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Growth Models for Lettuce Cultivars Growing in Spring

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Abstract

The objectives of this study were to adjust the Gompertz and logistic models to fit the fresh and dry matters of leaves and fresh and dry matters of shoots of four lettuce cultivars and indicate the model that best describes the growth in spring. Cultivars Ceres, Gloriosa, Grandes Lagos, and Rubinela were grown in protected environment and in soilless system, in the spring of 2016 and 2017. Seven days after transplantation, fresh and dry leaf matters and fresh and dry shoot matters were weighed every four days until beginning of flowering. The Gompertz and logistic models were adjusted as a function of accumulated thermal sum. The parameters of the Gompertz and logistic models and their confidence intervals were estimated, the assumptions of the models were verified, the goodness-of-fit measures and critical points were calculated, and the parametric and intrinsic nonlinearities quantified. The logistic and Gompertz growth models fitted well to fresh and dry leaf and shoot matters of cultivars Ceres, Gloriosa, Grandes Lagos, and Rubinela, under spring conditions. The logistic model is the most suitable to describe the growth of lettuce cultivars.

Keywords*:* *Lactuca sativa* L., non-linear models, growth curve, soilless cultivation, leaf green

1. Introduction

Lettuce (*Lactuca sativa* L.) is an annual leafy green vegetable originated from temperate climate and cultivated in several continents (Tadic et al., 2017). Its leaves are consumed without restrictions because of the high nutrient and fiber contents that provide health benefits (Martins, Butelli, Petroni, & Tonelli, 2011; Kosma, Triantafyllidis, Papasavvas, Salahas, & Patakas, 2013). It is a leafy green vegetable appreciated by the Brazilian population, justifying the production of 14 million plants annually (Santos et al., 2015).

Lettuce cultivars are classified into the group's iceberg, looseleaf (lollo and oakleaf), butterhead, romaine, and others, corresponding to 47.0%, 38.5%, 5.0%, 4.28%, 1.0%, and 4.22%, respectively, of the lettuce traded at CEAGESP-the General Warehousing Company of São Paulo (CEAGESP, 2017). Different genetic materials are on the market, with adaptations to growing seasons and morphological characteristics of leaves and head. Despite the protected environment, high summer and spring temperatures still compromise the quality and palatability of lettuce leaves. In Rio Grande do Sul, during the warmer months the average daily temperature varies from 18 to 26 °C (Kuinchtner & Buriol, 2001), but the ideal temperature for the crop is between 15.5 °C and 18.3 °C, with minimum of 7.2 °C and maximum of 23.9 °C (Maynard & Hochmuth, 2007).

Statistical models can be used in studies involving animal or plant growth process. Nonlinear models provide estimates of parameters with biological interpretation (Fernandes, Pereira, Muniz, & Savian, 2014). Thus, the models are an alternative for evaluating the growth curve of the crops, based on the accumulated thermal sum, and allow inferring on growth rate, stabilization, and reduction of production at the end of the cycle (Mischan & Pinho, 2014).

Nonlinear models aim to condense information from a series of data, from a given period, into a set of biologically interpretable parameters (Terra, Muniz, & Savian, 2010). The models were used in the plant production area to describe the accumulation of dry matter of garlic (Puiatti et al., 2013), the vegetative growth of coffee trees (Pereira, Fernandes, Scalco, & Morais, 2016), and the modeling of yield traits of crotalaria (Bem et al., 2018). In addition, they were used to describe the production of zucchini and pepper (Lúcio, Nunes, & Rego, 2015), strawberry (Diel et al., 2018), and salad-type tomato (Sari, Lúcio, Santana, & Savian, 2019).

In studies with lettuce, the Gompertz, logistic, and expolinear models were adjusted for cultivar Grand Rapids to fit different concentrations of the nutrient solution in summer (Macedo, 2004). However, studies describing the growth of lettuce cultivars with nonlinear models in other seasons and grown in protected environment were not found.

We assume that the Gompertz and logistic models are suitable to describe the growth of four lettuce cultivars in spring and that it is possible to select the most appropriate model. The objectives of this study were to adjust the Gompertz and logistic models for the fresh and dry matters of leaves and shoots of four lettuce cultivars and indicate the model that best describes the growth in spring.

2. Material and Methods

We conducted two experiments with lettuce cultivars: one in the spring of 2016 (experiment 1) and the other in the spring of 2017 (experiment 2), in a protected environment in Santa Maria, Rio Grande do Sul State (29º42′ S, 53º49′ W and 95 m altitude). The climate of the region is humid subtropical Cfa, with hot summers and no defined dry season, according to Köppen classification (Alvares, Stape, Sentelhas, Gonçalves, & Sparovek, 2013).

The cultivars evaluated were: Ceres (lollo-green crisp-consistent, loose leaves, and non-heading), Gloriosa and Grandes Lagos (iceberg-light green leaves, crisp, consistent, prominent ribs, compact head), and Rubinella (lollo, loose purple leaves, non-heading). The selection of these cultivars was based on the meteorological characteristics of the spring season and based on the seed companies' recommendations. Seedlings were produced in 200-cell expanded polystyrene trays filled with commercial Plantmax® substrate, in the floating system. Plants with four to five leaves were transplanted on 10/14/2016 (experiment 1) and 10/19/2017 (experiment 2).

Plants were grown in eight benches made 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 culture channels were waterproofed with clear plastic film of 100 µm and filled with washed gravel number two. The benches were raised (0.85 m) on fixed masonry blocks at the two end portions, 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). 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 plant density of 11.11 m^{-2}. Each bench consisted of four rows, totaling 44 pots with 3 L volume (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 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 Mo, Mo for lettuce crop, with electrical conductivity (EC) maintained at 1.33 dS m^{-1} and pH between 5.5 and 6.5. EC and pH were monitored throughout the crop cycle and corrected when they showed a variation of 20%, higher or lower, in relation to the standard.

The evaluations started with eight plants of each cultivar, at day seven after transplantation and were carried out every four days until the beginning of flowering. In experiment 1, eight evaluations were carried out, totalizing 64 plants of each cultivar. In experiment 2, ten evaluations were carried out, totalizing 80 plants of each cultivar. Including the four cultivars, in the two experiments, 576 plants were evaluated. These plants had fresh leaf matter (FLM, in g $plant^{-1}$), dry leaf matter (DLM, in g $plant^{-1}$), fresh shoot matter (FSM, in g $plant^{-1}$) and dry shoot matter (DSM, in g $plant^{-1}$), determined. To obtain the dry matters, the material was packed into paper bags and incubated in a forced circulation oven (60±5 ºC) to constant matter.

Data on indoor air temperature 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. We used these data to calculate the daily thermal sum by the method of Gilmore and Rogers (1958) and Arnold (1960), using Equations 1 and 2:

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

where, Tmax: maximum daily temperature as ºC; Tmin: daily minimum temperature as ºC; Tb: lettuce base temperature = 10 ºC (Brunini, 1976).

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

where, aST: accumulated thermal sum; $\sum$ STd: sum of the daily thermal sum.

The fitting of the Gompertz and logistic models to each trait (dependent variable) was performed with the repetitions of each evaluation as a function of the accumulated thermal sum (independent variable). The equation used for the Gompertz model (Windsor, 1932) was: $y_i = a \cdot \exp[-\exp(b - cx_i)]$, and for the logistic model (Nelder, 1961) 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; xi 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 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. Data for the traits that did not fulfill these assumptions were Box-Cox transformed using the Action software.

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 tested using the adjusted coefficient of determination (R^2aj) in which the best fit is the one that is closest to 1, and by the Akaike Information Criterion (AIC) and the residual standard deviation (RSD), in which the best fit for both is the one that is 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). To select the best model to describe the growth of the plants, we choose the one that provides the lowest intrinsic and parametric nonlinearity values. The inflection point (IP), the maximum acceleration point (MAP), and the maximum deceleration point (MDP) were calculated according to the equations described in Mischan and Pinho (2014). Inferences about plant growth were based on these critical points. The calculations were performed using the Microsoft Office Excel® applications and the software R (R Development Core Team, 2018).

3. Results and Discussion

The assumptions of normality, independence and homogeneity of errors for the Gompertz and logistic models, in the two experiments, fitted for fresh and dry leaf and shoot matters of the lettuce cultivars were met, with p-values greater than or equal to 0.05 obtained from the Shapiro-Wilk, Bartlett, and Durbin-Watson tests, respectively (Table 1). Bem et al. (2018) found similar results, in which the assumptions for the description of the yield traits of *Crotalaria juncea* were met.

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

Character [(1)]	Cultivars	Gompertz			Logistic		
		SW	DW	BP	SW	DW	BP
Experiment 1: Spring 2016							
FLM	Ceres	0.72	0.06	0.27	0.61	0.07	0.31
	Gloriosa	0.95	0.72	0.05	0.91	0.09	0.25
	Grandes Lagos	0.98	0.80	0.21	0.88	0.22	0.45
	Rubinela	0.76	0.08	0.10	0.47	0.10	0.33
DLM	Ceres	0.86	0.08	0.19	0.67	0.12	0.63
	Gloriosa	0.11	0.05	0.07	0.25	0.09	0.05
	Grandes Lagos	0.63	0.06	0.07	0.93	0.06	0.29
	Rubinela	0.48	0.07	0.05	0.90	0.07	0.06
FSM	Ceres	0.77	0.08	0.15	0.48	0.09	0.22
	Gloriosa	0.98	0.05	0.05	0.86	0.06	0.40
	Grandes Lagos	0.98	0.34	0.18	0.80	0.32	0.31
	Rubinela	0.82	0.06	0.14	0.53	0.05	0.43
DSM	Ceres	0.90	0.10	0.28	0.53	0.09	0.66
	Gloriosa	0.14	0.05	0.06	0.19	0.06	0.08
	Grandes Lagos	0.81	0.07	0.09	0.96	0.10	0.40
	Rubinela	0.56	0.08	0.05	0.06	0.05	0.09

Experiment 2: Spring 2017							
FLM	Ceres	0.54	0.94	0.26	0.74	0.05	0.83
	Gloriosa	0.14	0.62	0.09	0.21	0.26	0.05
	Grandes Lagos	0.39	0.94	0.44	0.89	0.64	0.44
	Rubinela	0.22	0.40	0.05	0.10	0.50	0.52
DLM	Ceres	0.92	0.11	0.10	0.45	0.06	0.84
	Gloriosa	0.62	0.05	0.07	0.18	0.05	0.44
	Grandes Lagos	0.93	0.07	0.13	0.72	0.06	0.06
	Rubinela	0.63	0.65	0.11	0.93	0.47	0.58
FSM	Ceres	0.77	0.76	0.33	0.75	0.09	0.80
	Gloriosa	0.13	0.78	0.07	0.14	0.31	0.09
	Grandes Lagos	0.34	0.94	0.45	0.87	0.58	0.42
	Rubinela	0.15	0.43	0.08	0.15	0.50	0.48
DSM	Ceres	0.97	0.11	0.05	0.32	0.06	0.92
	Gloriosa	0.48	0.06	0.09	0.17	0.10	0.31
	Grandes Lagos	0.80	0.06	0.11	0.63	0.06	0.09
	Rubinela	0.90	0.65	0.73	0.90	0.56	0.73

Note. (1) FLM = fresh leaf matter; DLM = dry leaf matter; FSM = fresh shoot matter; and DSM = dry shoot matter.

For all traits of the cultivars, the asymptotic values (*a*), which represent the maximum matter increment, were higher in the Gompertz model than in the logistic model (Tables 2 and 3). The estimates of parameter *c*, which represents the growth rate, were higher in the logistic model (Tables 2 and 3).

Table 2. Estimation of the parameters *a*, *b*, and *c*, lower limit (LL) and upper limit (UL) of the confidence interval (CI95%) of the Gompertz model for the characters as a function of accumulated thermal sum (as °C) of lettuce cultivars (Ceres, Gloriosa, Grandes Lagos e Rubinela) in two experiments

Character (1)	Parameter	Experiment 1: Spring, 2016			Experiment 2: Spring, 2017		
		Estimates	IC95%		Estimates	IC95%	
			LL	UL		LL	UL
Ceres							
FLM	*a* (*)	312.1481	278.2443	346.0520	750.2246	443.4583	1056.9908
	b (*)	3.6242	2.8703	4.3781	2.2751	2.0317	2.5185
	c (*)	0.0108	0.0083	0.0134	0.0042	0.0030	0.0053
DLM	*a* (ns)	28.3716	21.2897	35.4536	30.0257	19.1948	40.8565
	b (ns)	2.4230	2.0355	2.8104	2.2653	1.9238	2.6069
	c (ns)	0.0060	0.0044	0.0076	0.0048	0.0033	0.0063
FSM	*a* (*)	427.8148	361.0197	494.6099	1003.7866	507.1240	1500.4492
	b (*)	3.1176	2.5210	3.7141	2.2607	2.0421	2.4793
	c (*)	0.0085	0.0064	0.0106	0.0038	0.0027	0.0049
DSM	*a* (ns)	43.8345	25.6849	61.9841	39.2241	22.3457	56.1025
	b (ns)	2.2446	1.9253	2.5638	2.2307	1.9333	2.5281
	c (ns)	0.0047	0.0032	0.0063	0.0043	0.0029	0.0057
Gloriosa							
FLM	*a* (ns)	692.3494	475.8664	908.8323	633.3563	455.2993	811.4133
	b (ns)	2.4516	2.0094	2.8937	2.7182	2.2074	3.2290
	c (ns)	0.0058	0.0040	0.0077	0.0061	0.0043	0.0079
DLM	*a* (ns)	18.9974	15.4884	22.5065	19.5761	15.7532	23.3990
	b (ns)	2.9768	2.0791	3.8746	2.5549	2.0452	3.0645
	c (ns)	0.0091	0.0058	0.0125	0.0068	0.0049	0.0087
FSM	*a* (ns)	816.0510	532.2432	1099.8587	677.1060	483.7648	870.4472
	b (ns)	2.3874	1.9974	2.7774	2.7137	2.2156	3.2118
	c (ns)	0.0054	0.0037	0.0071	0.0060	0.0043	0.0078
DSM	*a* (ns)	20.5879	16.6625	24.5132	21.3163	16.7958	25.8369
	b (ns)	2.9297	2.0800	3.7793	2.5509	2.0286	3.0732
	c (ns)	0.0088	0.0057	0.0120	0.0067	0.0047	0.0086

Grandes Lagos							
FLM	*a* (*)	534.6712	418.9440	650.3983	1062.3655	585.4987	1539.2323
	b (ns)	2.7902	2.2829	3.2976	2.2928	2.0175	2.5682
	c (ns)	0.0071	0.0052	0.0090	0.0042	0.0029	0.0055
DLM	*a* (ns)	25.6114	21.3975	29.8252	25.8669	15.5527	36.1811
	b (ns)	3.0330	2.4268	3.6392	2.3410	1.6217	3.0603
	c (ns)	0.0084	0.0062	0.0105	0.0059	0.0030	0.0088
FSM	*a* (ns)	726.7452	492.9028	960.5876	1269.4461	617.4770	1921.4152
	b (ns)	2.5914	2.1254	3.0575	2.2855	2.0157	2.5554
	c (*)	0.0060	0.0041	0.0078	0.0040	0.0027	0.0053
DSM	*a* (ns)	30.8455	24.5910	37.1000	29.2898	16.9617	41.6180
	b (ns)	2.8457	2.2982	3.3932	2.3362	1.6441	3.0283
	c (ns)	0.0074	0.0054	0.0095	0.0058	0.0029	0.0086
Rubinela							
FLM	*a* (ns)	408.3864	39.5865	777.1864	551.1602	321.4904	780.8299
	b (ns)	2.4535	1.9245	2.9824	2.3328	2.0411	2.6245
	c (ns)	0.0045	0.0020	0.0070	0.0044	0.0031	0.0057
DLM	*a* (ns)	31.9655	-12.4523	76.3832	15.2111	10.8093	19.6130
	b (ns)	2.2157	1.8910	2.5404	2.4490	1.9645	2.9335
	c (*)	0.0034	0.0011	0.0057	0.0058	0.0039	0.0077
FSM	*a* (ns)	591.4820	-89.5338	1272.4979	638.9751	355.8407	922.1094
	b (ns)	2.4086	1.9587	2.8585	2.3275	2.0514	2.6035
	c (ns)	0.0040	0.0016	0.0063	0.0042	0.0030	0.0055
DSM	*a* (ns)	44.2640	-31.5674	120.0955	17.2401	11.9484	22.5319
	b (ns)	2.2109	1.9439	2.4780	2.4282	1.9708	2.8856
	c (*)	0.0031	0.0008	0.0054	0.0056	0.0038	0.0074

Note. (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 5% probability of error. ns Non-significant.

The estimates of the parameters (*a*, *b* and *c*) of each trait for the Gompertz and logistic models were compared between the experiments (Tables 2 and 3) and between the cultivars (Tables 4) using the criterion of overlapping confidence intervals.

By way of illustration of the comparison using the criterion of overlapping 95% confidence intervals (CI95%), the FLM of cv. Ceres, in the comparison of the estimate of parameter *a* of the logistic model between experiments 1 and 2 (Table 3), we found that the estimate of parameter *a* (287.2396 in experiment 1 lies outside the confidence interval of the estimate of parameter *a* in experiment 2 (344.4126 to 458.7919). As well, the estimate of parameter *a* (401.6022 in experiment 2 lies outside the confidence interval of the estimate of parameter *a* of experiment 1 (267.9975 to 306.4818). Therefore, the estimates of the parameter a are different between the experiments. Thus, if the two parameter estimates lie outside the CI of the other, we can conclude that the effect is significant. However, when at least one of the estimates is within the CI of the other, the effect is non-significant.

Tabela 3. 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 characters as a function of accumulated thermal sum (as °C) of lettuce cultivars (Ceres, Gloriosa, Grandes Lagos e Rubinela) in two experiments, in spring

Character(1)	Parameter	Experiment 1: Spring, 2016			Experiment 2: Spring, 2017		
		Estimates	IC95%		Estimates	IC95%	
			LL	UL		LL	UL
Ceres							
FLM	*a* (*)	287.2396	267.9975	306.4818	401.6022	344.4126	458.7919
	b (*)	-6.6774	-7.7433	-5.6114	-5.5844	-6.0763	-5.0924
	c (*)	0.0184	0.0152	0.0217	0.0117	0.0101	0.0133

DLM	*a* (ns)	21.1540	18.5834	23.7246	19.6631	16.8088	22.5175
	b (ns)	-5.2971	-5.9566	-4.6375	-5.2963	-5.9246	-4.6680
	c (ns)	0.0130	0.0108	0.0153	0.0118	0.0098	0.0139
FSM	*a* (*)	365.1177	334.9597	395.2757	472.7434	396.1543	549.3324
	b (ns)	-6.2999	-7.1941	-5.4057	-5.6615	-6.1318	-5.1911
	c (*)	0.0163	0.0136	0.0190	0.0115	0.0099	0.0131
DSM	*a* (ns)	27.6155	22.5652	32.6657	23.0673	19.3677	26.7669
	b (ns)	-5.1854	-5.7722	-4.5986	-5.3582	-5.9374	-4.7789
	c (ns)	0.0117	0.0096	0.0139	0.0115	0.0096	0.0134
Gloriosa							
FLM	*a* (ns)	496.2632	426.3758	566.1507	453.9529	403.4649	504.4415
	b (ns)	-5.4758	-6.2238	-4.7278	-6.2451	-7.0797	-5.4105
	c (ns)	0.0132	0.0107	0.0157	0.0142	0.0118	0.0166
DLM	*a* (ns)	16.8884	15.1143	18.6626	16.1301	14.5857	17.6745
	b (ns)	-5.8116	-7.1468	-4.4764	-5.4480	-6.2682	-4.6278
	c (ns)	0.0165	0.0122	0.0209	0.0138	0.0112	0.0163
FSM	*a* (ns)	551.5944	468.3603	634.8285	479.2687	425.8834	532.6539
	b (*)	-5.4480	-6.1282	-4.7678	-6.2698	-7.0848	-5.4547
	c (ns)	0.0128	0.0105	0.0151	0.0142	0.0118	0.0165
DSM	*a* (ns)	18.1122	16.1877	20.0367	17.3582	15.5845	19.1319
	b (ns)	-5.7801	-7.0547	-4.5055	-5.4797	-6.3212	-4.6382
	c (ns)	0.0162	0.0121	0.0203	0.0137	0.0111	0.0163
Grandes Lagos							
FLM	*a* (*)	417.3851	375.2177	459.5525	569.7647	480.7629	658.7665
	b (ns)	-6.0415	-6.8486	-5.2345	-5.6229	-6.1758	-5.0699
	c (*)	0.0150	0.0125	0.0175	0.0118	0.0100	0.0136
DLM	*a* (ns)	21.5397	19.7628	23.3166	20.1482	16.2920	24.0044
	b (ns)	-6.2871	-7.2299	-5.3443	-5.0677	-6.2884	-3.8471
	c (ns)	0.0165	0.0136	0.0194	0.0125	0.0085	0.0165
FSM	*a* (*)	505.5648	436.9364	574.1933	638.3743	527.4652	749.2834
	b (ns)	-5.9252	-6.7097	-5.1406	-5.6638	-6.2209	-5.1066
	c (ns)	0.0140	0.0114	0.0165	0.0117	0.0098	0.0135
DSM	*a* (ns)	24.5988	22.2425	26.9551	22.3294	17.9162	26.7427
	b (ns)	-6.1097	-6.9897	-5.2297	-5.1075	-6.2876	-3.9274
	c (ns)	0.0155	0.0128	0.0182	0.0124	0.0085	0.0162
Rubinela							
FLM	*a* (*)	195.2048	140.7449	249.6647	307.3870	262.5747	352.1993
	b (ns)	-6.2692	-7.3033	-5.2351	-5.6991	-6.2629	-5.1352
	c (ns)	0.0134	0.0100	0.0169	0.0121	0.0102	0.0139
DLM	*a* (ns)	11.8430	6.7680	16.9179	11.2851	9.8991	12.6710
	b (ns)	-5.6258	-6.3884	-4.8632	-5.5331	-6.3562	-4.7099
	c (ns)	0.0114	0.0082	0.0145	0.0131	0.0106	0.0157
FSM	*a* (*)	231.1328	157.0969	305.1687	339.1037	287.9442	390.2633
	b (ns)	-6.3331	-7.2960	-5.3702	-5.7433	-6.2883	-5.1984
	c (ns)	0.0132	0.0099	0.0165	0.0120	0.0102	0.0137
DSM	*a* (ns)	13.6390	6.8765	20.4014	12.4051	10.8351	13.9752
	b (ns)	-5.6868	-6.4001	-4.9734	-5.5512	-6.3377	-4.7647
	c (ns)	0.0111	0.0081	0.0142	0.0129	0.0105	0.0154

Note. (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 5% probability of error. ns: Non-significant.

The Gompertz model showed no difference for the parameters *a*, *b* and *c* for DLM and DSM of cv. Ceres between the experiments (Table 2). On the other hand, the parameters differed for FLM and FSM, with higher asymptotic values in experiment 2, indicating a greater matter production than in experiment 1. The estimates of all traits for cultivars Gloriosa and Rubinela were not different, except for the parameter *c* of DLM and DSM of cv. Rubinela. Finally, cv. Grandes Lagos showed no difference for the parameters for the traits DLM and DSM, but FLM and FSM differed for the parameters *a* and *c*, respectively. These results indicate that, for most cultivars, there was no difference in the estimates of the Gompertz model between the experiments.

In the logistic model, the parameters *a*, *b*, and *c* of the traits DLM and DSM of all cultivars were not different between the experiments (Table 3), and the same occurred with FLM of cv. Gloriosa, whereas cv. Ceres showed no difference for *b* of FSM. Higher asymptotic values were also found in experiment 2, which indicates higher matter production in relation to experiment 1. Cultivar Grandes Lagos showed no difference for parameters *a* and *c* of FLM and for FSM. Cultivar Rubinela differed between the experiments only for the asymptotic values of FLM and FSM. Thus, we can infer that there was no difference for most parameter estimates between the experiments for the same cultivar.

The comparison of cultivars in each experiment showed that in the Gompertz model, in experiment 1, there was no difference between the cultivars Gloriosa and Grandes Lagos and Gloriosa and Rubinela for all parameters of the traits FLM and FSM, as well as Grandes Lagos and Rubinela for FSM and Ceres and Rubinela for DSM (Table 4). These results indicate that the Gompertz model does not differ between these cultivars. In contrast, the Gompertz model differed for all traits of the cultivars Ceres and Gloriosa, since at least one of the three parameters (*a*, *b*, and *c*) was significant. Similar behavior was observed between the cultivars Ceres and Grandes Lagos. In experiment 2, the cultivars Ceres and Grades Lagos showed no difference for any of the traits, and Gloriosa and Rubinela showed no difference for FLM, DLM, and DSM. Gloriosa and Grandes Lagos were also similar regarding DLM, and DSM, Ceres and Rubinela for FLM and DLM, and Gloriosa and Rubinela for FSM and DSM. These results show that in experiment 2, the difference between the estimates of the parameters of the Gompertz model reduced.

Table 4. 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 Ceres, Gloriosa, Grandes Lagos and Rubinela, in two experiments, in spring

Cultivar	Cultivar	Experiment 1: Spring, 2016				Experiment 2: Spring, 2017			
		FLM	DLM	FSM	DSM	FLM	DLM	FSM	DSM
Gompertz									
a									
Ceres	Gloriosa	*	*	*	*	ns	ns	ns	*
Ceres	Grandes Lagos	*	ns	*	ns	ns	ns	ns	ns
Ceres	Rubinela	ns	ns	ns	ns	ns	*	ns	*
Gloriosa	Grandes Lagos	ns	*	ns	*	ns	ns	ns	ns
Gloriosa	Rubinela	ns	ns	ns	ns	ns	ns	ns	ns
Grandes Lagos	Rubinela	ns	ns	ns	ns	*	*	ns	ns
b									
Ceres	Gloriosa	*	ns	*	ns	ns	ns	ns	ns
Ceres	Grandes Lagos	*	*	ns	*	ns	ns	ns	ns
Ceres	Rubinela	*	ns	*	ns	ns	ns	ns	ns
Gloriosa	Grandes Lagos	ns	ns	ns	ns	ns	ns	ns	ns
Gloriosa	Rubinela	ns	ns	ns	ns	ns	ns	ns	ns
Grandes Lagos	Rubinela	ns	*	ns	*	ns	ns	ns	ns
c									
Ceres	Gloriosa	*	ns	*	*	*	*	*	*
Ceres	Grandes Lagos	*	*	*	*	ns	ns	ns	ns
Ceres	Rubinela	*	*	*	ns	ns	ns	ns	ns
Gloriosa	Grandes Lagos	ns	ns	ns	ns	*	ns	*	ns
Gloriosa	Rubinela	ns	*	ns	*	ns	ns	*	ns
Grandes Lagos	Rubinela	*	*	ns	*	ns	ns	ns	ns

Logístico									
a									
Ceres	Gloriosa	*	*	*	*	ns	*	ns	*
Ceres	Grandes Lagos	*	ns	*	ns	*	ns	*	ns
Ceres	Rubinela	*	*	*	*	*	*	*	*
Gloriosa	Grandes Lagos	*	*	ns	*	*	*	*	*
Gloriosa	Rubinela	*	ns	*	ns	*	*	*	*
Grandes Lagos	Rubinela	*	*	*	*	*	*	*	*
b									
Ceres	Gloriosa	*	ns	ns	ns	ns	ns	*	ns
Ceres	Grandes Lagos	ns	*	ns	*	ns	ns	ns	ns
Ceres	Rubinela	ns	ns	ns	ns	ns	ns	ns	ns
Gloriosa	Grandes Lagos	ns	ns	ns	ns	ns	ns	ns	ns
Gloriosa	Rubinela	ns	ns	ns	ns	ns	ns	ns	ns
Grandes Lagos	Rubinela	ns	ns	ns	ns	ns	ns	ns	ns
c									
Ceres	Gloriosa	*	ns	*	ns	*	ns	*	*
Ceres	Grandes Lagos	*	*	ns	*	ns	ns	ns	ns
Ceres	Rubinela	*	ns	ns	ns	ns	ns	ns	ns
Gloriosa	Grandes Lagos	ns	ns	ns	ns	ns	ns	*	ns
Gloriosa	Rubinela	ns	*	ns	*	ns	ns	ns	ns
Grandes Lagos	Rubinela	ns	*	ns	*	ns	ns	ns	ns

Note. 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 5% probability of error. ns = Non-significant.

The estimates of the logistic model parameters for FSM of Gloriosa and Grandes Lagos in experiment 1 and for DLM and DSM of Ceres and Grandes Lagos in experiment 2 were not different (Table 4). In the other comparisons, difference was found in at least one of the three parameters of the logistic model. The logistic model requires specific models for each trait and cultivar, because the differences were predominant. Different models were also needed to estimate the production of salad-type tomato in two years of cultivation (Sari et al., 2019).

Goodness-of-fit measures are used to define the most appropriate model. The logistic and Gompertz models presented satisfactory values of goodness of fit (high R^2, low AIC, and intermediate RSD) and close to each other (Tables 5 and 6). These measures were also used by Puiatti et al. (2013) for the selection of nonlinear models to describe dry matter accumulation in garlic.

The Gompertz and logistic models satisfactorily described the growth curve of lettuce cultivars, with R^2aj values greater than or equal to 0.850, for both models. Macedo (2003) adjusted growth models for different nutrient solutions to fit dry leaf matter of cultivar Grace Lake, in summer, in Viçosa (Minas Gerais-Brazil), and found coefficients of determination greater than or equal to 0.98 for the Gompertz, logistic, and expolinear models.

Table 5. Coefficient of determination (R^2), 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 Gompertz model for characters[(1)] as a function of the accumulated thermal sum (in °C) of lettuce cultivars (Ceres, Gloriosa, Grandes Lagos e Rubinela) in two experiments

Statistic		Experiment 1: Spring, 2016				Experiment 2: Spring, 2017			
		FLM	DLM	FSM	DSM	FLM	DLM	FSM	DSM
Ceres									
R²aj		0.955	0.969	0.963	0.968	0.975	0.956	0.977	0.961
AIC		6.367	0.404	6.497	0.671	5.457	0.100	5.553	0.162
RSD		23.087	1.168	24.608	1.335	16.817	1.208	18.038	1.252
PE		1.100	3.671	1.805	7.877	8.606	6.022	11.962	8.205
IN		0.144	0.141	0.144	0.144	0.113	0.142	0.112	0.133
IP	x	334.312	404.207	365.093	473.159	546.418	472.769	592.465	514.098
	y	114.833	10.437	157.384	16.126	275.992	11.046	369.272	14.430
MAP	x	245.533	243.653	252.385	270.278	315.268	271.913	340.240	292.290
	y	22.770	2.070	31.208	3.198	54.726	2.190	73.222	2.861
MDP	x	423.090	564.762	477.800	676.040	777.568	673.625	844.690	735.906
	y	213.047	19.364	291.991	29.918	512.042	20.493	685.103	26.771
Gloriosa									
R²aj		0.961	0.908	0.966	0.914	0.956	0.940	0.958	0.937
AIC		6.904	1.431	6.892	1.475	6.302	0.145	6.326	0.202
RSD		30.129	1.953	29.957	1.996	30.566	1.381	31.180	1.502
PE		4.818	2.021	5.846	2.118	4.095	2.327	4.237	2.579
IN		0.160	0.244	0.151	0.234	0.165	0.170	0.162	0.175
IP	x	419.999	325.987	442.550	331.513	444.443	375.311	449.647	382.306
	y	254.701	6.989	300.208	7.574	232.999	7.202	249.093	7.842
MAP	x	255.117	220.593	264.148	222.607	287.082	233.932	290.179	238.069
	y	50.504	1.386	59.528	1.502	46.201	1.428	49.392	1.555
MDP	x	584.881	431.380	620.953	440.419	601.804	516.689	609.115	526.543
	y	472.541	12.966	556.970	14.052	432.277	13.361	462.137	14.549
Grandes Lagos									
R²aj		0.966	0.960	0.965	0.962	0.970	0.853	0.969	0.862
AIC		6.561	0.967	6.823	1.076	6.395	1.695	6.519	1.780
RSD		25.398	1.549	28.936	1.635	26.457	2.703	29.064	2.836
PE		2.879	1.914	5.085	2.574	9.405	5.167	11.581	5.652
IN		0.144	0.154	0.152	0.151	0.127	0.263	0.130	0.257
IP	x	393.916	362.054	434.393	381.972	545.019	394.544	568.836	406.217
	y	196.695	9.422	267.354	11.347	390.822	9.516	467.003	10.775
MAP	x	258.044	247.168	273.066	252.786	316.246	232.339	329.303	238.872
	y	39.002	1.868	53.013	2.250	77.495	1.887	92.601	2.137
MDP	x	529.788	476.940	595.719	511.157	773.791	556.748	808.369	573.563
	y	364.923	17.480	496.017	21.053	725.084	17.655	866.420	19.991
Rubinela									
R²aj		0.939	0.936	0.944	0.937	0.970	0.939	0.972	0.944
AIC		9.097	3.428	9.322	3.615	8.397	2.281	8.558	2.459
RSD		12.579	0.657	13.222	0.696	14.499	0.909	15.071	0.938
PE		21.812	45.197	33.693	65.254	8.357	3.999	9.406	4.435
IN		0.218	0.216	0.215	0.215	0.129	0.175	0.126	0.169
IP	x	549.183	651.039	608.003	713.882	531.316	420.175	549.160	433.355
	y	150.237	11.759	217.594	16.284	202.760	5.596	235.066	6.342
MAP	x	333.753	368.249	365.057	403.130	312.114	255.052	322.078	261.592
	y	29.790	2.332	43.146	3.229	40.205	1.110	46.611	1.258
MDP	x	764.613	933.829	850.948	1024.634	750.517	585.298	776.242	605.118
	y	278.731	21.817	403.697	30.211	376.177	10.382	436.112	11.767

Note. [(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}.

Table 6. Coefficient of determination (R^2), 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 Logistc model for characters [(1)] as a function of the accumulated thermal sum (in °C) of lettuce cultivars (Ceres, Gloriosa, Grandes Lagos e Rubinela) in two experiments

Statistic		Experiment 1				Experiment 2			
		FLM	DLM	FSM	DSM	FLM	DLM	FSM	DSM
Ceres									
R²aj		0.958	0.965	0.965	0.964	0.975	0.956	0.976	0.961
AIC		6.318	0.515	6.470	0.786	9.443	0.459	5.891	0.532
RSD		22.483	1.239	24.261	1.420	17.048	1.213	18.347	1.258
PE		0.534	1.150	0.705	1.951	1.487	1.402	1.789	1.627
IN		0.118	0.097	0.106	0.095	0.076	0.095	0.075	0.090
IP	x	362.084	406.675	386.553	441.679	477.290	448.513	492.783	465.346
	y	143.620	10.577	182.559	13.808	200.801	9.832	236.372	11.534
MAP	x	290.671	305.567	305.747	329.504	364.731	336.988	378.153	350.971
	y	60.701	4.470	77.158	5.836	84.869	4.155	99.902	4.875
MDP	x	433.497	507.783	467.360	553.855	589.850	560.037	607.413	579.721
	y	226.539	16.684	287.959	21.780	316.734	15.508	372.841	18.193
Gloriosa									
R²aj		0.959	0.907	0.963	0.913	0.959	0.942	0.961	0.940
AIC		6.961	1.436	6.958	1.483	6.861	0.676	6.896	0.845
RSD		31.047	1.958	31.014	2.005	29.759	1.351	30.288	1.470
PE		1.351	0.862	1.503	0.878	1.000	0.821	1.008	0.881
IN		0.107	0.173	0.100	0.165	0.107	0.112	0.105	0.115
IP	x	415.163	351.994	426.523	356.614	439.440	395.383	442.443	400.516
	y	248.131	8.444	275.797	9.056	226.977	8.065	239.634	8.679
MAP	x	315.315	272.229	323.419	275.362	346.772	299.807	349.508	304.259
	y	104.873	3.569	116.566	3.828	95.932	3.409	101.281	3.668
MDP	x	515.012	431.759	529.628	437.866	532.109	490.960	535.378	496.774
	y	391.390	13.320	435.029	14.285	358.022	12.721	377.987	13.690
Grandes Lagos									
R²aj		0.966	0.961	0.964	0.962	0.969	0.850	0.968	0.859
AIC		6.555	0.946	6.836	1.081	6.655	2.082	6.847	2.179
RSD		25.321	1.532	29.145	1.640	26.874	2.730	29.585	2.866
PE		0.911	0.695	1.310	0.840	1.625	1.696	1.865	1.772
IN		0.102	0.111	0.104	0.108	0.085	0.177	0.087	0.172
IP	x	403.304	381.132	424.484	394.111	476.856	405.174	485.628	412.937
	y	208.692	10.770	252.783	12.299	284.882	10.074	319.187	11.165
MAP	x	315.390	301.297	330.136	309.159	365.169	299.881	372.708	306.462
	y	88.204	4.552	106.839	5.198	120.405	4.258	134.904	4.719
MDP	x	491.218	460.967	518.833	479.062	588.542	510.468	598.547	519.412
	y	329.181	16.988	398.727	19.400	449.359	15.890	503.470	17.611
Rubinela									
R²aj		0.941	0.935	0.945	0.936	0.970	0.941	0.972	0.946
AIC		5.134	-0.729	5.236	-0.613	5.427	-0.151	5.506	-0.088
RSD		12.434	0.664	13.088	0.703	14.536	0.893	15.126	0.922
PE		3.097	5.607	3.804	6.974	1.490	1.095	1.577	1.146
IN		0.138	0.134	0.133	0.133	0.085	0.114	0.083	0.110
IP	x	465.901	495.515	481.162	510.262	472.903	421.577	479.591	428.931
	y	97.602	5.921	115.566	6.819	153.694	5.643	169.552	6.203
MAP	x	368.030	379.519	381.105	392.095	363.623	321.235	369.620	327.172
	y	41.252	2.503	48.844	2.882	64.959	2.385	71.661	2.622
MDP	x	563.773	611.510	581.218	628.430	582.183	521.919	589.563	530.689
	y	153.953	9.340	182.289	10.757	242.428	8.900	267.443	9.784

Note [(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}.

Although the models showed satisfactory goodness-of-fit, for most of the traits, the Gompertz model overestimated the parameter *a*. The largest overestimation occurred for cv. Grandes Lagos, in experiment 2, with asymptotic values of 1062.3655 for FLM and 1269.4461 for FSM (Table 3), that is, these estimates were exceedingly higher than the maximum values observed in the dataset, which were 500.88 g plant^{-1} for FLM and 541.26 g plant^{-1} for FSM. Overestimation of parameter *a* also occurred with cv. Rubinela, in experiment 1, with estimated values of 31.9655 for DLM and 44.2640 for DSM, which were higher than the maximum values of 10.00 g plant^{-1} of DLM and 10.51 g plant^{-1} of DSM found in the data set. Overestimation of parameters in the Gompertz model was also reported in the description of strawberry production (Diel et al., 2018).

Intrinsic nonlinearity (IN) and parameter-effects nonlinearity (PE) are used to help to determine the most suitable model. The logistic model had lower IN values for most of the traits of the cultivars in the two experiments and smaller PE than the Gompertz model (Tables 5 and 6). The lower IN and, especially PE, indicate better suitability of the logistic model. It is also worth noting that the high values of PE of the Gompertz model for cv. Rubinela (experiment 1) in relation to DLM (45.197) and FSM (65.254) are associated with overestimation of parameters. High PE values were also found in the curve fitting of the Gompertz model to salad-type tomato data (Sari et al., 2019).

The findings of this study implies that, regardless of cultivation, trait, and experiment, the logistic model is the most suitable for describing the growth of lettuce cultivars, as it exhibits a close to the ideal behavior, based on the five measures of goodness of fit (R^2aj, AIC, RSD, IN, and PE). Cultivar Ceres was selected from experiment 1 to serve as an example of the shape of the logistic growth curve of each trait, with the respective critical points (Figure 1). The other growth curves can be constructed using the respective parameter estimates (Table 3).

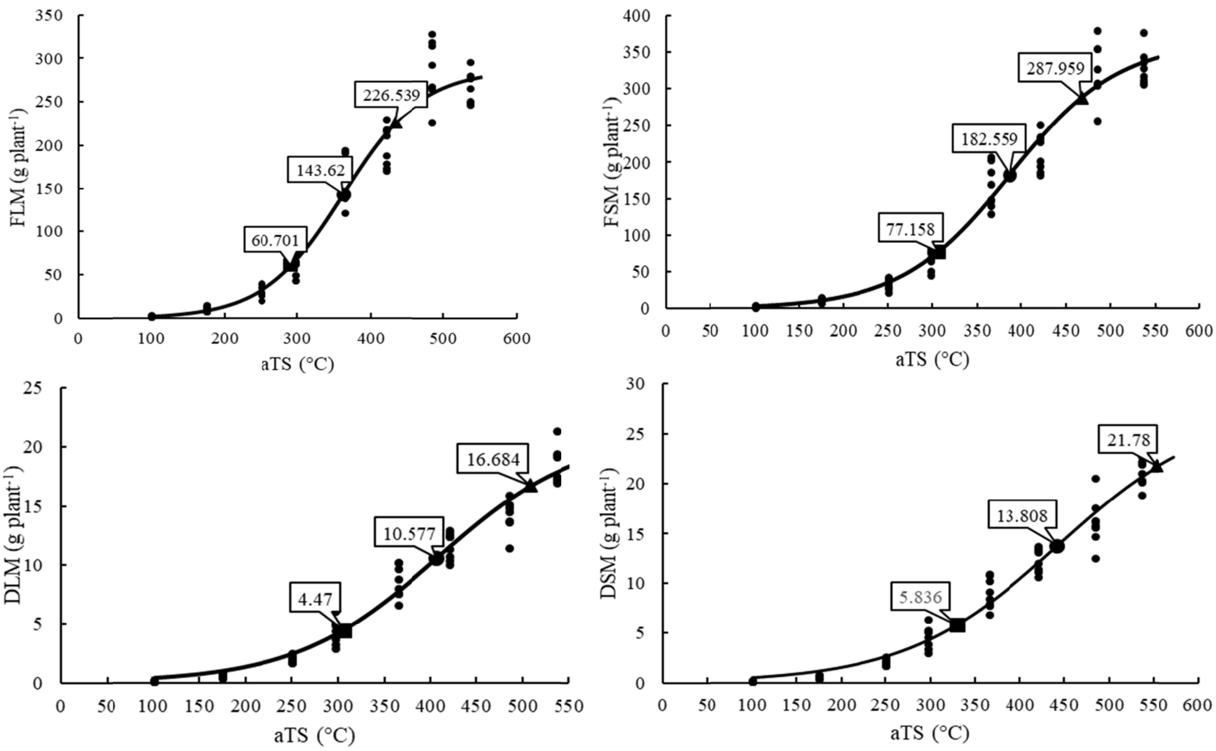

Figure 1. Logistic model plot for fresh leaf matter (FLM, as g plant^{-1}), dry leaf matter (DLM as g plant^{-1}), fresh shoot matter (FSM, as g plant^{-1}), and shoot dry matter (DSM, as g plant^{-1}) as a function of the accumulated thermal sum (aTS, as °C), for the cultivator Ceres, in experiment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

Note. ■ maximum acceleration point (MAP); ● inflection point (IP); ▲ maximum deceleration point (MDP).

The maximum acceleration point (MAP) occurred at the beginning of the curve, when the plants had small volume and young leaves (Tables 5 and 6). In most cultivars, in both experiments, the inflection point (PI) is the closest to the harvest stage, for most traits and cultivars, due to the appearance of senescent outer leaves. Therefore, the critical points are important for a better understanding of the growth curve and its biological responses. Regarding the aTS among the cultivars, in the logistic model, cv. Ceres required the lowest accumulated thermal sum and showed lower values for the traits than cultivars Gloriosa and Grandes Lagos, which accumulated higher aTS values. Opposite behavior was observed for cv. Rubinela, with higher aTS and lower FLM compared with other cultivars.

Therefore, the results of this study indicate that the cultivar of the group purple crisp lettuce produced smaller plants, independent of the accumulated thermal sum. This study confirms that the logistic model and its critical points are important to assist in the selection of promising lettuce cultivars. The logistic model was also indicated to describe the length, diameter, and volume of the pequi fruit (*Caryocar brasiliense*) (Rodrigues, Mattos, Morais, & Muniz, 2018) and to describe the production curve of strawberry cultivars (Diel et al., 2018).

The parameters (*a*, *b*, and *c*) can be used for the simulation and prediction of growth in the research or production of cultivars Ceres, Gloriosa, Grandes Lagos, and Rubinela, in the spring. However, it is advisable to use the thermal sum of the growing site in order to obtain responses close to the real growing conditions. In this way, predictions can be used, but the values obtained will approximate those found in this study and will follow the growth curve pattern. In addition, because studies addressing the theme are scarce, these models are a reference for further research on these cultivars growing in the spring.

4. Conclusions

The logistic and Gompertz growth models satisfactorily fit the fresh and dry leaf and shoot matters of cultivars Ceres, Gloriosa, Grandes Lagos, and Rubinela, under spring conditions. The Logistic model was shown the most suitable to describe the growth of lettuce cultivars.

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