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Modeling the Growth of Sudangrass Cultivars at Sowing Times

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Abstract

This study aimed to fit the Gompertz and Logistic growth models to evaluate the description of fresh and dry masses of shoot as a function of accumulated thermal sum and accumulated solar radiation, to compare the fittings, and to indicate which one best describes the growth of two sudangrass cultivars at four sowing times. Eight uniformity trials were conducted with the sudangrass crop. Five plants were collected from each trial for weighing of fresh and dry shoot masses. These evaluations were carried out three times a week starting from 15 days after plant emergence. The Gompertz and Logistic models were fitted to the masses as a function of accumulated thermal sum and accumulated solar radiation. The parameters and their confidence intervals were estimated. The points of maximum acceleration, inflection, maximum deceleration and asymptotic deceleration, and fit quality indicators were calculated. The intrinsic nonlinearity and the parameter-effects nonlinearity were quantified. The independent variables accumulated thermal sum and accumulated solar radiation can be used to fit the models. Both models satisfactorily describe the growth of fresh and dry shoot masses of cultivars BRS Estribo and CG Farrapo. The Logistic model is more accurate.

Keywords: *Sorghum sudanense* (Piper) Stapf., nonlinear models, yield traits, cover crops

1. Introduction

In the no-till system, cover crops are used in rotation with cash crops to control losses of soil, water, and nutrients by water erosion (Cardoso, Silva, Carvalho, Freitas, & Avanzi, 2012), to promote nutrient cycling, and to increase soil organic matter contents (Pacheco et al., 2013).

Sudangrass [*Sorghum sudanense* (Piper) Stapf.] is among the many species that have been investigated as alternative cover crop options. Sudangrass belongs to the family Poaceae, develops well in regions with hot and dry climate, and tolerates acid and low fertility soils. It yields high amounts of biomass, reaching 84.3 $t \cdot ha^{-1}$ of fresh mass and 15.8 $t \cdot ha^{-1}$ of dry mass (Arenhardt et al., 2016) and providing good soil cover and high weed suppressive effect (Borges, Freitas, Mateus, Sá, & Alves, 2014). It has good nutritional quality and can be used in animal feed (Mattos, 2003). Reports on the growth and development of this species are scarce, indicating the need for studies to obtain more information on this process.

The fitting of growth models provides a valuable tool to study plant behavior and the occurrence of phenological stages (Lucena, Leite, Pereira, & Cavalcante, 2016). It is possible to plan periods and types of management more appropriate for the crop using these models, aiming to reach higher yields (Pereira, Morais, Scalco, & Fernandes, 2014). In addition, the fit of models in function of meteorological variables makes it possible to understand the growth according to the environmental characteristics (Oliveira, Ribeiro, Silva, Xavier, & Freitas, 2017).

Different statistical models can be used to study plant growth. The nonlinear models provide the best fits and have an advantage over linear models because they have biologically interpretable parameters (Fernandes, Pereira, Muniz, & Savian, 2014).

The nonlinear Gompertz and Logistic models are used to describe plant growth, as they have the same sigmoidal shape of the growth curves. These two models were studied to describe the growth of sunflower (Bem et al., 2018), cocoa (Muniz, Nascimento, & Fernandes, 2017), and coffee cultivar Rubi MG 1192 (Pereira et al., 2014) and were considered adequate.

The objectives of this work were to fit the Gompertz and Logistic growth models to evaluate the description of fresh and dry shoot masses as a function of accumulated thermal sum and accumulated solar radiation, to compare the fittings, and to indicate which one best describes the growth of two sudangrass cultivars at four sowing times.

2. Material and Methods

Eight uniformity trials were conducted with sudangrass [*Sorghum sudanense* (Piper) Stapf.] in the experimental area located between coordinates 29º42′ S, 53º49′ W and 95 m altitude. According to Köppen's classification, the climate of the region is humid subtropical Cfa, with hot summers and no defined dry season (Alvares, Stape, Sentelhas, Gonçalves, & Sparovek, 2013). The soil is classified as Sandy Dystrophic Red Argisol (Santos et al. 2013).

The uniformity trials consisted of two cultivars (BRS Estribo and CG Farrapo) sown at four dates (12/20/2016, 01/20/2017, 02/07/2017, and 02/24/2017), during the period recommended for the crop in the state of Rio Grande do Sul, between October and February (Silveira, Santanna, Montardo, & Trentin, 2015). In each experiment, sowing was performed in rows spaced 0.4 m apart, with density of 25 $kg \cdot ha^{-1}$ of viable seeds, in an area of 9 m × 16 m (144 m^2). The basal fertilization consisted of 33 $kg \cdot ha^{-1}$ of N, 132 $kg \cdot ha^{-1}$ of P_2O_5, and 132 $kg \cdot ha^{-1}$ of K_2O. When the plants had three to four leaves, 67.5 $kg \cdot ha^{-1}$ of N (150 $kg \cdot ha^{-1}$ of urea) was applied as topdress.

Plants were evaluated three times a week, the first evaluation started from 15 days after plant emergence. At each evaluation, five plants were collected from each experiment and fresh shoot mass (FSM, g $plant^{-1}$) was weighed with a digital scale. For dry shoot mass (DSM, g $plant^{-1}$), the fresh material was packed in paper bags and dried in an oven at 60 °C to constant mass. In total, 17, 18, 26 and 21 evaluations were performed in BRS Estribo and 19, 20, 22 and 20 evaluations in CG Farrapo for the FSM trait at times 1, 2, 3 and 4, respectively. For the DSM trait were performed 20, 24, 27 and 21 evaluations in BRS Estribo and 22, 24, 26 and 23 evaluations in CG Farrapo at times 1, 2, 3 and 4, respectively.

Maximum and minimum air temperatures, as degree Celsius, and the incident global solar radiation, as $MJ \cdot m^{-2}$, from the first sowing date (December 20, 2016) to the last evaluation of the fourth sowing date (May 29, 2017) were obtained from the records of the INMET Automatic Meteorological Station, which is located at 30 m from the experimental area.

With the temperature data, the daily thermal sum was calculated by the method proposed by Arnold (1960), according to Equation 1:

$$\text{STd} = \frac{\text{Tmax} + \text{Tmin}}{2} - \text{Tb} \tag{1}$$

where, STd is the daily thermal sum, Tmax is the maximum temperature of the day, Tmin is the minimum temperature of the day, and Tb is the minimum base temperature of grain sorghum BRS 511, which is 10.8 °C (Bandeira et al., 2016). Because no base temperature studies were found for sudangrass, we used the base temperature of the grain sorghum, as they belong to the same genus. Then, the accumulated thermal sum (ATS) was calculated by summing the STd values from the period between the emergence of the plants and the last evaluation of each cultivar in each date. We use the same procedure to calculate the accumulated solar radiation (ASR), i.e., summing the daily values of the incident global solar radiation of the same period.

The Gompertz and Logistic models were adjusted to fit fresh and dry shoot masses obtained from the five plants collected for each evaluation, according to ATS and ASR. For the Gompertz model, we used Equation 2 and for the Logistic model, we used Equation 3:

$$y_i = a \cdot \exp[-\exp(b - cx)] + \varepsilon_i \tag{2}$$

$$y_i = a/[1 + \exp(-b - cx)] + \varepsilon_i \tag{3}$$

where, y_i represents the i-th observation of the dependent variable and i = 1, 2, ..., n; *a* is the asymptotic value or final growth value; *b* is the curve allocation parameter, which has no biological interpretation, but is fundamental to the sigmoidal shape of the curve; *c* is the maximum relative growth rate or precocity index; *x* is the independent variable; and ε_i is the random error associated with the i-th observation which is assumed to have a normal distribution, independent form and constant variances. The parameters were estimated using the ordinary least squares method, using the Gauss-Newton iterative process.

The assumptions of normality, homoscedasticity, and independence of errors were tested by the Shapiro-Wilk, Bartlett, and Durbin-Watson tests, respectively.

In each model, the points of maximum acceleration (PMA), inflection (PI), maximum deceleration (PMD), and asymptotic deceleration (PAD) were calculated using the equations described by Mischan and Pinho (2014). These critical points can be used to infer about the growth of the crop.

The lower and upper limits of the 95% confidence interval were calculated. Plant growth models were compared between cultivars at each sowing date and between sowing dates in each cultivar by the overlapping of confidence intervals of the parameters. For example, to compare dates, if at least one of the estimates of a trait for a given date is contained in the confidence interval of the parameter of the same trait of another date, the dates are not different. If none of the estimates is contained within the interval of the other, then they are different.

To evaluate the quality of fit of the models, the following indicators were calculated: adjusted coefficient of determination (R^2aj); the Akaike information criterion (AIC); and residual standard deviation (RSD). The intrinsic nonlinearity (IN) and the parameter-effects nonlinearity (PE) were quantified. The best models are those with the highest R^2aj and the lowest AIC, RSD, IN and PE. Calculations were performed using the software R (R Development Core Team, 2018) and the Microsoft Office Excel® application.

3. Results and Discussion

In choosing a growth model, one of the factors that must be taken into consideration is how the data disperses. Plant growth studies usually present data in the sigmoid shape, which are characteristic of nonlinear models, such as Gompertz and Logistic. In Figure 1, for example, were plotted the data from the trials with the sudangrass cultivars. It is possible to observe that the fresh shoot mass (FSM) and the dry shoot mass (DSM) as a function of accumulated solar radiation (ASR), showed dispersion in the sigmoidal shape, justifying the fit of the Gompertz and Logistic models.

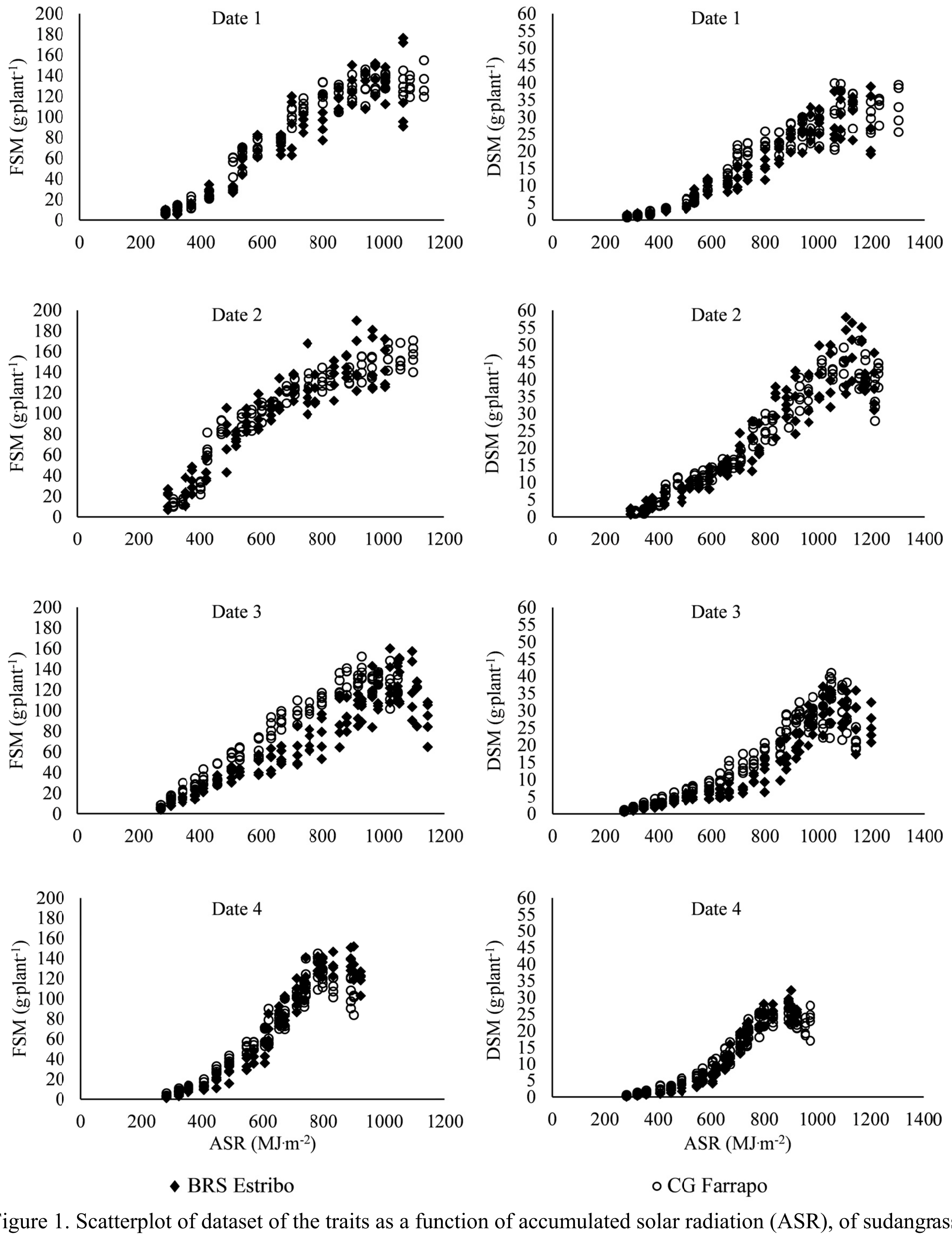

Figure 1. Scatterplot of dataset of the traits as a function of accumulated solar radiation (ASR), of sudangrass cultivars BRS Estribo and CG Farrapo sown at four dates

After to fit the models, the residuals analyses carried out to evaluate assumptions of normality, homoscedasticity, and independence of the errors of the models fitted for fresh and dry shoot masses as a function of ATS and ASR showed that all assumptions were met, with p-values greater than 0.05 ($p > 0.05$) obtained from the Shapiro-Wilk, Bartlett, and Durbin-Watson tests, respectively. These results agree with those reported by Ribeiro, Mattos, Morais and Muniz (2018) in the study of pequi (*Caryocar brasiliense*) growth.

The estimates of the parameters *a*, *b*, and *c* are used to predict the growth of the plant and to compare the growth of the cultivars within each sowing date and between the sowing dates of the same cultivar. One way to do the comparison is by the overlapping of confidence intervals of the parameters, a method used by Bem et al. (2018) to compare sowing dates of crotalária juncea.

The Gompertz and Logistic models of FSM as a function of ATS showed that the cultivars BRS Estribo and CG Farrapo were not different at date 2, that is, they had similar values for the parameters *a*, *b*, and *c* (Table 1). In this condition, it is assumed that the cultivars had the same growth behavior. At dates 1 and 3, the cultivars showed similar asymptotic values (parameter *a*), that is, they did not differ for the trait at the end of the crop cycle. For DSM, the models showed that the cultivars had the same growth behavior at dates 1, 2 and 3. At date 4, the cultivars differed in the asymptotic value, and BRS Estribo had asymptote higher than CG Farrapo, both for FSM and DSM. However, the cultivars did not differ in the precocity index.

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

Trait [1]	Parameter [2]	Estimate	LL	UL	Estimate	LL	UL	Estimate	LL	UL	Estimate	LL	UL
		Gompertz						Logistic					
		BRS Estribo			CG Farrapo			BRS Estribo			CG Farrapo		
Date 1 (12/20/2016)													
FSM	a (ns) (ns)	147.7166	133.1482	162.2851	136.7571	132.5847	140.9295	138.6315	128.8570	148.4059	133.1332	129.8595	136.4070
	b (ns) (ns)	3.1465	2.4628	3.8303	3.8216	3.3773	4.2659	-5.5960	-6.6111	-4.5810	-6.3638	-7.0162	-5.7114
	c (*) (*)	0.0075	0.0057	0.0093	0.0097	0.0086	0.0109	0.0121	0.0096	0.0145	0.0147	0.0131	0.0163
DSM	a (ns) (ns)	34.8720	30.6655	39.0784	33.1462	31.2391	35.0533	31.7754	29.4122	34.1386	31.6443	30.1955	33.0931
	b (ns) (ns)	3.0350	2.3776	3.6924	3.3030	2.7309	3.8750	-5.8497	-6.8501	-4.8492	-5.7634	-6.6634	-4.8633
	c (ns) (ns)	0.0060	0.0045	0.0075	0.0072	0.0059	0.0085	0.0105	0.0085	0.0126	0.0113	0.0094	0.0132
Date 2 (01/20/2017)													
FSM	a (ns) (ns)	165.3004	146.4820	184.1188	156.6290	150.0656	163.1924	153.7560	141.3565	166.1555	150.9557	145.4085	156.5030
	b (ns) (ns)	2.1239	1.6604	2.5874	2.3898	2.0827	2.6969	-3.8300	-4.5207	-3.1393	-3.9795	-4.4732	-3.4858
	c (ns) (ns)	0.0058	0.0043	0.0074	0.0068	0.0059	0.0077	0.0092	0.0072	0.0112	0.0098	0.0085	0.0112
DSM	a (ns) (ns)	52.8258	45.0829	60.5686	53.3124	46.4294	60.1953	46.3964	42.8319	49.9609	45.7447	42.8408	48.6486
	b (ns) (ns)	2.8482	2.1985	3.4979	2.3876	1.9918	2.7834	-5.8537	-6.8618	-4.8456	-5.0966	-5.7338	-4.4593
	c (ns) (ns)	0.0052	0.0037	0.0066	0.0043	0.0034	0.0053	0.0098	0.0079	0.0117	0.0085	0.0073	0.0097
Date 3 (02/07/2017)													
FSM	a (ns) (ns)	145.3179	124.3713	166.2646	142.3280	135.0317	149.6242	129.1003	118.3388	139.8618	133.4360	129.1684	137.7036
	b (*) (ns)	2.3823	1.8900	2.8746	2.9402	2.5677	3.3126	-4.6729	-5.4191	-3.9266	-5.3787	-5.9044	-4.8529
	c (*) (*)	0.0047	0.0035	0.0060	0.0070	0.0060	0.0079	0.0084	0.0068	0.0101	0.0115	0.0102	0.0127
DSM	a (ns) (ns)	42.8488	33.5872	52.1105	34.5175	30.5277	38.5072	34.2185	31.0511	37.3858	31.4017	29.3163	33.4871
	b (ns) (ns)	3.0877	2.4123	3.7630	3.1608	2.4842	3.8375	-6.8787	-7.9525	-5.8048	-6.0836	-7.0767	-5.0904
	c (ns) (ns)	0.0048	0.0034	0.0062	0.0060	0.0045	0.0076	0.0104	0.0085	0.0123	0.0107	0.0087	0.0126
Date 4 (02/24/2017)													
FSM	a (*) (*)	166.5907	147.4389	185.7425	142.2458	123.4944	160.9972	143.7331	135.6813	151.7849	125.9214	116.3544	135.4885
	b (ns) (*)	3.1988	2.6717	3.7260	2.6310	2.1364	3.1257	-6.5338	-7.2993	-5.7684	-5.1675	-5.9187	-4.4163
	c (ns) (ns)	0.0075	0.0060	0.0091	0.0069	0.0053	0.0086	0.0145	0.0126	0.0164	0.0125	0.0103	0.0146
DSM	a (*) (*)	38.5865	31.5646	45.6085	28.9069	25.5407	32.2731	30.0266	27.8012	32.2520	25.5919	24.0349	27.1490
	b (ns) (*)	3.6499	2.9794	4.3205	3.1986	2.5916	3.8056	-8.0167	-8.9683	-7.0651	-6.4429	-7.3349	-5.5509
	c (ns) (ns)	0.0074	0.0056	0.0091	0.0074	0.0058	0.0091	0.0159	0.0137	0.0181	0.0139	0.0117	0.0160

Note. [1] FSM: fresh shoot mass, g plant^{-1}; DSM: dry shoot mass, g plant^{-1}. [2] First column of parentheses represents the comparison of the parameters of the Gompertz model among the cultivars and the second column of parentheses represents the comparison of the parameters of the Logistic model among the cultivars. (*) significant at 5% probability of error. (ns) not significant.

Comparing the models of FSM as a function of ASR between the cultivars, we found that BRS Estribo and CG Farrapo did not differ in growth behavior at date 2 (Table 2). In addition, no difference was found for parameters *a* and *b* at the dates 1 and 3, indicating that the final value of growth of the cultivars was similar in these two dates. There was no difference between the cultivars for DSM at dates 1, 2, and 3 of the Gompertz model and dates 1 and 2 of the Logistic model. In the Logistic model, at date 3, the cultivars differed only in parameter *b*, thus having the same asymptotic value and the same precocity index. At date 4, there were differences between the cultivars, except for parameter *c* in the Gompertz model of DSM. At that date, the cultivars showed different final values of growth for FSM and DSM, and BRS Estribo was superior to CG Farrapo.

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

Trait [1]	Parameter [2]	Gompertz						Logistic					
		BRS Estribo			CG Farrapo			BRS Estribo			CG Farrapo		
		Estimate	LL	UL	Estimate	LL	UL	Estimate	LL	UL	Estimate	LL	UL
Date 1 (12/20/2016)													
FSM	a (ns) (ns)	157.5072	136.3393	178.6751	139.9595	134.5924	145.3266	142.3092	130.2936	154.3249	134.2892	130.5627	138.0157
	b (ns) (ns)	2.4092	1.8805	2.9378	2.9128	2.5480	3.2776	-4.6283	-5.4645	-3.7922	-5.1706	-5.7201	-4.6210
	c (*) (*)	0.0042	0.0031	0.0054	0.0057	0.0050	0.0064	0.0073	0.0058	0.0089	0.0090	0.0080	0.0100
DSM	a (ns) (ns)	38.9466	31.5645	46.3288	34.6232	31.9265	37.3198	33.3124	29.9354	36.6894	32.3684	30.5826	34.1543
	b (ns) (ns)	2.5292	1.9545	3.1039	2.7593	2.2453	3.2733	-5.2108	-6.1090	-4.3127	-5.0097	-5.8031	-4.2162
	c (ns) (ns)	0.0035	0.0024	0.0046	0.0044	0.0035	0.0053	0.0067	0.0053	0.0081	0.0071	0.0059	0.0084
Date 2 (01/20/2017)													
FSM	a (ns) (ns)	155.6587	143.6141	167.7032	152.7294	147.4974	157.9614	148.0270	139.3323	156.7217	148.7353	144.0440	153.4266
	b (ns) (ns)	2.4630	1.9590	2.9670	2.7045	2.3687	3.0404	-4.2882	-5.0599	-3.5165	-4.3881	-4.9287	-3.8474
	c (ns) (ns)	0.0055	0.0043	0.0067	0.0061	0.0054	0.0069	0.0084	0.0067	0.0100	0.0087	0.0076	0.0099
DSM	a (ns) (ns)	53.1173	45.5248	60.7098	49.7498	45.0390	54.4607	46.4395	42.9037	49.9752	44.4370	42.1348	46.7391
	b (ns) (ns)	2.5375	2.0266	3.0484	2.4125	2.0513	2.7738	-5.1667	-5.9643	-4.3692	-4.8706	-5.4275	-4.3137
	c (ns) (ns)	0.0036	0.0027	0.0045	0.0036	0.0029	0.0043	0.0068	0.0055	0.0080	0.0066	0.0057	0.0075
Date 3 (02/07/2017)													
FSM	a (ns) (ns)	157.0524	126.3304	187.7744	147.4673	138.1783	156.7564	133.8488	119.5894	148.1081	135.7613	130.5336	140.9890
	b (ns) (ns)	1.9345	1.5596	2.3093	2.2105	1.9474	2.4737	-4.0088	-4.6270	-3.3906	-4.2287	-4.6307	-3.8267
	c (*) (*)	0.0030	0.0021	0.0039	0.0043	0.0037	0.0050	0.0057	0.0045	0.0068	0.0073	0.0065	0.0081
DSM	a (ns) (ns)	40.3016	32.3756	48.2277	36.8112	30.9823	42.6401	33.9301	30.7953	37.0649	32.1363	29.4733	34.7992
	b (ns) (*)	3.2675	2.4667	4.0682	2.5572	1.9972	3.1172	-6.9857	-8.1814	-5.7901	-5.2988	-6.1901	-4.4074
	c (ns) (ns)	0.0041	0.0028	0.0053	0.0038	0.0028	0.0049	0.0083	0.0067	0.0099	0.0073	0.0059	0.0087
Date 4 (02/24/2017)													
FSM	a (*) (*)	147.7594	137.2317	158.2871	132.6186	119.4853	145.7519	138.0029	132.2227	143.7831	122.1188	114.7901	129.4474
	b (*) (*)	4.6265	3.8146	5.4385	3.3604	2.6941	4.0266	-8.2732	-9.2920	-7.2543	-6.3542	-7.3179	-5.3904
	c (*) (*)	0.0079	0.0065	0.0094	0.0063	0.0049	0.0077	0.0132	0.0115	0.0150	0.0110	0.0091	0.0128
DSM	a (*) (*)	30.0615	27.7609	32.3622	26.2948	24.3496	28.2400	27.7710	26.5328	29.0091	24.7095	23.6013	25.8176
	b (*) (*)	5.6082	4.7013	6.5151	4.4128	3.5662	5.2595	-9.9048	-11.0077	-8.8018	-7.8805	-8.9704	-6.7907
	c (ns) (*)	0.0087	0.0072	0.0102	0.0074	0.0059	0.0089	0.0145	0.0128	0.0163	0.0123	0.0105	0.0141

Note. [1] FSM: fresh shoot mass, g plant^{-1}; DSM: dry shoot mass, g plant^{-1}. [2] First column of parentheses represents the comparison of the parameters of the Gompertz model among the cultivars and the second column of parentheses represents the comparison of the parameters of the Logistic model among the cultivars. (*) significant at 5% probability of error. (ns) not significant.

The comparisons showed that the cultivars BRS Estribo and CG Farrapo had distinct growth behaviors within the sowing dates. These differences were more evident for fresh shoot mass. Differences in growth between cultivars were observed in studies of dry mass accumulation during sugarcane formation (Batista et al., 2013).

Besides the comparisons between the cultivars, comparisons were made between the sowing dates within each cultivar. We found that in the models fitted as a function of ATS, the FSM of cv. BRS Estribo showed no difference between dates 1 and 4 and 2 and 3 in the Gompertz model, as well as between dates 1 and 4 of the Logistic model. For the parameter *a* in the Gompertz model, there were differences only between the asymptotic values of the trait between dates 3 and 4. In the Logistic model, dates 1 and 3 and 2 and 4 showed no difference in the parameter *a*. For DSM, there were no differences between dates 1 and 3 and 1 and 4 in the Gompertz model, while in the Logistic model, there were no differences between dates 1 and 3. The parameter *a* showed similar values in the dates 3 and 4, in the Gompertz model, and 1 and 4, in the Logistic model.

Cultivar CG Farrapo showed similar behavior between dates 2 and 4 and 3 and 4 in the Gompertz model and between 3 and 4 in the Logistic model for FSM. Similar asymptotic values were found between dates 1 and 3 and 1 and 4 of both models. DSM showed no differences between dates 1 and 3 in both models.

Regarding the models fitted as a function of ASR, there was no similar behavior of cv. BRS Estribo for the trait FSM, between the dates in the Gompertz model, whereas in the Logistic model, similar behavior was observed between dates 1 and 2. For the Gompertz model, all dates showed similar values of *a*, that is, non-different final value of growth. For the trait DSM, the dates 1 and 3 were not different in the Gompertz model, whereas in the Logistic model, these same dates showed similar values of *a* and *c*, but different for parameter *b*.

In the models of cv. CG Farrapo, similar behavior for FSM was found in dates 1 and 4 of the Gompertz model, as well as in dates 1 and 3 of both models for DSM. Similar behavior for the asymptotic value was found in dates 1 and 3 and 2 and 3, in the Gompertz model, and 1 and 3, in the Logistic model, for FSM.

Therefore, as for the cultivars, there were differences in behavior between the sowing dates of each cultivar. In crotalária juncea, Bem et al. (2018) observed differences between sowing dates for fresh and dry masses of the plants. These results are due to differences in the meteorological conditions and/or biotic factors that affect the crop and result in different responses of the plant in its growth.

In order to indicate the model that best describes the growth of the sudangrass cultivars in the four sowing dates, we calculated the adjusted coefficient of determination (R^2aj), the Akaike information criterion (AIC), the residual standard deviation (RSD) and quantified the parameter-effects nonlinearity (PE) and the intrinsic nonlinearity (IN). For the traits FSM and DSM, both models were appropriate, with R^2aj values equal to or greater than 0.8721 when fitted for ATS (Table 3), and equal to or greater than 0.8646 when as a function of ASR (Table 4). From these values, we can infer that both the independent variables ATS and ASR were adequate to model the growth of the sudangrass cultivars.

Table 3. Fit quality indicators and critical points of the Gompertz and Logistic models for the traits of fresh shoot mass (FSM) and dry shoot mass (DSM) as a function of accumulated thermal sum (°C) for sudangrass cultivars BRS Estribo and CG Farrapo in four sowing times

Statistic [(1)]		Gompertz				Logistic			
		BRS Estribo		CG Farrapo		BRS Estribo		CG Farrapo	
		FSM	DSM	FSM	DSM	FSM	DSM	FSM	DSM
Date 1 (12/20/2016)									
R^2aj		0.8993	0.8928	0.9642	0.9169	0.8976	0.8974	0.9659	0.9110
AIC		5.5479	2.7021	4.4262	2.5172	5.5635	2.6589	4.3803	2.5841
RSD		15.4716	3.7498	8.8715	3.4264	15.5952	3.6680	8.6616	3.5455
PE		0.9414	1.1395	0.2708	0.4922	0.5675	0.5529	0.1956	0.3336
IN		0.1418	0.1584	0.0883	0.1330	0.1223	0.1190	0.0737	0.1110
PI	x	419.3274	507.0559	392.1039	460.9001	463.2785	554.5061	433.2996	509.9653
	y	54.3419	12.8287	50.3101	12.1938	69.3157	15.8877	66.5666	15.8221
PMA	x	291.0689	346.2634	293.3569	326.6025	354.2518	429.6683	343.6309	393.4355
	y	10.7754	2.5438	9.9759	2.4179	29.2963	6.7149	28.1344	6.6872
PMD	x	547.5859	667.8485	490.8510	595.1977	572.3052	679.3439	522.9684	626.4952
	y	100.8193	23.8008	93.3392	22.6229	109.3352	25.0605	104.9989	24.9571
PAD	x	658.8378	807.3205	576.5046	711.6879	653.0615	771.8116	589.3862	712.8091
	y	125.1532	29.5454	115.8677	28.0832	125.9118	28.8600	120.9180	28.7409
Date 2 (01/20/2017)									
R^2aj		0.8792	0.8741	0.9495	0.9148	0.8745	0.8871	0.9371	0.9270
AIC		5.6060	3.5399	4.6896	2.9804	5.6436	3.4320	4.9089	2.8251
RSD		15.9574	5.7387	10.1285	4.3320	16.2629	5.4332	11.3116	4.0097
PE		1.3576	1.5475	0.4622	1.4263	0.8180	0.6211	0.3693	0.5202
IN		0.0916	0.1766	0.0579	0.1089	0.1051	0.1216	0.0747	0.0830
PI	x	363.2564	552.9506	350.8924	553.5216	415.4570	596.8194	404.3784	599.5227
	y	60.8106	19.4335	57.6206	19.6125	76.8782	23.1981	75.4779	22.8723
PMA	x	198.6521	366.1052	209.5792	330.4009	272.6006	462.5487	270.5541	444.6053
	y	12.0580	3.8534	11.4255	3.8889	32.4925	9.8047	31.9007	9.6670
PMD	x	527.8607	739.7959	492.2057	776.6423	558.3135	731.0902	538.2028	754.4402
	y	112.8206	36.0546	106.9022	36.3867	121.2635	36.5917	119.0550	36.0777
PAD	x	670.6391	901.8662	614.7813	970.1781	664.1276	830.5449	637.3268	869.1879
	y	140.0512	44.7568	132.7043	45.1690	139.6486	42.1395	137.1053	41.5475

Date 3 (02/07/2017)									
R²aj		0.8721	0.8967	0.9532	0.8850	0.8758	0.9086	0.9598	0.8935
AIC		5.5022	2.7346	4.5516	2.7663	5.4733	2.6138	4.4004	2.6913
RSD		15.3054	3.8503	9.4845	3.9011	15.0846	3.6234	8.7865	3.7549
PE		1.7585	2.8176	0.5242	1.2864	0.8139	0.8563	0.2747	0.5979
IN		0.1109	0.1576	0.0782	0.1527	0.0990	0.1119	0.0622	0.1126
PI	x	503.4340	641.7491	423.0108	523.0511	554.4819	662.8515	469.5409	570.2227
	y	53.4595	15.7632	52.3595	12.6983	64.5501	17.1092	66.7180	15.7008
PMA	x	300.0530	441.7177	284.5440	363.7896	398.2114	535.9451	354.5747	446.7821
	y	10.6004	3.1257	10.3823	2.5179	27.2821	7.2312	28.1983	6.6360
PMD	x	706.8150	841.7805	561.4776	682.3126	710.7524	789.7579	584.5071	693.6632
	y	99.1821	29.2451	97.1414	23.5588	101.8182	26.9872	105.2376	24.7657
PAD	x	883.2285	1015.2885	681.5842	820.4566	826.5023	883.7577	669.6628	785.0959
	y	123.1210	36.3038	120.5877	29.2450	117.2551	31.0789	121.1930	28.5205
Date 4 (02/24/2017)									
R²aj		0.9513	0.9580	0.9227	0.9253	0.9589	0.9654	0.9253	0.9362
AIC		4.8499	1.4899	4.9604	1.8443	4.6828	1.3039	4.9264	1.6883
RSD		11.0127	2.0619	11.5937	2.4556	10.1133	1.8722	11.3978	2.2691
PE		1.4031	2.5545	1.6202	1.3287	0.5222	0.7083	0.7364	0.5449
IN		0.1286	0.1389	0.1193	0.1484	0.0831	0.0884	0.0915	0.1001
PI	x	423.9332	495.9976	379.0141	430.2752	451.2401	504.6552	414.1579	463.9403
	y	61.2853	14.1952	52.3293	10.6343	71.8664	15.0133	62.9607	12.7960
PMA	x	296.3861	365.2122	240.3725	300.8098	360.2878	421.7518	308.6077	369.1084
	y	12.1521	2.8147	10.3763	2.1086	30.3744	6.3454	26.6103	5.4082
PMD	x	551.4804	626.7830	517.6556	559.7407	542.1924	587.5586	519.7081	558.7721
	y	113.7012	26.3360	97.0854	19.7295	113.3587	23.6812	99.3111	20.1837
PAD	x	662.1153	740.2267	637.9138	672.0396	609.5610	648.9654	597.8893	629.0142
	y	141.1444	32.6925	120.5181	24.4914	130.5453	27.2716	114.3679	23.2438

Note. (1) R^2aj: adjusted coefficient of determination; AIC: Akaike information criterion; RSD: residual standard deviation; IN: intrinsic nonlinearity; PE: parameter-effects nonlinearity; PI: point of inflection; PMA: point of maximum acceleration; PMD: point of maximum deceleration; PAD: point of asymptotic deceleration.

Comparing the models, based on the fit quality indicators, we found that overall, the Logistic model presented the highest R^2aj and the lowest AIC and RSD values, indicating its suitability to describe the sudangrass growth. It also had the lowest of PE and IN values, showing that it is closer to linear, confirming its better quality. Prado et al. (2013) and Muniz et al. (2017) had similar conclusions, reporting a better performance of the Logistic model to describe the growth of dwarf coconut and cacao, respectively.

We can use the critical points of the growth curves to infer on crop growth. The main point to consider is the inflection point, which represents the time when the plant reaches the middle of the cycle, the highest growth rate, and from which the growth rate begins to slow. Comparing the models fitted as a function of ATS (Table 3) and ASR (Table 4), we see that in the Logistic model the plants reached PI with higher fresh and dry shoot masses, but they needed greater accumulation of thermal sum and/or solar radiation than in the Gompertz model.

Table 4. Fit quality indicators and critical points of the Gompertz and Logistic models for the traits of fresh shoot mass (FSM) and dry shoot mass (DSM) as a function of accumulated solar radiation ($MJ \cdot m^{-2}$) for sudangrass cultivars BRS Estribo and CG Farrapo in four sowing times

Statistic	Gompertz				Logistic			
	BRS Estribo		CG Farrapo		BRS Estribo		CG Farrapo	
	FSM	DSM	FSM	DSM	FSM	DSM	FSM	DSM
Date 1 (12/20/2016)								
R²aj	0.8994	0.8919	0.9614	0.9152	0.8981	0.8972	0.9634	0.9111
AIC	5.5464	2.7101	4.5026	2.5366	5.5590	2.6611	4.4490	2.5830
RSD	15.4595	3.7651	9.2134	3.4601	15.5598	3.6723	8.9643	3.5429
PE	1.4748	2.2078	0.3832	0.7799	0.7591	0.8879	0.2385	0.4676

IN		0.1281	0.1783	0.0908	0.1514	0.1168	0.1250	0.0718	0.1139
PI	x	567.7546	721.9606	510.4711	628.3964	630.5885	776.1997	576.2484	700.8406
	y	57.9437	14.3277	51.4882	12.7371	71.1547	16.6561	67.1446	16.1842
PMA	x	340.9463	447.2333	341.8081	409.2162	451.1584	580.0265	429.4762	516.6013
	y	11.4895	2.8410	10.2095	2.5256	30.0735	7.0397	28.3786	6.8403
PMD	x	794.5629	996.6880	679.1342	847.5765	810.0186	972.3728	723.0206	885.0799
	y	107.5015	26.5818	95.5249	23.6309	112.2357	26.2726	105.9105	25.5282
PAD	x	991.2974	1234.9875	825.4332	1037.6943	942.9228	1117.6788	831.7350	1021.5464
	y	133.4483	32.9976	118.5810	29.3345	129.2521	30.2559	121.9679	29.3986
Date 2 (01/20/2017)									
R^2aj		0.8816	0.8910	0.9464	0.9292	0.8765	0.8976	0.9340	0.9376
AIC		5.5859	3.3985	4.7508	2.7961	5.6272	3.3371	4.4420	2.6695
RSD		15.7976	5.3386	10.4429	3.9496	16.1298	5.1750	11.5820	3.7066
PE		0.7562	1.5868	0.3196	0.9959	0.4943	0.6500	0.2626	0.4303
IN		0.0880	0.1377	0.0575	0.0891	0.1025	0.1026	0.0732	0.0742
PI	x	449.8334	703.4069	439.9603	669.8794	511.9898	762.9632	502.5705	739.4541
	y	57.2636	19.5408	56.1860	18.3019	74.0135	23.2197	74.3676	22.2185
PMA	x	274.0614	436.6189	283.3963	402.6465	354.7527	568.4901	351.7371	539.5142
	y	11.3547	3.8747	11.1410	3.6291	31.2818	9.8138	31.4315	9.3906
PMD	x	625.6055	970.1949	596.5244	937.1123	669.2269	957.4364	653.4038	939.3941
	y	106.2399	36.2535	104.2406	33.9552	116.7452	36.6256	117.3038	35.0463
PAD	x	778.0708	1201.6078	732.3286	1168.9112	785.6928	1101.4831	765.1264	1087.4901
	y	131.8822	45.0037	129.4003	42.1506	134.4452	42.1786	135.0886	40.3598
Date 3 (02/07/2017)									
R^2aj		0.8646	0.8801	0.9548	0.8747	0.8691	0.8975	0.9581	0.8852
AIC		5.5591	2.8726	4.5177	2.8521	5.5257	2.7189	4.4420	2.7657
RSD		15.7465	4.1488	9.3170	4.0716	15.4851	3.8365	8.9700	3.8981
PE		2.6416	2.3572	0.7096	1.9144	1.1021	0.8023	0.3640	0.7930
IN		0.0935	0.2006	0.0555	0.1596	0.0984	0.1335	0.0579	0.1185
PI	x	646.9873	799.4523	508.5073	666.7369	709.4531	842.9775	577.0935	726.3944
	y	57.7763	14.8261	54.2502	13.5421	66.9240	16.9650	67.8805	16.0682
PMA	x	325.1009	563.9750	287.1111	415.8039	476.3871	684.0584	397.3661	545.8556
	y	11.4564	2.9398	10.7572	2.6852	28.2856	7.1703	28.6897	6.7912
PMD	x	968.8737	1034.9296	729.9036	917.6699	942.5192	1001.8966	756.8209	906.9333
	y	107.1911	27.5066	100.6491	25.1243	105.5632	26.7598	107.0716	25.3451
PAD	x	1248.0792	1239.1835	921.9435	1135.3301	1115.1517	1119.6084	889.9455	1040.6588
	y	133.0630	34.1457	124.9420	31.1884	121.5679	30.8170	123.3050	29.1877
Date 4 (02/24/2017)									
R^2aj		0.9459	0.9587	0.9152	0.9276	0.9581	0.9669	0.9251	0.9407
AIC		4.9406	1.4576	5.0510	1.8044	4.6960	1.2555	4.9285	1.6117
RSD		11.6086	2.0459	12.1445	2.4183	10.2133	1.8321	11.4131	2.1876
PE		0.7080	0.7356	1.0204	0.7341	0.3379	0.3308	0.5016	0.3560
IN		0.1369	0.1111	0.1561	0.1502	0.0916	0.0786	0.1048	0.1002
PI	x	583.8386	647.5544	530.0817	595.7359	624.4562	681.6803	579.7270	640.7866
	y	54.3577	11.0590	48.7877	9.6733	69.0014	13.8855	61.0595	12.3547
PMA	x	462.3869	536.4276	378.2640	465.8083	525.0526	591.0428	459.5737	533.7015
	y	10.7785	2.1929	9.6740	1.9181	29.1634	5.8687	25.8067	5.2217
PMD	x	705.2903	758.6813	681.8995	725.6634	723.8599	772.3178	699.8803	747.8718
	y	100.8485	20.5175	90.5146	17.9467	108.8395	21.9023	96.3120	19.4877
PAD	x	810.6380	855.0732	813.5868	838.3631	797.4884	839.4532	788.8781	827.1899
	y	125.1895	25.4697	112.3614	22.2783	125.3409	25.2229	110.9142	22.4423

Note. (1) R^2aj: adjusted coefficient of determination; AIC: Akaike information criterion; RSD: residual standard deviation; IN: intrinsic nonlinearity; PE: parameter-effects nonlinearity; PI: point of inflection; PMA: point of maximum acceleration; PMD: point of maximum deceleration; PAD: point of asymptotic deceleration.

Figures 2 and 3 show the growth curves with their respective critical points for the Logistic model, which is the most indicated. It can be seen that cv. CG Farrapo required less accumulation of thermal sum and/or solar radiation to reach the PI compared with cv. BRS Estribo, but presented lower FSM and DSM. Differences between the thermal sum requirements to reach the inflection point were also observed by Deprá, Lopes, Noal, Reininger and Cocco (2016) in maize cultivars.

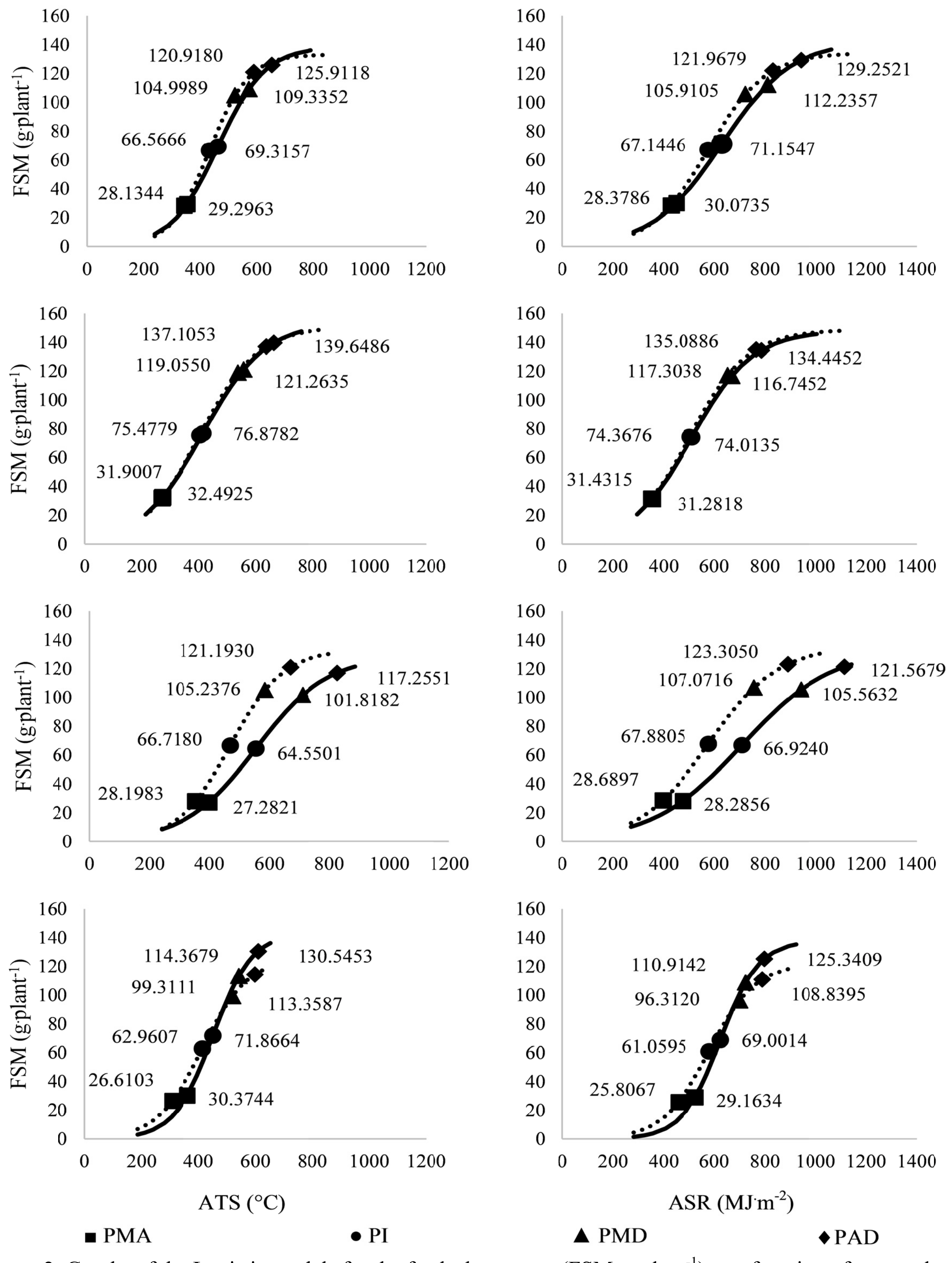

Figure 2. Graphs of the Logistic models for the fresh shoot mass (FSM, g plant^{-1}) as a function of accumulated thermal sum (STA, in °C) and accumulated solar radiation (ASR, in MJ·m^{-2}), of sudangrass cultivars BRS Estribo (—) and CG Farrapo (······) in four sowing times

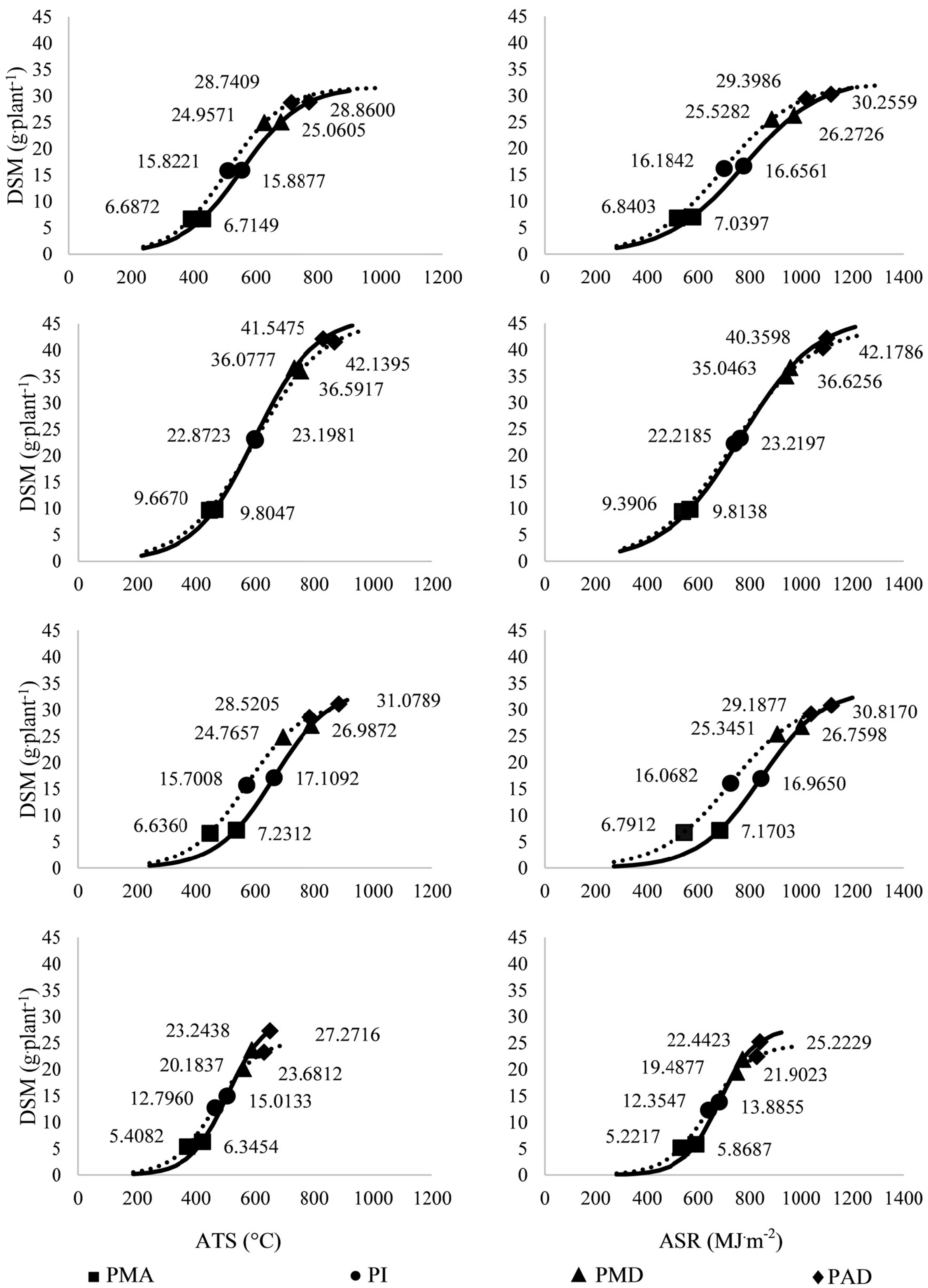

Figure 3. Graphs of the Logistic models for the dry shoot mass (DSM, g plant^{-1}) as a function of accumulated thermal sum (STA, in °C) and accumulated solar radiation (ASR, in MJ·m^{-2}), of sundangrass cultivars BRS Estribo (—) and CG Farrapo (······) in four sowing times

In general, for the other points, cv. CG Farrapo reaches PMA, PMD, and PAD with lower of ATS and/or ASR values compared with cv. BRS Estribo. Therefore, we can infer that cv. CG Farrapo has a shorter cycle, with growth rate acceleration and deceleration taking place earlier than in cv. CG Farrapo. Hence, we recommend that the cultural practices, such as topdressing, weed and pest control, should be carried out earlier in cv. CG Farrapo than in cv. BRS Estribo.

Analyzing the sowing dates, we observe that the second date (20/01) presented the highest FSM and DSM values at all the critical points, which can indicate the best sowing date for the crop, aiming at greater yield of fresh and dry shoot masses.

Overall, differences were found between the cultivars within the sowing dates and between the sowing dates within each cultivar. In this way, the researcher carrying out studies with Sudan grass should choose the model that best describes the growth of a particular cultivar at a given time of interest.

Because the information of the present study was generated from the data obtained for cultivars BRS Estribo and CG Farrapo grown in the environmental conditions in which they were studied, the use of these models could produce results with some discrepancies, however this is expected. Nevertheless, due to the representativeness of the database used to fit the models in this study (three weekly evaluations of five plants during the crop cycle, in two cultivars sown in four dates) and the fact that no studies were found with growth models for Sudangrass, these models can be used as reference for further investigations in the crop.

4. Conclusions

The independent variables accumulated thermal sum and accumulated solar radiation can be used satisfactorily to fit the Gompertz and Logistic models to fit cultivars of sudangrass.

There is difference between the growth models of the cultivars within sowing dates and between the sowing dates within a cultivar for the traits fresh shoot mass and dry shoot mass.

The Gompertz and Logistic models satisfactorily describe the growth of fresh shoot mass and dry shoot mass of the sudangrass cultivars BRS Estribo and CG Farrapo sown at four dates. The Logistic model is more indicated as it presents better fit quality indicators.

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