483.455	31.589	280.111	11.572	347.753	14.223

FLM: fresh leaf matter, as g/plant; DLM: dry leaf matter, as g/plant; FSM: fresh shoot matter, as g/plant; and DSM: dry shoot matter, as g/plant.

Analyzing the five goodness-of-fit measures (R^2, AIC, RSD, IN, and PE) showed that the logistic model was suitable for all traits and experiments for the cultivars Crocantela, Elisa, Rubinela, and Vera, and the most suitable for describing growth in lettuce cultivars. The cultivar Crocantela in experiment 2 served as example of the shape of the logistic growth curve and the respective critical points for each trait (Fig. 1).

Critical points are used to describe crop growth (Tab. 4). The logistic model, for most of the cultivars in experiment 2, showed that the inflection point (IP) coincided with the plant stage closest to harvest, with the appearance of senescent outer leaves, which in practice is one of the criteria used for the commercial classification of the product. Also, the maximum acceleration point occurred at the beginning of the curve in experiment 2, with small plants still showing young leaves. In general, among the cultivars, cv. Elisa reached IP with the lowest ATS, independent of the experiment. However, 'Rubinela' required a greater accumulated thermal sum and showed lower values for the traits than the cultivars Vera (experiment 1) and Crocantela (experiment 2). These results indicate that the cultivars Vera and Crocantela were able to use the accumulated thermal sum efficiently. The maximum deceleration points (MDP) referred to the final growth stage of the cultivars, in which the crop was close to the beginning of flowering. Therefore, the inflection point is an alternative for future projections related to crop planning.

In this study, the logistic model described the growth of the lettuce satisfactorily in order to assist in the selection of promising cultivars. In addition, the logistic model was used to describe the growth curve of pruned coffee trees (Pereira *et al*., 2016), the accumulation of macronutrients in an onion crop (Pôrto *et al*., 2006), the production of strawberry cultivars from different seedling origins grown on organic substrates (Diel *et al*., 2018), the production of tomato genotypes (Sari *et al*., 2019), and the length, diameter, and matter of cocoa fruits (Muniz *et al*., 2017) and Asian pears (Ribeiro *et al*., 2018).

Simulation and prediction (parameters *a*, *b*, and *c*) can be used in the research or production of the cultivars Crocantela, Elisa, Rubinela, and Vera in summer. However, the thermal sum of the growing site should be used to achieve conditions close to the real ones. Therefore, these models are a reference for further research, and the obtained values should maintain the pattern of the growth curve.

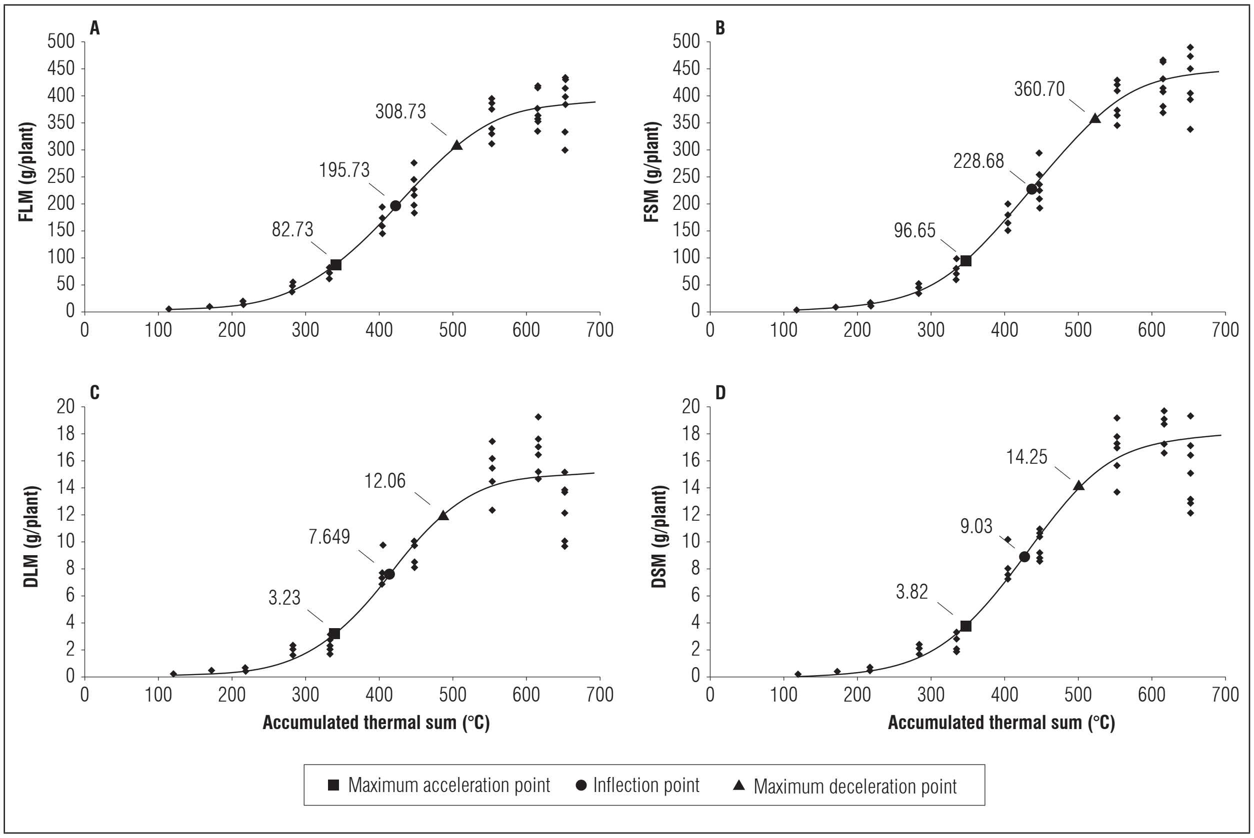

Figure 1. Logistic model plot for fresh leaf matter (FLM, as g/plant), dry leaf matter (DLM, as g/plant), fresh shoot matter (FSM, as g/plant), and dry shoot matter (DSM, as g/plant) as a function of the accumulated thermal sum (ATS, as °C) for the cultivar Crocantela in experiment 2.

CONCLUSION

The logistic growth model fit well to the fresh and dry matter of the leaves and shoots of the cultivars Crocantela, Elisa, Rubinela, and Vera and describes the growth of lettuce.

Conflict of interests: The manuscript was prepared and reviewed with the participation of the authors, who declare that there exists no conflict of interest that puts at risk the validity of the presented results.

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