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Gompertz and Logistic models for morphological traits of sudangrass cultivars during sowing seasons

Modelos Gompertz e Logístico para caracteres morfológicos de cultivares de capim-sudão em épocas de semeadura

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Abstract

The use of mathematical models in the study plant growth allows the identification of phases important to the cultivars and comparison between cultivars of the same species. The objectives of this work were to fit the Gompertz and Logistic growth models for the traits of plant height and stem length as a function of the accumulated thermal sum and accumulated solar radiation, to compare the fittings and the behavior of the sudangrass cultivars and indicate the model that best describes the growth of the cultivars during four sowing seasons. Were conducted eight uniformity trials with sudangrass. At 15 days after emergence, were began the collect and evaluation of five plants from each trial. Were measured plant height and stem length. The models were fitted using the values obtained for the traits of the five plants in each evaluation as a function of the accumulated thermal sum and accumulated solar radiation. Were estimated the parameters, determined their interval of confidence, critical points in the growth curves and quality indicators of the fit. The intrinsic nonlinearities and the parameter effect were also quantified. The accumulated thermal sum and accumulated solar radiation are adequate for the use as an independent variable in the model fitted. Both models were adequate to describe the growth of the traits plant height and stem length of cultivars BRS Estribo and CG Farrapo. However, the Logistic model is more accurate.
Key words: Nonlinear models. Cover crop. *Sorghum sudanense* (Piper) Stapf.

Resumo

A utilização de modelos matemáticos no estudo do crescimento de plantas possibilita a identificação de fases importantes para a cultura e a comparação entre cultivares de uma mesma espécie. Os objetivos deste trabalho foram ajustar modelos de crescimento, Gompertz e Logístico, para os caracteres altura de planta e comprimento de colmo em função da soma térmica acumulada e da radiação solar acumulada, comparar os ajustes e o comportamento das cultivares de capim-sudão e indicar o modelo que melhor descreve o crescimento das cultivares em quatro épocas de semeadura. Foram conduzidos oito ensaios

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de uniformidade com capim-sudão. Aos 15 dias após a emergência, foi iniciada a coleta e avaliação de cinco plantas de cada ensaio. Foram mensurados a altura de planta e o comprimento de colmo. O ajuste dos modelos foi realizado com os valores dos caracteres das cinco plantas em cada avaliação, em função da soma térmica acumulada e da radiação solar acumulada. Foram estimados os parâmetros, determinado o intervalo de confiança dos parâmetros, os pontos críticos das curvas de crescimento e os indicadores de qualidade do ajuste. Também foram quantificadas as não linearidades intrínseca e do efeito do parâmetro. A soma térmica acumulada e a radiação solar acumulada são adequadas para serem utilizadas como variável independente no ajuste dos modelos. Para descrever o crescimento dos caracteres altura de planta e comprimento de colmo das cultivares BRS Estribo e CG Farrapo ambos os modelos são adequados. Entretanto, o modelo Logístico apresenta maior precisão.
Palavras-chave: Modelos não lineares. Planta de cobertura. *Sorghum sudanense* (Piper) Stapf.

Introduction

The sudangrass (*Sorghum sudanense* (Piper) Stapf.), which belongs to the Poaceae family, is an annual species originated from southern Egypt and Sudan and cultivated in hot climates. Its purpose is to serve as fodder for animal feed and soil cover plant. The sudangrass is considered a rustic plant and is tolerant of acid soils, low fertility, and water deficit (SATTELL et al., 1998).

As it is a crop of which interest is fast growth, both for the supply of fodder and soil protection, the cultural treatments must be conducted according to the plant´s needs and during the seasons in which it is most responsive. To do this, we must understand how the sudangrass grows, which can be accomplished by adjusting mathematical models.

These models are used to predict the occurrence of a specific phenomenon in many fields of study. In the agronomic field, the modeling has been used to estimate the period of occurrence of phenological phases (LEE et al., 2003), in the identification of intrinsic characteristics of the physiology of each species, in the form in which each organ contributes to the final growth (BENINCASA, 2003), as well as to predict crop yield (GOMES et al., 2014). Furthermore, the modeling allows to study the growth processes, relating them to the number of days since the cultivation or plant emergence (AUGOSTINHO et al., 2008), or even relating them to the meteorological variables of the environment in which the plant is found (OLIVEIRA et al., 2017). However, for these models to be reliable, it is necessary that, when fitted, they describe the phenomenon as close as possible to reality (BRITO et al., 2007).

Models can be linear or nonlinear. The nonlinear models are the most indicated to describe the growth curves of living organisms, given that, when well-adjusted, they can present a smaller number of parameters when compared to the linear models and, also presenting parameters of biological interpretation (ARCHONTOULIS; MIGUEZ, 2015).

The nonlinear models most often used to represent plant growth are the Gompertz and Logistic models since they present sigmoidal curves. Both models were used to describe the growth of morphological traits of sunn hemp (BEM et al., 2017), of cashew fruits (MUIANGA et al., 2016), and of coffee fruits (FERNANDES et al., 2014).

Thus, the objectives of this work were to fit the Gompertz and Logistic growth models to the traits of plant height and stem length as a function of the accumulated thermal sum and accumulated solar radiation, compare the fittings and the behavior of the sudangrass cultivars and indicate the model that best describes the growth during four sowing seasons.

Material and Methods

Eight uniformity trials (blank experiments) with sudangrass [*Sorghum sudanense* (Piper) Stapf.] were conducted in the experimental area of the Department of Plant Science of the Federal University of Santa Maria (29º42'S, 53º49'W and

95 m altitude) in the agricultural year of 2016/2017. The region presents a Cfa subtropical climate, with hot summers and no defined dry season (ALVARES et al., 2013), with a soil classified as a Sandy Dystrophic Red Argisol (SANTOS et al., 2013).

The trials were composed by the combination of two cultivars (BRS Estribo and CG Farrapo), sown during four seasons (December 20th, 2016, January 20th, 2017, February 7th, 2017 and February 24th, 2017). The cultural practices were performed homogeneously in all uniformity trials.

The area was prepared for sowing with light harrowing and the application of base fertilization in the dose of 33 kg ha^{-1} of N, 132 kg ha^{-1} of P_2O_5, and 132 kg ha^{-1} of K_2O (660 kg ha^{-1} of the commercial formula 5-20-20). Sowing was performed in rows spaced 0.4 m, using a density of 25 kg ha^{-1} of viable seeds for both cultivars. All sowing was done within the recommended season for cultivation in Rio Grande do Sul, from October to February (SILVEIRA et al., 2015). Each uniformity trial occupied an area of 9 m × 16 m (144 m²). When the plants presented three to four leaves, was applied nitrogen fertilization using 67.5 kg ha^{-1} of N (150 kg ha^{-1} of urea).

Plant collects and evaluations were performed three times a week, from 15 days after plant emergence until the end of the flowering stage. Were randomly collected five plants from each trial for each evaluation and measured plant height (PH, in cm), distance from the soil surface to the insertion of the last expanded leaf of the main stem, and stem length (SL, in cm). To determine the SL, the leaves were removed from the plant and was measured the distance from the soil surface to the growing point.

In the period between the first sowing season (December 20th, 2016) and the last evaluation of the fourth sowing season (May 29th, 2017), were collected the records of maximum and minimum air temperature, in °C, and incident global solar radiation, in MJ m^{-2} from the INMET Automatic Weather Station, located 30 m from the experimental area. With the data of temperature was calculated the daily thermal sum by the method proposed by Arnold (1960) according to the equation:

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

Where STd is the daily thermal sum, Tmax is the maximum daily temperature, Tmin is the minimum daily temperature, and Tb is the inferior base temperature of the saccharine sorghum BRS 511 of 10.8ºC (BANDEIRA et al., 2016) used as a reference, because were not found studies on the base temperature of the sudangrass and the saccharine sorghum is from the same genre as the sudangrass. Subsequently, were calculated the accumulated thermal sum (ATS) by summing the STd of the period between the plant emergence and the end of the evaluations of each cultivar in each season. To obtain the accumulated solar radiation (ASR) was adopted the same process, summing the daily incident global solar radiation data from the same period.

To fit the Gompertz and Logistic models, to each trait, were used the values of the five plants of each evaluation in function of the accumulated thermal sum (ATS) and accumulated solar radiation (ASR). The equation used in the Gompertz model was: $y_i = a\ exp[-exp(b\text{-}cx)]$, and the Logistic equation was: $y_i = a/[1+exp(-b\text{-}cx)]$, where y_i represents i-th observation of the dependent variable where i = 1, 2, ..., n; *a* is the asymptotic value or final growth value; *b* is the curve allocation parameter, having no biological interpretation but fundamental to the sigmoidal shape of the curve; *c* is the maximum relative growth rate or precocity index; and *x* is the independent variable. The initial estimates of the parameters were performed using the ordinary least square method.

After the fit, were applied the Shapiro-Wilk, Bartlett, and Durbin-Watson tests to verify the assumptions of normality, homoscedasticity, and residue independence, respectively. In the cases where the assumptions were not met, were performed data transformations with the Box-Cox transformation using the Action software.

Were calculated the critical points of the function of each model from which inferences can be made regarding the growth of the culture. Were calculate the inflection point (IP), maximum acceleration point (MAP), maximum deceleration point (MDP), and the asymptotic deceleration point (ADP) according to the equations described by Mischan and Pinho (2014).

The comparison between the growth models, fitted for the traits of the plant height and stem length, was carried out by overlapping the confidence intervals of the parameter estimates of each model. To do this, were calculated the lower and upper limits of the 95% confidence interval. According to the criterion, when at least one parameter estimate of a trait for a given season was contained in the confidence interval of the parameter of the same trait of another season, they do not differ. However, if none of the estimates were contained in the confidence interval of the other, the estimates of the parameters differ. These comparisons were conducted, first, between the cultivars within each sowing season and, later, between sowing seasons of each cultivar for each model.

The evaluation of the adjustment quality of the models was performed based on the adjusted coefficient of determination (R^2aj), with the best adjustment presenting the highest value for R^2aj; Akaike's information criterion (AIC), where the best model presents the lowest AIC value; and residual standard deviation (RSD), where the best adjustment presents the lowest RSD value.

The behavior of the nonlinear models was analyzed using the nonlinearity measures of Bates and Watts curves (1988), in which the nonlinearity is decomposed into intrinsic nonlinearity (IN) and nonlinearity of the parameter effect (PE) based on the geometric concept of curvature. Thus, the model to be chosen is the one with the lowest IN and PE values.

Statistical analyses were performed using statistical software R (R DEVELOPMENT CORE TEAM, 2018) and the Microsoft Office Excel® application.

Results and Discussion

After the fit the Gompertz and Logistic models, were verified by the tests of Shapiro-Wilk, Bartlett, and Durbin-Watson, the assumptions of normality, homoscedasticity, and residue independence, respectively. From the p-values of the tests used in the residue analysis of the models, were observed that the residues of the models fitted to plant height and stem length data of the sudangrass cultivars sown in four seasons, as a function of ATS and ASR, presented normal distribution, homogeneity, and independence, fulfilling all assumptions (p-value> 0.05).

In the Table 1, the estimates of the parameters of the Gompertz and Logistic models of the PH and SL traits as a function of the accumulated thermal sum, as well as the comparison between the cultivars within each sowing season. For the comparison, the criterion of overlapping of confidence intervals was adopted, as well as a study conducted by Bem et al. (2017), in which the authors stated that the cultivars present the same growth behavior if parameters *a, b*, and *c* are equal.

The sowing seasons determined different cultivar behaviors using the Gompertz model when considering the PH models as a function of the ATS. When verifying only the final growth value (parameter *a*), there was no difference between the cultivars at seasons 1, 2, and 4, which can indicate that there was no difference in the final height of the plants for these cultivars. When using the Logistic model, we observed that the cultivars did not differ in seasons 1 and 3, and presented values similar to those of parameters *a, b,* and *c*, which means they had similar growth curves that can be used for both cultivars during these seasons. For parameter *c*, there was no difference between seasons 1, 2, and 3, indicating that, during these seasons, the precocity index (parameter *c*) did not differ between cultivars.

Table 1. Estimates of parameters and lower limit (LL) and upper limit (UL) of the 95% confidence interval of the Logistic and Gompertz models, for the traits as a function of the accumulated thermal sum, of sudangrass cultivars BRS Estribo and CG Farrapo sown at four seasons.

Trait[1]	Parameter [2]	Estimate	LL	UL	Estimate	LL	UL	Estimate	LL	UL	Estimate	LL	UL
		Logistic						Gompertz					
		BRS Estribo			CG Farrapo			BRS Estribo			CG Farrapo		
Season 1 (December 20, 2016)													
PH	a (ns) (ns)	272.2806	260.2211	284.3400	272.9707	264.8668	281.0745	298.6110	278.6330	318.5890	302.7843	285.4505	320.1181
	b (ns) (*)	-4.1055	-4.4671	-3.7440	-3.9206	-4.2150	-3.6261	2.1496	1.9197	2.3795	1.8661	1.6813	2.0510
	c (ns) (*)	0.0075	0.0067	0.0083	0.0072	0.0066	0.0079	0.0044	0.0038	0.0050	0.0029	0.0026	0.0033
SL	a (ns) (ns)	226.9769	216.0497	237.9040	228.6435	221.2084	236.0785	248.4020	231.1422	265.6618	248.1316	235.3630	260.9001
	b (ns) (*)	-4.8961	-5.3939	-4.3983	-4.5641	-4.9846	-4.1436	2.5965	2.2895	2.9034	2.2792	2.0312	2.5271
	c (ns) (*)	0.0088	0.0078	0.0099	0.0083	0.0075	0.0092	0.0052	0.0045	0.0060	0.0035	0.0030	0.0039
Season 2 (January 20, 2017)													
PH	a (*) (*)	286.7595	275.6887	297.8303	274.0865	265.2905	282.8826	315.0364	295.0572	335.0157	288.6996	276.7502	300.6489
	b (ns) (ns)	-3.7322	-4.0302	-3.4343	-3.6715	-3.9092	-3.4338	1.9117	1.7158	2.1076	1.8941	1.7477	2.0404
	c (ns) (*)	0.0068	0.0062	0.0075	0.0066	0.0061	0.0071	0.0040	0.0035	0.0045	0.0032	0.0029	0.0035
SL	a (*) (*)	248.3721	239.0200	257.7241	238.9838	231.1065	246.8610	281.2486	263.6262	298.8711	249.9414	239.7287	260.1541
	b (ns) (ns)	-4.5306	-4.8649	-4.1963	-4.4345	-4.7590	-4.1100	2.2840	2.0799	2.4880	2.3156	2.1206	2.5106
	c (ns) (*)	0.0081	0.0073	0.0088	0.0079	0.0072	0.0085	0.0045	0.0040	0.0050	0.0038	0.0034	0.0042
Season 3 (February 7, 2017)													
PH	a (ns) (ns)	270.6889	260.0750	281.3029	261.2353	253.6453	268.8254	306.0414	282.5019	329.5808	295.0529	275.6170	314.4887
	b (ns) (*)	-5.2914	-5.6955	-4.8872	-5.1508	-5.5429	-4.7587	2.6430	2.3505	2.9356	2.2099	1.9686	2.4513
	c (ns) (*)	0.0086	0.0078	0.0093	0.0092	0.0084	0.0100	0.0047	0.0040	0.0053	0.0035	0.0030	0.0040
SL	a(*) (*)	230.7705	221.8118	239.7292	215.1551	209.0839	221.2263	260.3281	242.3249	278.3312	241.8388	226.0378	257.6397
	b(ns) (ns)	-6.2474	-6.7498	-5.7450	-6.6294	-7.2066	-6.0522	3.1800	2.8410	3.5189	2.9107	2.5443	3.2770
	c(*) (*)	0.0099	0.0090	0.0109	0.0118	0.0107	0.0129	0.0055	0.0047	0.0062	0.0045	0.0038	0.0051
Season 4 (February 24, 2017)													
PH	a(*) (ns)	216.0795	210.3211	221.8379	230.8569	224.3751	237.3388	234.6569	222.2895	247.0243	239.8315	230.0164	249.6467
	b(*) (ns)	-6.1129	-6.6080	-5.6178	-5.2457	-5.6530	-4.8383	3.1709	2.7929	3.5489	3.3921	3.0027	3.7815
	c(*) (*)	0.0134	0.0122	0.0145	0.0121	0.0110	0.0131	0.0076	0.0066	0.0086	0.0062	0.0054	0.0069

continue

continuation

SL	a(*) (ns)	183.4369	178.5688	188.3051	189.7987	184.9466	194.6508	200.2694	190.1659	210.3728	194.0038	188.0824	199.9253
	b(*) (ns)	-7.6033	-8.1793	-7.0273	-6.3622	-6.9017	-5.8227	4.0337	3.5880	4.4794	4.4544	3.9693	4.9396
	c(*) (*)	0.0161	0.0148	0.0174	0.0144	0.0131	0.0157	0.0091	0.0081	0.0102	0.0078	0.0070	0.0087

(1) PH: plant height; SL: stem length. (2) First column of parentheses represents the comparison of the parameters of the Logistic model among the cultivars and the second column of parentheses represents the comparison of the parameters of the Gompertz model among the cultivars. (*) significant at 5% probability of error. (ns) not significant.

Concerning the SL trait, was verified a distinct behavior among cultivars during all sowing seasons when using the Gompertz model. However, there were no differences in the final growth value between the cultivars in seasons 1 and 4. When using the Logistic model, was verified that the cultivars did not differ during season 1, presenting the same growth behavior. In the season 2, the cultivars differed only by the value of *a*, not differing in the parameters *b* and *c*. In the seasons when there were differences between the cultivars regarding PH, was observed that during season 2, cultivar BRS Estribo showed plants with greater height and lower precocity index when compared to cultivar CG Farrapo. Contrary behavior was observed for season 4. At seasons in which differences between cultivars in the SL occurred, was verified that in the seasons 2 and 3, cultivar BRS Estribo presented higher values of stem length and lower precocity index when compared to cultivar CG Farrapo. In season 4, was verified a reduction of SL and PH, as well as the inversion of cultivar behavior, indicating a stronger effect on cultivar BRS Estribo than on CG Farrapo by late sowing.

When the Gompertz and Logistic models were fitted as a function of ASR, were verified no differences between cultivars regarding PH at seasons 1 and 3 (Table 2). At the second sowing season, were observed that the cultivars did not differ for parameters *b* and *c*, differing only in relation to plant height at the end of the development cycle. The cultivars presented the same behavior for SL at season 1 for Gompertz and Logistic models. As occurred in the models adjusted as a function of ATS, cultivar BRS Estribo presented higher values for PH and SL when compared to cultivar CG Farrapo at the seasons in which there were differences between cultivars apart from season 4 in which an inversion in behavior occurred. Martins Filho et al. (2008) reported differences between the cultivar behaviors in growth curves of common bean cultivars.

Table 2. Estimates of parameters and lower limit (LL) and upper limit (UL) of the 95% confidence interval of the Logistic and Gompertz models, for the traits as a function of the accumulated solar radiation, of sudangrass cultivars BRS Estribo and CG Farrapo sown at four seasons.

Trait[1]	Parameter[2]	Estimate	LL	UL	Estimate	LL	UL	Estimate	LL	UL	Estimate	LL	UL
		Logistic						Gompertz					
		BRS Estribo			CG Farrapo			BRS Estribo			CG Farrapo		
		Season 1 (December 20, 2016)											
PH	a (ns) (ns)	289.8315	271.2266	308.4365	281.4033	270.6392	292.1673	341.2897	302.4530	380.1264	302.7843	285.4505	320.1181
	b (ns) (ns)	-3.6808	-3.9982	-3.3635	-3.5855	-3.8651	-3.3058	1.7905	1.6002	1.9808	1.8661	1.6813	2.0510
	c (ns) (ns)	0.0047	0.0042	0.0053	0.0048	0.0043	0.0052	0.0025	0.0021	0.0030	0.0029	0.0026	0.0033
SL	a (ns) (ns)	239.9277	223.7383	256.1170	234.7009	225.5497	243.8521	278.4845	247.3030	309.6660	248.1316	235.3630	260.9001
	b (ns) (ns)	-4.3748	-4.8153	-3.9343	-4.1842	-4.5692	-3.7991	2.1710	1.9042	2.4378	2.2792	2.0312	2.5271
	c (ns) (ns)	0.0056	0.0049	0.0063	0.0055	0.0049	0.0061	0.0030	0.0025	0.0036	0.0035	0.0030	0.0039
		Season 2 (January 20, 2017)											
PH	a (*) (*)	282.5812	271.6914	293.4710	266.7604	259.5685	273.9523	306.3783	288.7832	323.9733	288.6996	276.7502	300.6489
	b (ns) (ns)	-3.5325	-3.8202	-3.2447	-3.5977	-3.8229	-3.3724	1.8669	1.6802	2.0535	1.8941	1.7477	2.0404
	c (ns) (ns)	0.0051	0.0046	0.0056	0.0053	0.0049	0.0057	0.0031	0.0027	0.0035	0.0032	0.0029	0.0035
SL	a (*) (*)	241.6785	232.6544	250.7027	231.7932	225.4065	238.1798	266.6605	252.3288	280.9922	249.9414	239.7287	260.1541
	b (ns) (ns)	-4.3029	-4.6431	-3.9627	-4.3685	-4.6821	-4.0550	2.2578	2.0582	2.4575	2.3156	2.1206	2.5106
	c (ns) (ns)	0.0061	0.0055	0.0067	0.0063	0.0058	0.0068	0.0036	0.0032	0.0040	0.0038	0.0034	0.0042
		Season 3 (February 7, 2017)											
PH	a (ns) (ns)	274.0560	261.5655	286.5465	266.2251	256.9013	275.5489	315.4056	286.1268	344.6844	295.0529	275.6170	314.4887
	b (ns) (ns)	-4.8599	-5.2696	-4.4503	-4.4750	-4.8307	-4.1194	2.3127	2.0375	2.5879	2.2099	1.9686	2.4513
	c (ns) (ns)	0.0062	0.0056	0.0068	0.0063	0.0057	0.0069	0.0032	0.0027	0.0037	0.0035	0.0030	0.0040
SL	a (*) (*)	234.7482	224.6374	244.8590	219.8951	212.1895	227.6008	267.2630	245.5019	289.0242	241.8388	226.0378	257.6397
	b (ns) (ns)	-5.8191	-6.3090	-5.3292	-5.7054	-6.2263	-5.1846	2.8843	2.5445	3.2242	2.9107	2.5443	3.2770
	c (ns) (ns)	0.0072	0.0065	0.0079	0.0080	0.0072	0.0088	0.0039	0.0033	0.0044	0.0045	0.0038	0.0051
		Season 4 (February 24, 2017)											
PH	a (*) (*)	211.3329	206.7953	215.8705	225.2591	220.0870	230.4312	221.7466	213.2629	230.2303	239.8315	230.0164	249.6467
	b (*) (*)	-7.2980	-7.9007	-6.6954	-6.3112	-6.8280	-5.7943	4.1626	3.6470	4.6783	3.3921	3.0027	3.7815
	c (*) (ns)	0.0115	0.0105	0.0125	0.0104	0.0095	0.0113	0.0071	0.0062	0.0080	0.0062	0.0054	0.0069

continue

continuation

SL	a (*) (*)	178.6086	174.8984	182.3190	186.0547	182.3058	189.8036	186.7693	180.5158	193.0227	194.0038	188.0824	199.9253
	b (*) (*)	-9.0626	-9.7352	-8.3900	-7.7547	-8.4038	-7.1056	5.3911	4.8195	5.9627	4.4544	3.9693	4.9396
	c (*) (ns)	0.0139	0.0128	0.0149	0.0126	0.0115	0.0136	0.0088	0.0078	0.0098	0.0078	0.0070	0.0087

[1] PH: plant height; SL: stem length. [2] First column of parentheses represents the comparison of the parameters of the Logistic model among the cultivars and the second column of parentheses represents the comparison of the parameters of the Gompertz model among the cultivars. (*) significant at 5% probability of error. (ns) not significant.

Were also compared the sowing seasons within each cultivar using both models (Table 3). When analyzing these comparisons based on the models fitted as a function of the ATS, was verified that, regarding the Logistic model, the PH did not differ between seasons 1 and 2 for cultivar CG Farrapo, while, with the Gompertz model, this behavior was observed for PH and SL traits. When was observed only the final growth value, it is possible to notice that seasons 1, 2, and 3 for both cultivars, evaluated using the Gompertz model, and seasons 1 and 3 of cultivar BRS Estribo and 1 and 2 of cultivar CG Farrapo, evaluated using the Logistic model, presented the same behavior between sowing seasons, resulting in plants with equal PH and SL. Season 4 presented distinct behavior from the other seasons, with smaller values for PH and SL.

Table 3. Comparison of the parameters estimates, based on the overlapping of the confidence intervals of Logistic and Gompertz models, between sowing times of the sudangrass, cultivars BRS Estribo and CG Farrapo (December 20, 2016, January 20, 2017, February 7, 2017, and February 24, 2017).

		--------------- Logistic ---------------				--------------- Gompertz ---------------			
Season	Season	BRS Estribo		CG Farrapo		BRS Estribo		CG Farrapo	
		PH	SL	PH	SL	PH	SL	PH	SL
As a function of accumulated thermal sum									
Parameter *a*									
1	2	*	*	ns	*	ns	*	ns	ns
1	3	ns	ns	*	*	ns	ns	ns	ns
1	4	*	*	*	*	*	*	*	*
2	3	*	*	*	*	ns	*	ns	ns
2	4	*	*	*	*	*	*	*	*
3	4	*	*	*	*	*	*	*	*
Parameter *b*									
1	2	*	ns	ns	ns	*	*	ns	ns
1	3	*	*	*	*	*	*	*	*
1	4	*	*	*	*	*	*	*	*
2	3	*	*	*	*	*	*	*	*
2	4	*	*	*	*	*	*	*	*
3	4	*	*	ns	ns	*	*	*	*
Parameter *c*									
1	2	ns	ns	ns	ns	ns	ns	ns	ns
1	3	*	ns	*	*	ns	ns	*	*
1	4	*	*	*	*	*	*	*	*
2	3	*	*	*	*	ns	*	ns	ns
2	4	*	*	*	*	*	*	*	*
3	4	*	*	*	*	*	*	*	*
As a function of accumulated solar radiation									
Parameter *a*									
1	2	ns	ns	*	ns	ns	ns	ns	ns
1	3	ns	ns	*	*	ns	ns	ns	ns
1	4	*	*	*	*	*	*	*	*
2	3	ns	ns	ns	*	ns	ns	ns	ns
2	4	*	*	*	*	*	*	*	*
3	4	*	*	*	*	*	*	*	*
Parameter *b*									
1	2	ns	ns	ns	ns	ns	ns	ns	ns
1	3	*	*	*	*	*	*	*	*
1	4	*	*	*	*	*	*	*	*
2	3	*	*	*	*	*	*	*	*
2	4	*	*	*	*	*	*	*	*
3	4	*	*	*	*	*	*	*	*

continue

continuation

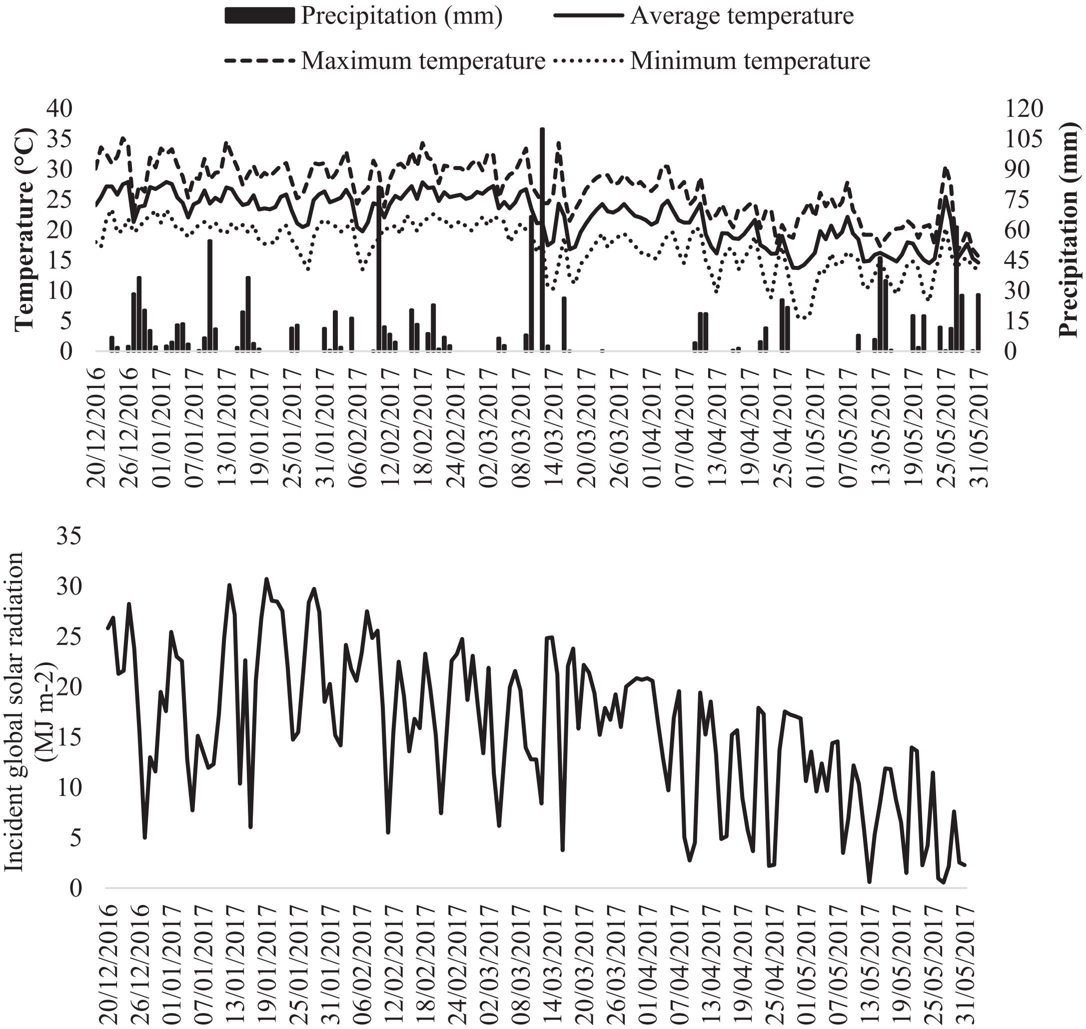
				Parameter *c*					
1	2	ns	ns	*	*	*	ns	ns	ns
1	3	*	*	*	*	*	*	*	*
1	4	*	*	*	*	*	*	*	*
2	3t	*	*	*	*	ns	ns	ns	ns
2	4	*	*	*	*	*	*	*	*
3	4	*	*	*	*	*	*	*	*

PH: plant height, in cm; SL: stem length, in cm. (*) significant at 5% probability of error. (ns) not significant.

When comparing the sowing seasons of each cultivar with the models fitted as a function of ASR, was verified that, by the Gompertz model, cultivar BRS Estribo presented the same behavior in seasons 1 and 2 for PH, which also occurred for cultivar CG Farrapo in PH and SL. Parameters *a* and *c* did not differ between seasons 2 and 3 for PH and SL in both cultivars. By the Logistic model, cultivar BRS Estribo presented the same behavior in seasons 1 and 2 for PH and SL. The final growth of this cultivar did not differ between seasons 1, 2, and 3 for both traits. Cultivar CG Farrapo presented distinct behavior between seasons. However, there was no difference between parameters *a* and *c* of the PH for cultivar BRS Estribo in seasons 2 and 3, and parameters *a* and *b* of SL in seasons 1 and 2. Therefore, when the adjustment was done in function of the ATS, season 4 presented the lowest values for PH and SL. Bem et al. (2017) found different behaviors between sowing seasons in the sunn hemp crop.

When observing the meteorological data of the season in which the tests were conducted (Figure 1), we observed that, over time, a drought period occurred, and the temperatures and global solar radiation incident reduced. These facts can explain the reduction in the values of PH and SL in season 4 since it was the one most affected by the changes in meteorological conditions. A reduction of plant development was observed in soybean (MELGES et al., 1989) and maize (MOZAMBANI; BICUDO, 2009) when submitted to smaller amounts of solar radiation and lower temperatures and light quantity, respectively. Thus, we can affirm that late sowing, even in the season preferred by the sudangrass, tends to reduce the crop cycle and, consequently, the growth of the plants, as indicated by Silveira et al. (2015).

Figure 1. Daily minimum, maximum and average air temperatures, in °C, precipitation, in mm, and incident global solar radiation, in MJ m^{-2}, corresponding to the period during which the trials with the cultivars of sudangrass, BRS Estribo and CG Farrapo were conducted. Data obtained at the INMET Automatic Weather Station of Federal University os Santa Maria (Source: INMET Network Data).



We indicated the models to describe the sudangrass growth using quality indicators, which evaluate the fit quality. For PH and SL in all models fitted according to the ATS, were observed that the values of the adjusted coefficient of determination (R^2aj) were equal to or superior to 0.9524, demonstrating the good capacity of the models in explaining the growth curves (Table 4).

Table 4. Fit quality indicators, curvature nonlinearity measures and critical points of Logistic and Gompertz models fitted to the traits plant height (PH) and stem length (SL) as a function of accumulated thermal sum (ºC) for cultivars BRS Estribo and CG Farrapo in four sowing seasons.

Statistic [1]		------------------ Logistic ------------------				------------------ Gompertz ------------------			
		BRS Estribo		CG Farrapo		BRS Estribo		CG Farrapo	
		PH	SL	PH	SL	PH	SL	PH	SL
Season 1 (December 20, 2016)									
R²aj		0.9572	0.9548	0.9653	0.9563	0.9576	0.9597	0.9637	0.9614
AIC		5.7675	5.6268	5.5754	5.6351	5.7587	5.5151	5.6200	5.5122
RSD		17.4066	16.2296	15.8469	16.3552	17.3269	15.3227	16.2045	15.3539
IN		0.0570	0.0662	0.0515	0.0657	0.0534	0.0733	0.0483	0.0665
PE		0.3529	0.3729	0.2151	0.2269	0.6604	0.6716	0.3374	0.3098
IP	x	549.8603	553.3317	542.2487	548.1281	487.1498	498.6664	466.2146	478.9974
	y	136.1403	113.4884	136.4853	114.3217	109.8529	91.3820	105.5146	87.5518
MAP	x	373.4787	404.4964	360.1016	389.9677	269.0454	313.8278	258.5482	301.8465
	y	57.5397	47.9659	57.6855	48.3180	21.7825	18.1200	20.9223	17.3605
MDP	x	726.2420	702.1670	724.3959	706.2885	705.2541	683.5051	673.8809	656.1482
	y	214.7409	179.0110	215.2852	180.3254	203.8075	169.5389	195.7587	162.4328
ADP	x	856.8883	812.4096	859.3127	823.4383	894.4387	843.8349	854.0115	809.8095
	y	247.2984	206.1514	247.9252	207.6650	252.9989	210.4592	243.0074	201.6379
Season 2 (January 20, 2017)									
R²aj		0.9580	0.9723	0.9718	0.9711	0.9524	0.9730	0.9669	0.9680
AIC		5.7289	5.1733	5.2013	5.1453	5.8537	5.1501	5.3638	5.2454
RSD		17.1419	12.9679	13.1669	12.7931	18.2504	12.8097	14.2825	13.4483
IN		0.0496	0.0462	0.0380	0.0449	0.0491	0.0534	0.0373	0.0529
PE		0.3268	0.3185	0.2838	0.2764	0.6648	0.6800	0.6162	0.5911
IP	x	548.5524	562.4343	555.1288	563.1636	479.0868	510.9289	485.1661	501.9311
	y	143.3795	124.1860	137.0433	119.4919	115.8954	103.4656	111.5096	97.1485
MAP	x	354.9892	398.9453	356.0050	395.9150	237.8972	295.6332	234.3906	287.6752
	y	60.5994	52.4872	57.9213	50.5032	22.9807	20.5160	22.1110	19.2634
MDP	x	742.1156	725.9234	754.2525	730.4123	720.2764	726.2245	735.9415	716.1870
	y	226.1601	195.8849	216.1652	188.4806	215.0181	191.9573	206.8811	180.2373
ADP	x	885.4883	847.0201	901.7439	854.2938	929.4852	912.9728	953.4651	902.0334
	y	260.4488	225.5835	248.9386	217.0566	266.9153	238.2885	256.8144	223.7398
Season 3 (February 7, 2017)									
R²aj		0.9657	0.9714	0.9667	0.9693	0.9542	0.9689	0.9553	0.9624
AIC		5.6432	5.3067	5.5620	5.3131	5.9280	5.3909	5.8550	5.5097
RSD		16.5047	13.9049	15.8413	13.9429	19.0601	14.5076	18.3702	15.4288
IN		0.0555	0.0591	0.0541	0.0623	0.0754	0.0778	0.0714	0.0860
PE		0.3416	0.3430	0.2599	0.2491	0.8442	0.7649	0.5623	0.5117
IP	x	617.6527	628.2961	561.7786	561.6924	566.1190	583.3360	505.7207	514.8199
	y	135.3440	115.3854	130.6177	107.5776	112.5863	95.7694	104.4589	84.6769

continue

continuation

MAP	x	463.9260	495.8508	418.1432	450.1100	359.9745	406.7873	325.0802	377.5317
	y	57.2033	48.7676	55.2055	45.4676	22.3245	18.9899	20.7130	16.7904
MDP	x	771.3795	760.7415	705.4141	673.2748	772.2635	759.8847	686.3613	652.1081
	y	213.4856	182.0030	206.0298	169.6875	208.8788	177.6787	193.8002	157.0991
ADP	x	885.2452	858.8440	811.8052	755.9242	951.0741	913.0237	843.0496	771.1924
	y	245.8528	209.5969	237.2665	195.4143	259.2942	220.5636	240.5762	195.0169
		Season 4 (February 24, 2017)							
R^2aj		0.9726	0.9832	0.9721	0.9737	0.9599	0.9769	0.9648	0.9708
AIC		5.0606	4.4082	5.1379	4.8735	5.4386	4.7169	5.3674	4.9801
RSD		12.3428	8.8425	12.7631	11.1790	14.9402	10.3541	14.3318	11.7922
IN		0.0561	0.0565	0.0507	0.0604	0.0938	0.0872	0.0748	0.0848
PE		0.2422	0.2346	0.2592	0.2306	0.5833	0.5453	0.5744	0.4364
IP	x	457.2238	473.5002	434.5329	442.5920	416.2010	440.8413	391.2437	402.2487
	y	108.0397	91.7186	115.4284	94.8994	86.3254	73.6750	92.6993	74.3932
MAP	x	358.7198	391.4857	325.4405	350.9767	289.8768	335.6579	252.5977	290.4329
	y	45.6630	38.7648	48.7858	40.1092	17.1173	14.6089	18.3812	14.7513
MDP	x	555.7278	555.5147	543.6253	534.2072	542.5253	546.0247	529.8898	514.0644
	y	170.4165	144.6722	182.0711	149.6895	160.1576	136.6875	171.9829	138.0201
ADP	x	628.6900	616.2630	624.4302	602.0669	652.0994	637.2612	650.1519	611.0538
	y	196.2539	166.6063	209.6754	172.3843	198.8136	169.6787	213.4931	171.3329

(1) R^2aj: adjusted coefficient of determination; AIC: Akaike's information criterion; RSD: residual standard deviation; IN: intrinsic nonlinearity; PE: parameter-effects nonlinearity; IP: inflection point; MAP: maximum acceleration point; MDP: maximum deceleration point; ADP: asymptotic deceleration point.

We also observed R^2aj values equal to or superior to 0.9415 at the models fitted according to the ASR (Table 5). Thus, we can infer that the Gompertz and Logistic models adjusted for the ASR can also be satisfactorily used to describe the growth curves for plant height and stem length of both cultivars of sudangrass sown in the four seasons, considering the ASR independent variable as an alternative to fit growth models in crops that have no defined base temperature or that do not respond to the thermal sum.

In some cases, when using the Gompertz model, the estimates of the asymptote were higher when compared to the estimates of the Logistic model. Although it did not overestimate the observed values, these superior values obtained for the parameter *a* influenced the quality of the fit. When comparing the Gompertz with the Logistic models, considering all the quality indicators, we found higher values of R^2aj and lower values of AIC and RSD for the Logistic model, indicating its superior adequacy to describe crop growth curves. These results are consistent with those found by Muianga et al. (2016) and Maia et al. (2009), who evaluated the quality of the fit of growth models, obtaining better performance from the Logistic model. In addition to the quality indicators, the nonlinearity measures of the Bates and Watts curves reinforce the choice of the Logistic model as preferred since, in most cases, it presents lower values for both intrinsic nonlinearity (IN) and nonlinearity of the parameter effect (PE). These measures indicate that this model behaves closer to linear, which is desired to better describe the growth curve of the sudangrass.

Table 5. Fit quality indicators, curvature nonlinearity measures and critical points of Logistic and Gompertz models fitted to the traits plant height (PH) and stem length (SL) as a function of accumulated solar radiation (MJ m^{-2}) for cultivars BRS Estribo and CG Farrapo in four sowing seasons.

Statistic[1]		------------------- Logistic -------------------				------------------- Gompertz -------------------			
		BRS Estribo		CG Farrapo		BRS Estribo		CG Farrapo	
		PH	SL	PH	SL	PH	SL	PH	SL
Season 1 (December 20, 2016)									
R^2aj		0.9551	0.9539	0.9605	0.9551	0.9541	0.9570	0.9557	0.9565
AIC		5.8166	5.3103	5.7045	5.6622	5.8377	5.5792	5.8182	5.6327
RSD		17.8366	16.3864	16.9010	16.5636	18.0258	15.8208	17.8947	16.3052
IN		0.0558	0.0678	0.0538	0.0661	0.0517	0.0783	0.0527	0.0755
PE		0.5923	0.6069	0.2983	0.2935	1.4115	1.3255	0.5402	0.4588
IP	x	778.2011	778.5745	749.3934	756.6479	708.8905	713.3724	640.8308	655.2578
	y	144.9157	119.9637	140.7016	117.3505	125.5535	102.4487	111.3881	91.2825
MAP	x	499.7706	544.1969	474.1381	518.4938	327.8449	397.1239	310.3363	378.5615
	y	61.2486	50.7027	59.4675	49.5981	24.8958	20.3144	22.0869	18.1002
MDP	x	1056.6317	1012.9522	1024.6487	994.8020	1089.9361	1029.6209	971.3254	931.9541
	y	228.5829	189.2250	221.9358	185.1028	232.9364	190.0707	206.6558	169.3543
ADP	x	1262.8658	1186.5563	1228.5309	1171.2032	1420.4565	1303.9360	1257.9977	1171.9616
	y	263.2390	217.9139	255.5841	213.1667	289.1584	235.9466	256.5347	210.2300
Season 2 (January 20, 2017)									
R^2aj		0.9572	0.9682	0.9751	0.9731	0.9569	0.9738	0.9742	0.9740
AIC		5.7478	5.3103	5.0779	5.0715	5.7557	5.1218	5.1159	5.0380
RSD		17.3060	13.9052	12.3800	12.3383	17.3728	12.6332	12.6166	12.1241
IN		0.0510	0.0480	0.0364	0.0437	0.0442	0.0466	0.0318	0.0436
PE		0.3529	0.3294	0.2456	0.2330	0.6260	0.5802	0.4502	0.4140
IP	x	691.8041	703.5239	682.5781	690.2852	597.9030	629.4565	590.1847	609.4036
	y	141.2905	120.8393	133.3802	115.8966	112.7103	98.0989	106.2066	91.9483
MAP	x	433.8900	488.2000	432.7138	482.1878	289.6647	361.1440	290.2987	356.1197
	y	59.7164	51.0727	56.3731	48.9837	22.3491	19.4519	21.0595	18.2323
MDP	x	949.7181	918.8478	932.4423	898.3825	906.1413	897.7691	890.0707	862.6875
	y	222.8648	190.6058	210.3873	182.8095	209.1088	182.0007	197.0427	170.5896
ADP	x	1140.7556	1078.3387	1117.5173	1052.5207	1173.5084	1130.5044	1150.1930	1082.3869
	y	256.6539	219.5041	242.2847	210.5257	259.5797	225.9287	244.6014	211.7634
Season 3 (February 7, 2017)									
R^2aj		0.9565	0.9682	0.9606	0.9656	0.9415	0.9618	0.9471	0.9565
AIC		5.8772	5.4148	5.7306	5.4246	6.1726	5.5940	6.0259	5.6558
RSD		18.5832	14.6758	17.2416	14.7512	21.5416	16.0828	19.9861	16.5999
IN		0.0612	0.0645	0.0566	0.0677	0.0832	0.0977	0.0670	0.1016
PE		0.3766	0.3632	0.3079	0.3255	1.0010	0.8905	0.6992	0.7280
IP	x	786.4155	804.3783	712.2588	715.5958	717.7906	743.4584	632.8089	650.8210
	y	137.0283	117.3743	133.1128	109.9476	116.0312	98.3206	108.5439	88.9675

continue

continuation

MAP	x	573.3104	622.3348	502.6477	550.4181	419.0781	495.3876	357.2198	435.6233
	y	57.9148	49.6081	56.2600	46.4693	23.0076	19.4958	21.5230	17.6412
MDP	x	999.5206	986.4219	921.8698	880.7735	1016.5032	991.5292	908.3980	866.0187
	y	216.1411	185.1400	209.9651	173.4258	215.2701	182.4119	201.3790	165.0594
ADP	x	1157.3680	1121.2619	1077.1292	1003.1210	1275.6076	1206.7067	1147.4451	1052.6820
	y	248.9109	213.2096	241.7985	199.7194	267.2281	226.4392	249.9842	204.8984
Season 4 (February 24, 2017)									
R^2aj		0.9740	0.9840	0.9721	0.9769	0.9599	0.9781	0.9612	0.9718
AIC		5.0019	4.3544	5.1350	4.7436	5.4215	4.6549	5.4603	4.9421
RSD		12.0338	8.6112	12.7689	10.4736	14.9398	10.0782	15.0624	11.5891
IN		0.0587	0.0542	0.0550	0.0609	0.0992	0.0843	0.0935	0.0879
PE		0.1803	0.1613	0.1934	0.1671	0.3942	0.3214	0.4195	0.3039
IP	x	635.7831	653.5988	606.4307	617.7802	585.7482	612.8892	551.2367	569.7745
	y	105.6664	89.3044	112.6295	93.0273	81.5760	68.7086	88.2291	71.3700
MAP	x	521.0534	558.6196	479.8863	512.8645	450.3203	503.4758	394.8378	446.6693
	y	44.6599	37.7444	47.6029	39.3180	16.1756	13.6241	17.4948	14.1518
MDP	x	750.5127	748.5779	732.9751	722.6959	721.1761	722.3026	707.6355	692.8796
	y	166.6730	140.8642	177.6563	146.7367	151.3461	127.4734	163.6894	132.4112
ADP	x	835.4932	818.9292	826.7069	800.4072	838.6468	817.2082	843.2965	799.6615
	y	191.9427	162.2210	204.5912	168.9839	187.8753	158.2407	203.1978	164.3702

(1) R^2aj: adjusted coefficient of determination; AIC: Akaike's information criterion; RSD: residual standard deviation; IN: intrinsic nonlinearity; PE: parameter-effects nonlinearity; IP: inflection point; MAP: maximum acceleration point; MDP: maximum deceleration point; ADP: asymptotic deceleration point.

The growth curves of each model present critical points with specific meanings from which it is possible to infer about the growth of the crop, establishing important periods for managing the crop cycle. In Tables 4 and 5, we present the inflection point (IP), maximum acceleration point (MAP), maximum deceleration point (MDP), and asymptotic deceleration point (ADP) values.

When comparing the models, we noticed that by the Gompertz model, the need for ATS or ASR is smaller to reach the MAP and IP when compared to the Logistic model and that the plants reach MAP and IP with lower PH and SL in the Gompertz model. Figures 2 and 3 show the growth curves and Logistic equations that are most indicated, with their respective critical points. Notice that cultivar CG Farrapo demands a lower accumulated thermal sum or accumulated solar radiation to reach MAP and IP when compared to cultivar BRS Estribo. The period between MAP and IP is important, given that it is during this phase that the plant growth rate increases until reaching a maximum rate, that is, it is in this period that the plant presents a rapid increase in height and stem length, requiring more nutrients. Thus, the prediction of the occurrence in this period is important since it is where the plant requires more attention, being more responsive to fertilization and control of invasive plants. Therefore, we can infer that fertilizing management and weed control should be performed earlier in the CG Farrapo cultivar when compared to BRS Estribo.

Figure 2. Graphs of the Logistic models for the plant height (PH, in cm) as a function of accumulated thermal sum (ATS, in °C) and accumulated solar radiation (ASR, in MJ.m-2), of sudangrass cultivars (—) CG Farrapo (·····) in four sowing seasons.

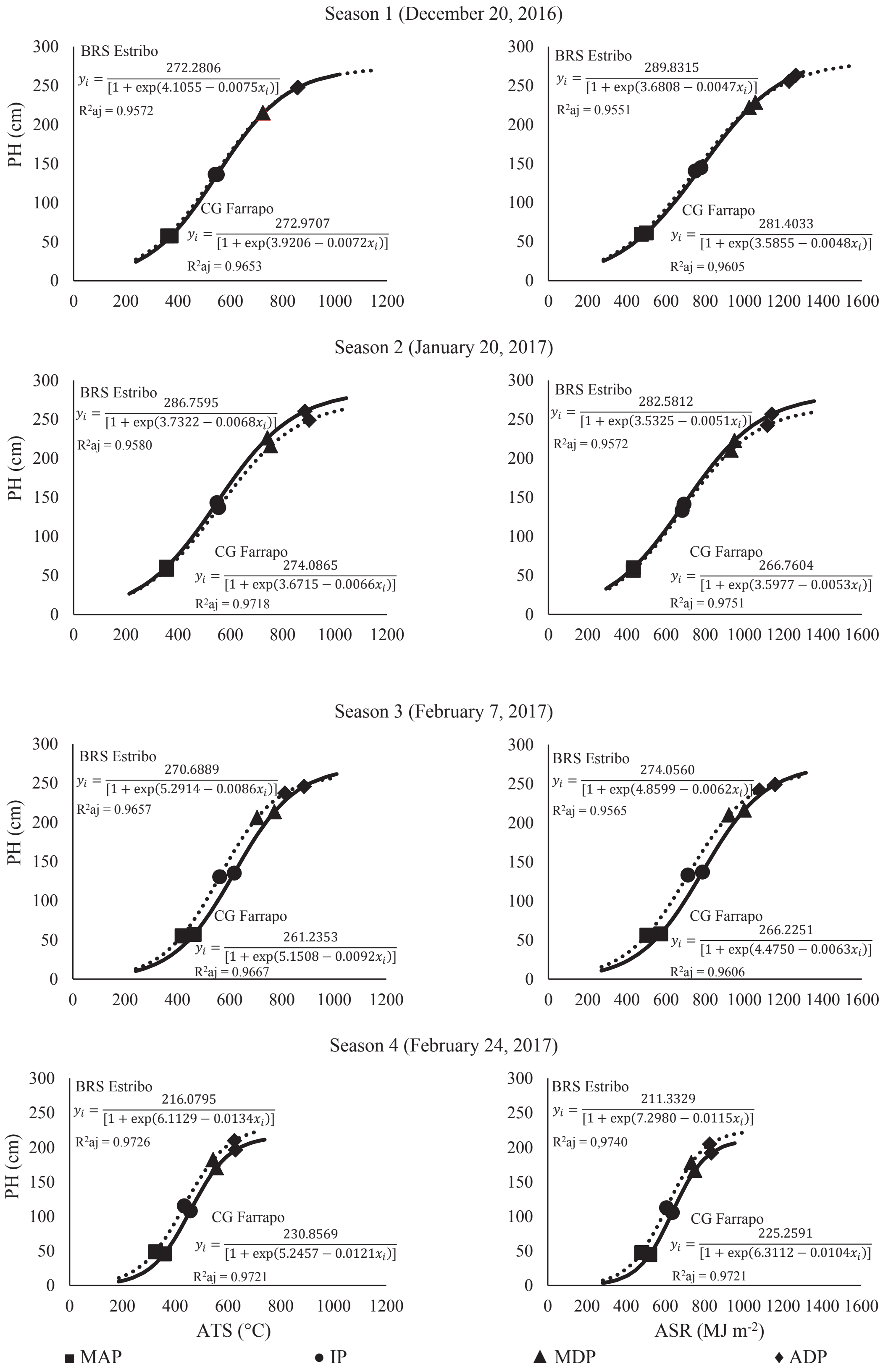
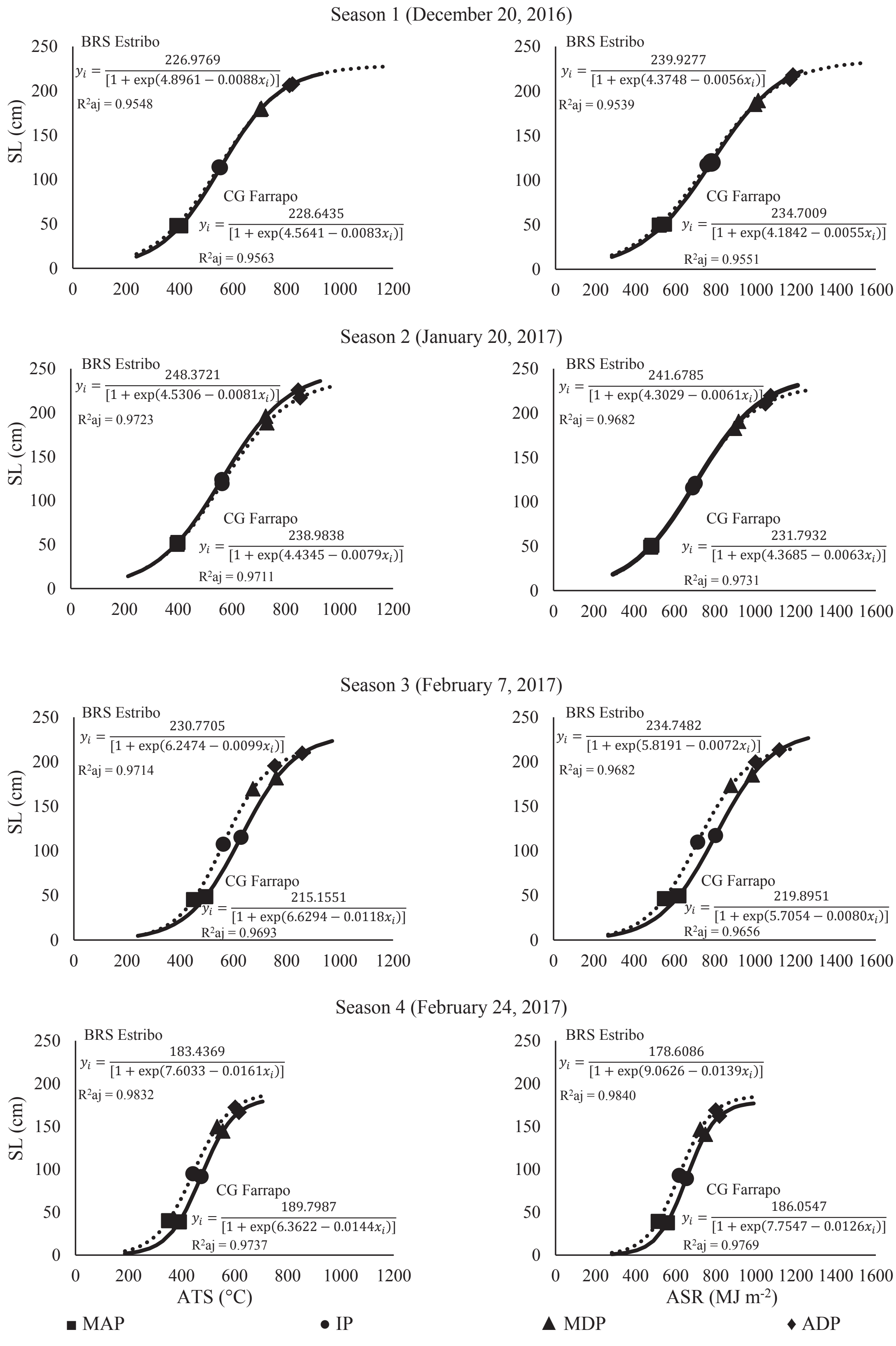


Figure 3. Graphs of the Logistic models for the stem length (SL, in cm) as a function of accumulated thermal sum (ATS, in °C) and accumulated solar radiation (ASR, in MJ.m[-2]), of sudangrass cultivars (**—**) CG Farrapo (·····) in four sowing seasons.



Among sowing seasons, was verified that the fourth season (February 24th, 2017), sown at the end of the sowing season indicated for the crop, showed the lowest values for PH and SL and demanded less ATS and ASR to reach all critical points of the growth curve (MAP, IP, MDP, and ADP). Therefore, we can affirm that the delay in the sowing period, exposing the plants to lower temperatures and incident global solar radiation, reduces the crop cycle, decreasing the period between MAP and IP, as well as the period from the IP to the MDP and ADP, when there is a marked decrease in the growth rate and the beginning of the growth stabilization, respectively. Because of the reduction of the crop cycle, the plants presented lower PH and SL.

Based on the results obtained in this work, it is possible to affirm that there is a difference between cultivars within sowing seasons and between sowing seasons of the same cultivar. Thus, we indicate using the model best fitted for a specific cultivar within the sowing season. It is worth noting that the models were adjusted using local meteorological data and for the four sowing seasons. Therefore, the use of the models with meteorological data of another location or sowing season can generate divergent, but expected results. However, since we found no modeling work using the growth of sudangrass and, especially, because of the representativeness of this database (three weekly evaluations of five plants during the crop cycle, in two cultivars sown in four seasons), these models become a reference for future research.

Conclusions

The accumulated thermal sum and accumulated solar radiation are suitable for use as an independent variable to adjust the Gompertz and Logistic models.

There was a difference between the cultivars at sowing seasons and between sowing seasons for the same cultivar regarding plant height and stem length for both models.

The Gompertz and Logistic models fitted to plant height and stem length of cultivars BRS Estribo and CG Farrapo in four sowing seasons satisfactorily describe the growth behavior. We indicate the Logistic model since it presents better quality indicators.

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