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CROP PRODUCTION
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Meteorological factors responsible for the growth and development of sugarcane at two locations in Rio Grande do Sul, Brazil

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ABSTRACT: *This study determined the meteorological variable that most contribute to the productivity of sugarcane stalks in the northwest and central regions of Rio Grande do Sul. The following sugarcane genotypes were used: UFSM XIKA FW, UFSM LUCI FW, UFSM PRETA FW, UFSM DINA FW, UFSM MARI FW, and IAC87-3396. The UFSM cultivars originate from a mutation process in the breeding program conducted at the Federal University of Santa Maria, Frederico Westphalen campus, and have low temperature tolerance. The productivity-associated morphological characters included in the models were average stem diameter, average stem number per meter of furrow, and average stem height. The following meteorological variables were used: minimum air temperature, precipitation, incident solar radiation, and accumulated thermal sum. Pearson's correlation, canonical correlations, and Stepwise regression were performed between morphological characters and meteorological variables: minimum air temperature had the greatest influence on sugarcane productivity in the studied regions, and accumulated thermal sum showed the highest correlation and contributed most to stem diameter and average stem height. Thus, the models indicated that the growth of sugarcane is positively associated with the accumulated thermal sum, and sugarcane can be cultivated at the studied regions.*
Key words: *Saccharum spp., degree-days, multiple regression, canonical correlation.*

Fatores meteorológicos responsáveis pelo crescimento e desenvolvimento da cana-de-açúcar em dois locais do Rio Grande do Sul

RESUMO: *O objetivo deste trabalho foi determinar a variável meteorológica com maior contribuição na produtividade de colmos de cana-de-açúcar na região noroeste e central do Rio Grande do Sul. Os genótipos de cana-de-açúcar utilizados foram: UFSM XIKA FW, UFSM LUCI FW, UFSM PRETA FW, UFSM DINA FW, UFSM MARI FW, IAC87-3396. As cultivares UFSM são provenientes do processo de mutação do programa de melhoramento da Universidade Federal de Santa Maria, campus de Frederico Westphalen, e possuem tolerância a baixas temperaturas. Os caracteres morfológicos responsáveis pela produtividade utilizados nos modelos foram diâmetro médio de colmo, número médio de colmos por metro de sulco e estatura média de colmos. As variáveis meteorológicas utilizadas foram a temperatura mínima do ar, precipitação pluviométrica, radiação solar incidente e soma térmica acumulada. Foi realizada a correlação de Pearson, correlações canônicas e regressão de Stepwise entre os caracteres morfológicos e as variáveis meteorológicas, nos quais foi constado que a temperatura mínima do ar é a variável com maior influência na produtividade da cana-de-açúcar nas regiões estudadas e, que a soma térmica acumulada é a variável com maior correlação e contribuição no diâmetro de colmo e estatura média dos colmos. Desse modo, os modelos indicam que o crescimento da cana-de-açúcar responde de forma positiva a soma térmica acumulada, e as regiões em estudo apresentam potencial para o cultivo da cana-de-açúcar.*
Palavras-chave: *Saccharum spp., graus-dia, regressão múltipla, correlação canônica.*

INTRODUCTION

Sugarcane (*Saccharum* ssp.) is one of the main crops of agronomic interest and is grown worldwide (CAPUTO et al., 2008). The distinguishing feature of this crop is its high potential to produce biomass and energy per unit area (SILVA et al., 2014), because of which it is used as raw material to produce sugar (FAO, 2019) and ethanol (WALTER et al., 2014). Brazil is one of the largest producers of sugarcane, with about 8.4 million hectares (ha) of planted area, production of 642.7 million tons, and average productivity of 76.1 tons ha^{-1} in the 2019/2020 crop season (CONAB, 2020).

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Techniques such as models for forecasting sugarcane productivity are important strategies for the operational management of the sugar–energy industry, influencing agricultural decisions and the operation and maintenance of the industry (BOCCA & RODRIGUES, 2016; EVERINGHAM et al., 2016; PAGANI et al., 2017). Simulation models of the growth and development of sugarcane can simulate different scenarios and ways to optimize resources and increase the understanding of the processes related to growth and productivity (SUGUITANI, 2006).

Sugarcane productivity can be simulated using variables such as stem diameter, stem number per linear meter of furrow, and plant height (MARTINS & LANDELL, 1995; OLIVEIRA et al., 2007; FABRIS et al., 2013). In this context, the use of multivariate techniques such as canonical correlations allows the determination of the associations between groups of characters and identification of characteristics and important variables for analyzing the performance of crops (CARVALHO et al., 2015).

The growth and development of plants and; consequently, the productivity of crops, are associated with several biotic and abiotic factors, with meteorological elements being the most relevant (SCHWERZ, 2020). The effect of meteorological elements on crops can be analyzed using statistical techniques such as stepwise regression, which is the most used. The method consists of testing the insertion or removal of independent variables in equations by using statistical significance and the correlation coefficient between dependent and independent variables as criteria (FIORENTIN et al., 2015).

Assuming that the minimum air temperature is the main limiting factor for the productivity of sugarcane stalks in southern Brazil, this study determined and quantified the influence of meteorological variables on the productivity of sugarcane cultivated in different regions of Rio Grande do Sul by analyzing the canonical correlation between morphological characters and meteorological variables and generating linear regression models from variables for each associated character.

MATERIALS AND METHODS

In this study, two field experiments were conducted from October 2017 to July 2018. The first experiment was conducted in the micro-region of Frederico Westphalen, in the state of Rio Grande do Sul, Brazil, in the Federal University of Santa Maria, with geographical coordinates 27°39′56″ LS–53°42′94″ LW and altitude of 566 m. According to the Köppen climate classification, the climate is Cfa type, subtropical with no defined dry season, with average annual air temperature of 19.1ºC (range, 0 to 38ºC) and accumulated precipitation of 1900–2200 mm (ALVARES et al., 2013). The soil of the experimental area is classified as Latossolo Vermelho aluminoférrico, with 67% clay, 2.5% organic matter (OM), 2.8 mg dm^{-3} of P, 139 mg dm^{-3} of K, 14.1 cmolc dm^{-3} of chlortetracycline (CTC), and base saturation of 55.9%.

The second experiment was conducted in the micro-region of Cruz Alta, in the state of Rio Grande do Sul, Brazil, in a rural property, with geographical coordinates 28°42′36″ S and 53°43′12″ W and altitude of 452 m. According to the Köppen climate classification, the climate is Cfa type, subtropical with no defined dry season, and average air temperature of 19.0°C (range, -1 to 38ºC) for the hottest and coldest months, respectively, and accumulated precipitation of 1900 to 2200 mm (ALVARES et al., 2013). The soil in the experimental area is classified as a typical Latossolo Vermelho distroférrico, with 56% clay, 2.8% OM, 4.0 mg d^{-3} of P, 88 mg dm^{-3} of K, 10.8 cmolc dm^{-3} of CTC, and base saturation of 54.9%.

The experiment conducted in the micro-region of Frederico Westphalen followed a randomized block design with a 6 × 2 factorial arrangement and treatments consisting of six cultivars—UFSM XIKA FW, UFSM MARI FW, UFSM DINA FW, UFSM PRETA FW, UFSM LUCI FW, and IAC87-3396—arranged in two row spacings (0.33 m × 1.5 m and 0.5 m × 1.5 m), with four replications. The experiment conducted in the micro-region of Cruz Alta followed a randomized block design with treatments consisting of the six above-mentioned cultivars arranged in a single row spacing (0.5 m × 1.5 m), with four replications.

The first five sugarcane cultivars used in both the experiments are protected materials at the Ministry of AgriCROP, Livestock, and Supply by Federal University of Santa Maria, and cultivar IAC87-3396 was selected because this genotype was used for inducing mutations to obtain the UFSM FW cultivars. UFSM FW cultivars are the first sugarcane cultivars protected by the Federal University of Santa Maria in the Ministry of AgriCROP, Livestock, and Supply and the first ones to be generated by mutation induction. The generation of new cultivars was confirmed by their morphological characters that were clearly distinguishable from those of the cultivar from which they originated, according to the guidelines regulated by law No. 9.456/97 of protection of cultivars.

The plant material used in this study was obtained by the propagation of pre-sprouted seedlings, with the planting of small stalks on June 28, 2017, in a protected environment and transplantation on October 18, 2017, in Frederico Westphalen, RS, and on October 29, 2017, in Cruz Alta, RS. Before the seedlings were transplanted, the soil was prepared for planting the seedlings by adjusting the pH, generating two subsoils, and securing a harrowing area for incorporating lime. Each row was fertilized with NPK, according to the technical indications for cultivation in the states of RS and SC (SOCIEDADE BRASILEIRA DE CIÊNCIA DO SOLO, 2016): 100 kg of N, 110 of P_2O_5, and 60 kg of K_2O were used in Frederico Westphalen; 70 kg of N, 110 of P_2O_5, and 60 kg of K_2O were used in Cruz Alta.

The data on incident global radiation, air temperature (minimum, average, and maximum), and precipitation were obtained from automatic meteorological stations linked to the National Institute of Meteorology (INMET) of Frederico Westphalen and Cruz Alta, which are located 500 m and 10,000 m from the experimental areas, respectively. The water balance for both locations was determined according to the methodology proposed by Rolim et al. (1998) (Figure 1). The available water capacity in the soil (AWC) needed to be measured to calculate the sequential water balance, which yielded values of 157 mm and 113 mm for Frederico Westphalen and Cruz Alta, respectively. For this, the meteorological data were grouped into ten-day periods, and the period for transplanting the sugarcane harvest was considered to be 27 periods.

At 38, 73, 103, 147, 175, 224, and 266 days after transplantation, biometric measurements of stem diameter were performed at the basal portion, close to the ground (MARTINS & LANDELL, 1995), and the height of the tillers with two stems per experimental unit and number of tillers per linear meter of furrow were determined. This count was performed on 2 m of the two central rows of a plot, totaling 4 linear meters per plot. The accumulation of stalk mass was determined on the basis of these data, which revealed the main morphological characters and determinants of stalk productivity per hectare

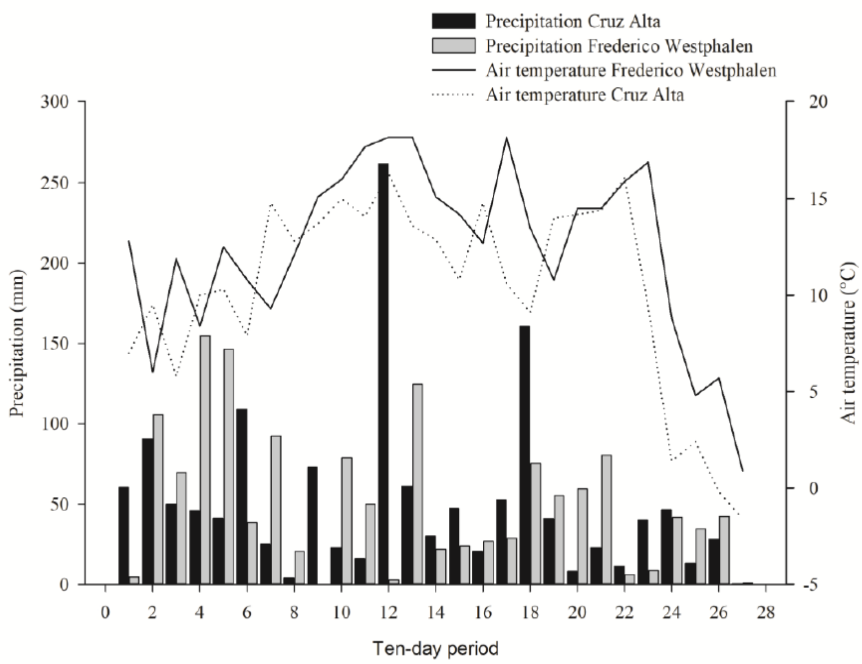

Figure 1 – (A) Accumulated global solar radiation (MJ m-2) during the experimental period with transplantation (ten-day period 1) on October 18 and October 29, 2017, and harvest (ten-day period 27) on 10 June and June 26, 2018, in Frederico Westphalen and Cruz Alta, respectively. (B) Accumulated thermal sum (°C day-1) during seven evaluations throughout the cycle.

(MARTINS & LANDELL, 1995; OLIVEIRA et al., 2007; FABRIS et al., 2013).

The daily thermal sum was determined by considering the lower baseline temperature (Tb) of 10°C for the cultivation of sugarcane (STRECK et al., 2010; CASTRO-NAVA et al., 2016; MORAIS et al., 2018), i.e., the degrees-day (DD_i). It was obtained using the following equations for days when the minimum temperature was higher than the Tb (NOVA et al., 1972; PEREIRA et al., 2002).

$$DD_i = Tm\text{-}Tb \quad (1)$$

Where, Tm represents the average temperature on the days when the Tb was greater than or equal to the minimum temperature (Tmin):

$$DD_i = \frac{(TM - Tb)^2}{2(TM\text{-}Tm)} \quad (2)$$

Where, TM and Tm represent the maximum and minimum temperature of the day, respectively.

The accumulated thermal sum or accumulation of $DD_{i,}$ from the transplanting date to emergence resulted in the sum of degrees-day (∑DD), which is the thermal constant necessary for plants to grow and/or develop.

The data were statistically analyzed using the Statistical Analysis System version 9.0 (SAS, 2002). Initially, the statistical assumptions of normality, linearity, and multicollinearity were tested ($p < 0.05$). Pearson's coefficients were estimated among all variables. The chi-square test was used to determine whether there was evidence to reject H_0 (CRUZ, 2013). Next, linear regression analysis was performed using the Stepwise method ($p \leq 0.15$), and the contribution of each variable for the characters was calculated from the partial determination coefficient. For this, the meteorological variables were considered independent input variables, and the morphological characters were considered dependent variables, and all interactions between meteorological variables and morphological characters were tested.

RESULTS AND DISCUSSION

During sugarcane cultivation in Frederico Westphalen, the average air temperature was 21.2ºC (range, 0.9ºC to 34.9ºC; Figure 2), accumulated global solar radiation was 4979 MJ m^{-2} day^{-1} (Figure 1), accumulated precipitation was 1395 mm, and accumulated water deficit was 20 mm (Figure 3). In Cruz Alta, the average air temperature was 19.6ºC (range, -1.6ºC to 35.5ºC), accumulated global solar radiation was 6097 MJ m^{-2} da^{-1}, accumulated

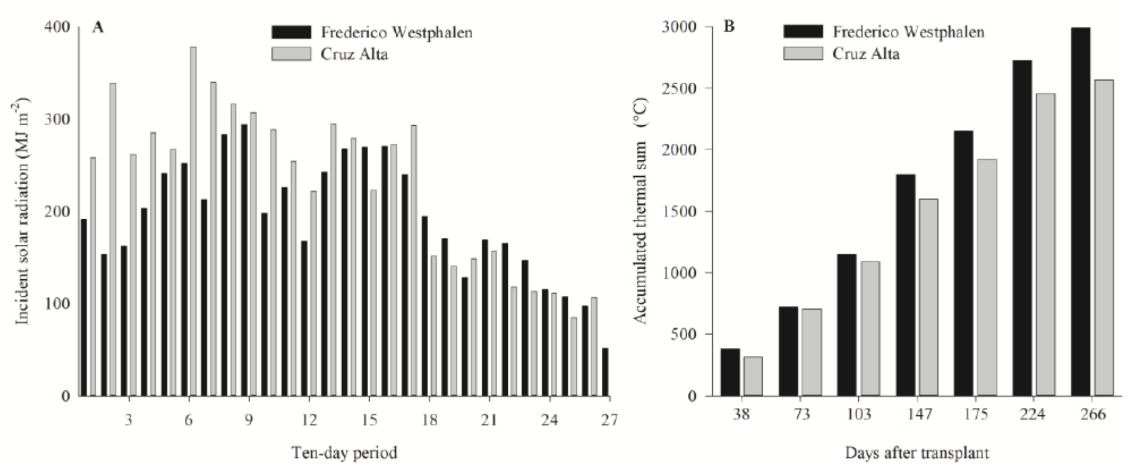

Figure 2 – Precipitation and minimum air temperature during the experimental period with transplantation (ten-day period 1) on October 18 and October 29, 2017, and harvest on June 10 and June 26, 2018 (ten-day period 27) in Frederico Westphalen and Cruz Alta, respectively.

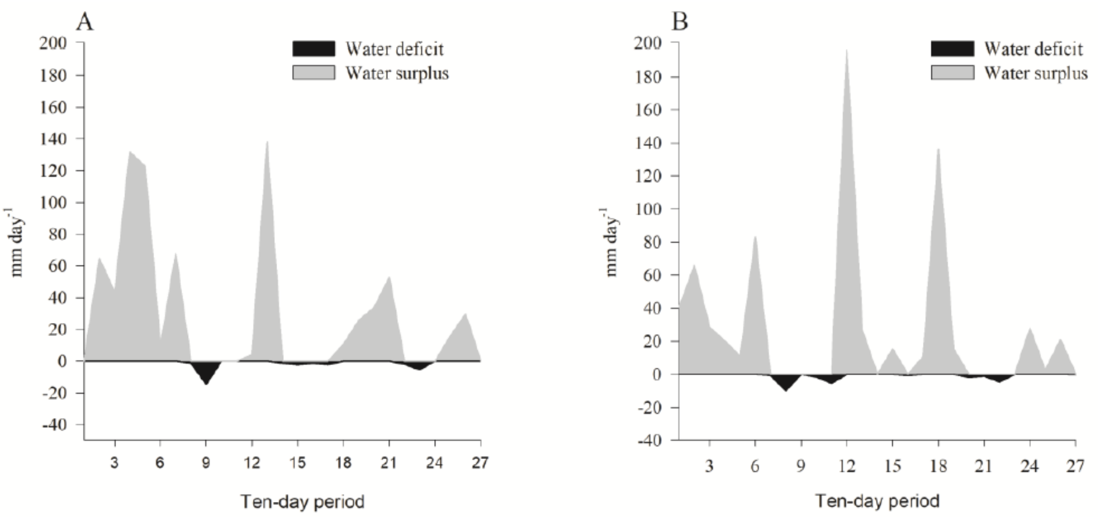

Figure 3 – Sequential water balance for Frederico Westphalen (A) during the experimental period with transplantation (ten-day period 1) on October 18 and October 29, 2017, and harvest (ten-day period 27) on June 10 and June 26, 2018, in Frederico Westphalen and Cruz Alta, respectively.

precipitation was 1383 mm, and accumulated water deficit was 23 mm.

Sugarcane cultivation requires average air temperature of above 21ºC (LOPES & LIMA, 2015) and adequately distributed accumulated precipitation of 1000 mm (INMAN-BAMBER & SMITH, 2005) to promote ideal growth and development. The water deficit observed in both the locations did not coincide with the critical development periods of the crop. Moreover, MAURI et al. (2017) indicated that accumulated water deficit of less than 40 mm does not negatively impact the growth and development of sugarcane. Thus, water conditions were not limiting factors to the crop.

The multicollinearity test suggested the need to exclude the variables average and maximum air temperature; thermal amplitude; accumulated solar radiation; accumulated precipitation; and minimum, average, and maximum relative humidity from the correlation analysis. Thus, the meteorological variables selected to generate the regression models were minimum air temperature, solar radiation, precipitation, and accumulated thermal sum (degrees-day).

Pearson's correlation analysis showed that the meteorological variable most correlated with the morphological characters responsible for productivity is accumulated thermal sum, with a degree of correlation from regular to very strong (Table 1). Similarly, CAETANO & CASAROLI (2017) reported a positive correlation between thermal sum and sugarcane productivity. This result can be explained by the fundamental role of thermal sum in the production of photosynthetic units, the production of photoassimilates, and the growth of stem biomass (SINGELS & BEZUIDENHOUT, 2002), which are determining factors in sugarcane productivity.

Canonical correlation analysis revealed significant effects for the first and second canonical pairs with coefficient r = 0.97 and 0.74 for Frederico Westphalen and coefficient r = 0.98 and 0.67 for Cruz Alta, respectively, revealing associations between morphological characters and meteorological variables (Table 2). Thus, any change in any meteorological variable might directly influence some morphological character, and thus affect productivity.

The highest absolute value of group I in the first canonical pair was found for the stem height character, which was positive with a correlation of 0.98 and 0.99 for Frederico Westphalen and Cruz Alta; respectively, being positively associated with the accumulated thermal sum (accumulated degrees-day) and negatively associated with the other variables.

Table 1 - Pearson's correlation between morphological characters of sugarcane and meteorological variables for Frederico Westphalen and Cruz Alta.

		---------------Frederico Westphalen--------------			------------------------Cruz Alta----------------------		
Variables		Correlation	Degree of correlation	Values p	Correlation	Degree of correlation	Values p
SD	Tmin	0.133	Weak	14.21 ns	-0.017	Weak	817.19 ns
	Pre	-0.512	Regular	0*	-0.053	Weak	502.89 ns
	Rad	0.007	Weak	896.39 ns	-0.565	Regular	0*
	ATS	0.817	Strong	0*	0.758	Strong	0*
SH	Tmin	-0.141	Weak	9.49 ns	-0.288	Weak	0.22*
	Pre	-0.407	Regular	0*	-0.007	Weak	922.57 ns
	Rad	-0.206	Weak	0.21*	-0.769	Strong	0*
	ATS	0.969	Very strong	0*	0.972	Very strong	0*
NSM	Tmin	0.486	Regular	0*	-0.365	Regular	0*
	Pre	-0.585	Regular	0*	-0.140	Weak	66.4 ns
	Rad	0.200	Weak	0.32*	-0.321	Regular	0.04*
	ATS	0.383	Regular	0*	0.532	Regular	0*

*significant at 5% probability; ns not significant; SD = stem diameter; SH = stem height; NSM = number of stems per meter; Rad = solar radiation; Tmin = minimum temperature; Pre = precipitation; ATS = accumulated thermal sum.

In the second canonical pair, at both locations, the highest absolute value for group I was observed for the number of stems per meter (NSM) character, with a correlation of 0.77 and 0.81 for Frederico Westphalen and Cruz Alta, respectively. NSM was positively associated with minimum temperature and negatively associated with pluviometric precipitation. Thus, increases in the minimum air temperature might imply higher emission of tillers, which, in turn, directly affects crop productivity (ESPÓSITO et al., 2012; FABRIS et al., 2013). Similar results were obtained by ARAÚJO et al. (2017) for sugarcane cultivation in southern Brazil.

In the Stepwise method, the first variable to be included was accumulated thermal sum (ATS), which most contributed to the models. Conversely, solar radiation was the variable with the lowest participation in the models, indicating a secondary effect of this variable on the productivity of sugarcane in Rio Grande do Sul. CARON et al. (2018) evaluated the productivity of sugarcane in agroforestry systems and reported productivity above 60 tons of stalks per hectare, which is compatible with the average for southern Brazil (CONAB, 2018) when cultivated under a reduction of 20% in the incidence of solar radiation. Therefore, these results corroborated those observed in this study, which showed that solar radiation was not the main determinant of sugarcane productivity.

The equations generated by Stepwise regression indicated the need to include more than one meteorological variable in the models (Table 3), corroborating the results obtained by SCHWERZ (2017) for cultivating sugarcane in an agroforestry system. Thus, the productivity of sugarcane can be assumed to be not affected by an isolated meteorological variable, but by a combination of variables. Moreover, KUMAR et al. (2016) showed that the combined use of meteorological variables and yield components allowed an adequate estimation of sugarcane productivity.

In the Stepwise method, the yield component that obtained the highest determination coefficient was plant height, with values of 0.95 and 0.96 for Frederico Westphalen and Cruz Alta,

Table 2 - Canonical loads for the characters that determine the production of tons of stalks per hectare at the two sites Frederico Westphalen and Cruz Alta. The experiment at Frederico Westphalen was conducted under two densities and that at Cruz Alta under a single planting density.

Variables	Frederico Westphalen				Cruz Alta		
	-------------------------Group I-------------------------				-------------------------Group I-------------------------		
	1º*	2º*	3º		1º*	2º*	3º
SD	0.88491	0.23333	0.40309	SD	0.88491	0.23333	0.40309
SH	0.98507	-0.1695	0.03016	SH	0.98507	-0.1695	0.03016
NSM	0.49106	0.77325	-0.4012	NSM	0.49106	0.77325	-0.4012
	------------------------Group II------------------------				------------------------Group II------------------------		
Tmin	-0.0313	0.88018	0.08638	Tmin	-0.0313	0.88018	0.08638
Pre	-0.4975	-0.5686	0.23232	Pre	-0.4975	-0.5686	0.23232
Rad	-0.1463	0.53774	0.50427	Rad	-0.1463	0.53774	0.50427
ATS	0.98287	-0.1657	-0.0769	ATS	0.98287	-0.1657	-0.0769
r	0.97	0.74	0.19	r	0.97	0.74	0.19
GL	12	6	2	GL	12	6	2

*Significant canonical pair by the 5% chi-square test; SD = stem diameter; SH = stem height; NSM = number of stems per meter; Tmin = minimum temperature; Pre = precipitation; Rad = solar radiation; ATS = accumulated thermal sum.

respectively. Moreover, ATS was the variable with the greatest contribution to the models at both the locations. KUMAR et al. (2016) revealed greater contribution of precipitation to the models, but in southeastern Brazil. These differences in results are attributed to the climatic differences between the regions, with the southeast region having lower precipitation and higher temperatures compared to the south region (ALVARES et al., 2013), indicating that the most important element limiting the cultivation of sugarcane in this case is precipitation.

Pearson's correlation, canonical correlation, and Stepwise regression analyses indicated that the most important meteorological variable for the growth and development of sugarcane in the central and northwest regions of the state of Rio Grande do Sul is air temperature, i.e., the ATS. This result differs from those of most studies reported in the literature, in which the main variable that determines the growth and development of sugarcane is precipitation (DIAS et al., 1999; DARLI et al., 2008; LI & YANG, 2014; KUMAR et al., 2016; ANDRADE JUNIOR et al., 2017). However, in the studied regions, the annual precipitation ranges from 1990 mm to 2500 mm, which is 500 to 1000 mm higher than that in the regions where sugarcane is traditionally grown (ALVARES et al., 2013). This volume, associated with the uniform distribution of precipitation (isoigro regime, i.e., normal rainfall values are well distributed throughout the year) in the southern region, does not affect sugarcane growth.

Thus, sugarcane breeding programs in southern Brazil must prioritize the development of genotypes with greater tolerance to low temperatures and less thermal demand, to boost the sugar–energy industry and contribute to the development of the industry in this region. This would decrease the energy dependence of the region and thus contribute to the research carried out in the improvement program of the Federal University of Santa Maria, which focuses on developing cultivars with lower thermal requirements for growth (KNAPP et al., 2019).

CONCLUSION

The regression models revealed the importance of temperature for the growth and development of sugarcane. The outcomes of the models suggested that the growth of sugarcane responds positively to the thermal sum and is less influenced by solar radiation and precipitation in the studied locations.

The results showed that the sugarcane crop can be explored in the studied locations, and sugarcane breeding programs in southern Brazil

Table 3 - Regression models for the morphological characters stem diameter (SH). stem height (SH). and number of stems per linear meters of furrow (NSM), which are responsible for sugarcane productivity in Frederico Westphalen and Cruz Alta.

Place	Regression equation	R^2	Contribution
Frederico W.	SD = 0.959 + 0.041(Tmin) – 0.001(Pre) + 0.001(ATS)	0.76	ATS = 66.8% Tmin = 8.9% Pre = 0.9%
	SH = -105.956 – 4.585(Tmin) – 0.127(Pre) + 0.212(Rad) + 0.149(ATS)	0.95	ATS = 93.9% Rad = 0.5% Tmin = 0.1% Pre = 0.2%
	NSM = 8.53 + 0.711(Tmin) – 0.002(Pre) + 0.002(ATS)	0.57	Pre = 34.3% Tmin =15.0% ATS = 7.8%
Cruz Alta	SD = 0.406 + 0.0007(Rad) + 0.0008(ATS)	0.59	ATS = 57.5% Rad = 2.1%
	SH = -168.864 – 2.412(Tmin) + 0.141(Rad) + 0.195(ATS)	0.96	ATS = 94.5% Rad = 1.0% Tmin = 0.4%
	NSM = 0.021 + 0.69(Tmin) + 0.005(ATS)	0.58	ATS = 28.3% Tmin = 29.3%

ATS = accumulated thermal sum; Rad = solar radiation; Tmin = minimum temperature; Pre = precipitation.

should prioritize research on tolerance to abiotic stress, especially minimum temperature, thereby decreasing the thermal constant of the crop to complete the cycle and increase productivity.

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AUTHORS' CONTRIBUTION

All authors contributed equally to the design and drafting of the manuscript. All authors critically reviewed the manuscript and approved the final version.

DECLARTION OF CONFLICT OF INTERESTS

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

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