Universidade Federal Rural do Semi-Árido
Pró-Reitoria de Pesquisa e Pós-Graduação
https://periodicos.ufersa.edu.br/index.php/caatinga
ISSN 1983-2125 (online)

http://dx.doi.org/10.1590/1983-21252024v3711959rc

Scientific Article

Calibration and evaluation of CSM-CROPGRO-soybean for soybean crop in the southwestern cerrado of Piauí

Calibração e avaliação do CSM-CROPGRO-soybean para cultura da soja no cerrado do sudoeste piauiense

João Irene Filho[1]*, Aderson S. de Andrade Júnior[2], Santiago V. Cuadra[3], Everaldo M. da Silva[1], Paulo F. de M. J. Vieira[2]

[1]Universidade Federal do Piauí, Bom Jesus, PI, Brazil. [2]Brazilian Agricultural Research Company, Embrapa Meio-Norte, Teresina, PI, Brazil. [3]Brazilian Agricultural Research Company, Embrapa Informática Agropecuária, Campinas, SP, Brazil.

ABSTRACT - The study aimed to calibrate and evaluate the DSSAT CSM-CROPGRO-Soybean model to simulate soybean grain yields in the Cerrado of the Southwestern region of Piaui. To parameterize the model, data from the 2019-2020 crop season was used from an experiment installed in the Serra do Quilombo, in Bom Jesus-PI (9º16'20.3" S, 44º44'56.9" O, and altitude 620 m). The BRS 8980 IPRO (BRS 8980), BMX 84I86 (Domínio), BMX 81I81RSF IPRO (Extrema), and BMX 8579 IPRO (Bonus) cultivars were evaluated on three sowing dates (11/29/2019, 01/14/2020, and 01/30/2020). The evaluation was conducted using soybean yield data collected in value for cultivation and use (VCU) experiments conducted by Embrapa Meio-Norte at Celeiro farm, Serra do Quilombo, Bom Jesus, PI, during four harvests and involving 61 genotypes. The best statistical indexes showing the efficiency of the calibration process were observed for the BRS 8980 (first sowing season) and Bônus (third sowing season) cultivars, with R^2 and D indexes above 0.90. The total biomass production showed high agreement with the measured values, capturing the decrease in production due to the sowing date. The model captured the variability depending on the sowing dates and the yield for simulations of four other agricultural seasons, independent of the season in which the model was calibrated. It was concluded that the model satisfactorily simulated plant growth and soybean grain yield for the conditions of the Cerrado of the Southwestern region of Piaui.

Keywords: Agricultural modeling. Growth analysis. Sowing time. Climate risk.

RESUMO - Objetivou-se, calibrar e avaliar o modelo DSSAT CSM-CROPGRO-Soybean na simulação do rendimento de grãos de soja na região do cerrado do Sudoeste Piauiense. Para a parametrização do modelo, foram utilizados dados do ano agrícola 2019-2020, de um experimento instalado na Serra do Quilombo, no município de Bom Jesus-PI (9º16'20,3" S, 44º44'56,9" O e altitude 620 m). Foram avaliadas as cultivares BRS 8980 IPRO (BRS 8980), BMX 84I86 (Domínio), BMX 81I81RSF IPRO (Extrema) e BMX 8579 IPRO (Bônus), em três datas de semeadura (29/11/2019, 14/01/2020 e 30/01/2020). A avaliação foi realizada com dados de rendimento de grãos de soja coletados em ensaios de valor de cultivo e uso (VCU) conduzido pela Embrapa Meio-Norte, na Fazenda Celeiro, Serra do Quilombo, Bom Jesus, PI, durante quatro safras e envolvendo 61 genótipos. Os melhores índices estatísticos que evidenciam a eficiência do processo de calibração foram observados para as cultivares BRS 8980 (1ª época de semeadura) e Bônus (3ª época de semeadura), com índices R^2 e D superiores a 0,90. A produção de biomassa total apresentou alta concordância com os valores medidos, capturando bem o decréscimo da produção em fundação da data de semeadura. O modelo capturou bem a variabilidade em função das datas de plantio, assim como o rendimento para simulações de outras quatro safras agrícolas, independentes da safra onde o modelo foi calibrado. Concluiu-se que o modelo simulou satisfatoriamente o crescimento das plantas e o rendimento de grãos de soja para as condições da região do cerrado do Sudoeste Piauiense.

Palavras-chave: Modelagem agrícola. Análise de crescimento. Época de semeadura. Risco climático.

Conflict of interest: The authors declare no conflict of interest related to the publication of this manuscript.

Received for publication in: May14, 2023.
Accepted in: September4, 2023.

***Corresponding author:**
<joaoirenefilho@ufpi.edu.br>

INTRODUCTION

In the southwest of Piauí, Brazil, soybean cultivation is one of the main agricultural activities, particularly in the Cerrado biome. However, the region is characterized by a relatively shorter rainy season than the central Cerrado region, increasing the risk of grain production in the second-crop season as well as first-crop season with later sowings. In addition, Extrema events have increased in Brazil, imposing the risk of adverse weather conditions on agricultural activity in the different regions of Brazil, which can totally or partially affect agricultural production. For example, Perondi et al. (2019) emphasize that these events are becoming more frequent and will lead to greater food shortages unless farming systems become more resilient to these changes.

Climate variability is one of the main factors affecting agricultural activities (BARBIERI et al., 2020). Particularly in Brazil, most variation in agricultural production is associated with rainfall variability. In this sense, agricultural forecasts using crop growth and yield simulation models are an important planning tool for agriculture. Crop growth and yield can be characterized using biophysical models, such as those in the DSSAT (*Decision Support System for Agrotechnology Transfer*) simulation platform (HOOGENBOOM et al., 2019b).

Biophysical modeling of agricultural systems is a mathematical equation set that expresses the relationships in the soil-plant-atmosphere system. The DSSAT simulation platform models are used to simulate crop sequences and crop rotation and to study the effects of different management practices on crop growth, development, and yield, considering the water balance and the carbon and nitrogen cycles in the soil (LI et al., 2015).

Before applying models, calibration and/or evaluation is necessary, which in the case of crop growth models consists of adjusting the model's genetic coefficients, aiming to improve the agreement between the values predicted by the model and experimental data or data from productive areas. Typically, the calibration process requires measuring biometric and phenological measures of crop growth and development through experiments or field collections (SOUZA et al., 2017).

Model performance is usually assessed using metrics and statistical indexes, including the correlation coefficient (r) and the root mean square error (RMSE), which are used to explain whether the simulated data is consistent with the observed data (YANG et al., 2014).

For the soybean crop, the DSSAT CSM-CROPGRO-Soybean model was applied with high performance in simulating soybean growth, development, and yield in different tropical environments (SILVA et al., 2021). Reis et al. (2020) concluded that the model has a high predictive capacity for MATOPIBA (a region with land belonging to Maranhão, Tocantins, Piauí, and Bahia states). However, the model has not yet been calibrated and evaluated for the climate and soil conditions of the Cerrado of the Southwestern region of Piaui.

The lack of local data on biometric and yield measurements in the field associated with measurements of environmental conditions and agrometeorological and soil measurements are essential for the calibration and evaluation of models (RICHETTI; JOHANN; OPAZO, 2021), which are needed steps before the application of the model. Therefore, this study aimed to calibrate and evaluate the DSSAT CSM-CROPGRO-Soybean model to simulate soybean yields to apply it in the Cerrado of the Southwestern region of Piaui.

MATERIAL AND METHODS

Model calibration

The data was collected from trials conducted on a farm located in Serra do Quilombo, 60 km from Bom Jesus, Piauí (latitude - 9º16'20.3" S, longitude - 44º44'56.9" W, and altitude of 620 m), during the 2019/2020 crop season (Figure 1). According to the Köppen classification, the climate of the region is tropical savannah Aw-type, with characteristics of hot sub-humid from October to March (rainy season) and hot semi-arid tropical from April to September (dry season) (ANDRADE JÚNIOR et al., 2005).

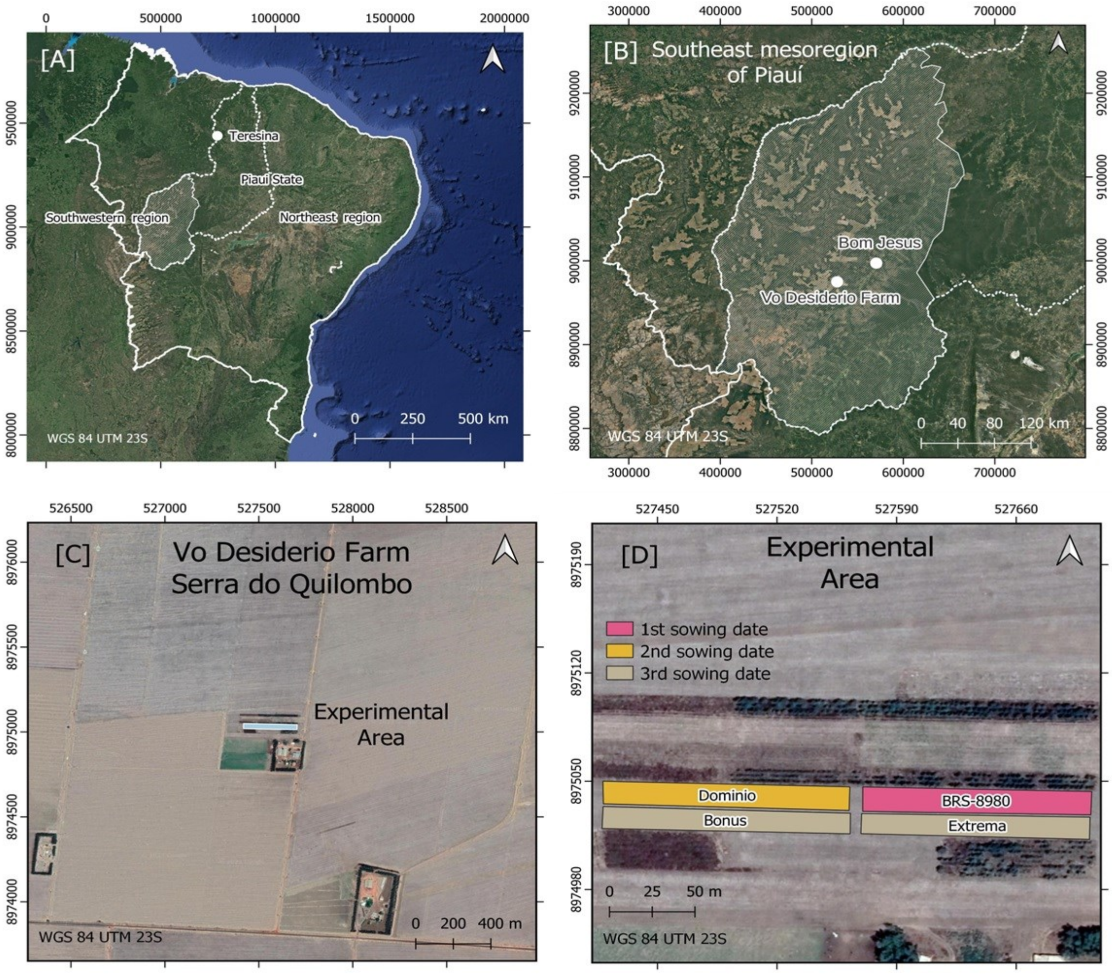

Figure 1. Location of the experimental area, highlighting the mesoregion of Southwest Piaui (A, B), Vô Desiderio farm (C), and the area where the trials were conducted (D). Serra do Quilombo, Bom Jesus, PI, Brazil.

Daily rainfall records (mm) were obtained from an automatic rain gauge installed in the experimental area. Daily climate data on air temperature (ºC) and relative air humidity (%) were collected by an automatic weather station installed at Colorado Farm, 2 km from the experimental area. Climatic information on wind speed (ms^{-1}) and solar radiation (MJ m^{-2} day^{-1}) was obtained from the NASA database using the *Nasa Power* module (NASA, 2023).

According to the Brazilian Soil Classification System, the soil of the experimental area is a Latossolo Amarelo Distrófico argissólico (PRAGANA et al., 2016). The chemical and physical characteristics of the soil are shown in Table 1. Four soybean cultivars were used on three sowing dates, whose growth habit and maturity group characteristics are shown in Table 2. The phytosanitary control procedures followed the technical guidelines for soybean cultivation in the region adopted by the farm owner. The soybeans were fertilized at sowing with simple superphosphate in the row (400 kg ha^{-1}) and 160 kg KCl ha^{-1} applied by broadcast.

Table 1. Soil chemical and physical properties in the experimental area at Vô Desidério farm, Bom Jesus, PI, Brazil.

Depth	OM	pH	P	K	Al	H+Al	Sand	Silt	Clay
m	g.dm^{-3}	water	mg.dm^3	-----------------	($cmol_c.dm^3$)	-----------------		%	
0.00-0.10	29.10	5.99	76.85	0.27	0.07	2.91	75.57	5.35	19.08
0.10-0.20	15.30	5.29	47.02	0.19	0.07	3.24	75.13	1.92	22.95
0.20-0.40	9.00	5.04	2.85	0.15	0.07	2.27	76.10	2.21	21.69
0.40-0.60	7.60	4.47	0.97	0.07	0.07	1.87	71.68	3.79	24.54

Table 2. Cultivars, maturity group, sowing date, date of physiological maturity, and harvesting date of the field experiment in the 2019/2020 crop season.

Cultivar	Growth habit	Maturity group	Sowing date	Date of physiological maturity	Harvesting date
BRS8980	Determinate	8.9	11/29/2019	04/06/2020	04/17/2020
Domínio	Indeterminate	8.4	01/14/2020	04/29/2020	05/06/2020
Extrema	Indeterminate	8.1	01/30/2020	04/06/2020	05/13/2020
Bônus	Indeterminate	7.9	01/30/2020	04/29/2020	05/06/2020

The crop growth and yield simulation platform used was DSSAT v4.7.5 (*Decision Support System for Agrotechnology Transfer*), which is a set of programs for simulating growth, development, and yield according to the soil-plant-atmosphere dynamics (JONES et al., 2010). Cultivar information is defined in three files (species, ecotype, and cultivar). The process of adjusting parameters inherent to these files, such as specific leaf area, solar radiation interception, and thermal time between the appearance of the first flower and physiological maturity, was conducted based on experimental data (HOOGENBOOM et al. 2019a, HOOGENBOOM et al. 2019b).

The soil profile was generated based on the chemical and physical analyses of the soil samples from the experimental area using the SBuild module of DSSAT (Table 3). Undeformed soil samples were collected at the same depths as the moisture sensors to draw up the retention curve, conducted at the Soil Physics Laboratory of Embrapa Meio-Norte in Teresina, Piauí. The values for the lower limit of soil water retention (SLLL) and field capacity (SDUL) were adjusted. The soil root growth factor (SRGF) for each layer was determined based on the soil chemical properties and by analyzing the variation in soil water content throughout the cycle.

Table 3. Input parameters were used to calibrate the soil (Latossolo Amarelo Distrófico argissólico) of the regions, incorporated into the DSSAT v 4.7 database.

SLB	SLLL	SDUL	SSAT	SRGF	SSKS	SBDM	SLOC	SLCL	SLSI
5	0.07	0.21	0.31	0.5	7.00	1.55	2.91	19.1	5.4
20	0.07	0.21	0.31	1.0	7.00	1.58	1.53	23.0	1.9
40	0.08	0.17	0.33	1.0	7.00	1.52	0.9	21.7	2.2
60	0.06	0.18	0.33	0.8	7.50	1.46	0.76	24.5	3.8
80	0.06	0.18	0.33	0.8	7.50	1.54	0.76	24.5	3.8
100	0.06	0.21	0.33	0.8	7.50	1.54	0.76	24.5	3.8
120	0.06	0.21	0.33	0.32	7.50	1.54	0.76	24.5	3.8
180	0.06	0.21	0.33	0.0	7.50	1.54	0.76	24.5	3.8

SLB= soil layer depth (cm), SLLL = lower limit or wilting point (cm^3), SDUL= upper limit (cm^3), SSAT= saturation (cm^3), SRGF= root growth factor, SSKS= hydraulic conductivity (cm h^{-1}), SBDM= soil bulk density (g cm^{-3}), SLOC= organic carbon (%), SLCL= clay (%), and SLSI= silt (%).

The performance of the *CSM-CROPGRO-Soybean* model was evaluated to simulate the water balance for different soil profile depths. The *Watbal.Out* module was used to summarize the soil water status at the beginning and end of a simulation (HOOGENBOOM; WILKENSP; TSUJI, 1999). The soil water balance simulation routines were characterized as proposed by Ritchie (1998).

The cultivars were calibrated by trial and error, using the standard CROPGRO cultivars, considering the same relative maturity group and growth habit. The crop development stages and the predicted and measured values for the dry matter of shoot, leaves, stems, pods (grain + legume), and grain were evaluated.

Model evaluation

The *DSSAT CSM-CROPGRO-Soybean* model was used, previously calibrated for the soil and climate conditions of the Cerrado region of Piauí, based on data from the field experiment conducted in the 2019/2020 crop season. The model was evaluated using parameters collected from soybean value for cultivation and use (VCU) experiments conducted by Embrapa Meio Norte at Celeiro farm (latitude - 9º23'52" S, longitude - 45º07'40" W, and altitude 640 m), located in the Serra do Quilombo, 90 km far from the experimental area (Vô Desidério farm).

The VCU experiments were conducted under rainfed conditions and sown on different dates (Table 4). Daily rainfall records (mm) were obtained from Xavier et al. (2022). The daily climate data was obtained from the NASA database using the *Nasa Power* module (NASA, 2023). The meteorological records used were daily data on air temperature (ºC), relative air humidity (%), wind speed (ms^{-1}), and solar radiation ($MJ\ m^{-2}\ day^{-1}$). The cultivars used in the VCU experiments to evaluate the model are shown in Table 5.

Table 4. Crop season and sowing and harvesting dates of field experiments in the 2016-2017, 2017-2018, 2018-2019, and 2019-2020 crop seasons at the Celeiro farm in Monte Alegre, PI, Brazil.

Crop season	Sowing date	Harvesting date
2016-2017	10.12.2016	02.04.2017
2017-2018	19.11.2017	14.03.2018
2018-2019	26.11.2018	16.03.2019
2019-2020	09.12.2019	03.04.2020

Table 5. Cultivars evaluated in VCU experiments in the 2016-2017, 2017-2018, 2018-2019, and 2019-2020 crop seasons at the Celeiro farm in Monte Alegre, PI, Brazil.

Determinate growth habit		Indeterminate growth habit		
5G8015	FTR2182	ADV (15/1002)	DM8184	MARACAI
AS3797	FTR4183	ADV4681	DM82I78	NS7780
AS3810	JAVAES	AS3810	DOMÍNIO	NSXI831615
AS3820	M8349	BONUS	EXTRA	RK7518
AS3850	M8372	BRS 8281	EXTREMA	RK8115
ATHENA	M8644	BRS7482	FTR1186	RK8317
BMX9086	M8808	BRS7981	FTR3178	ST797
BRS8182	NS8338	CERTA	FTR3179	SYN1285
BRS8383	NS8338	CRISTALINO	FTR4181	TMG1180
BRS8980	TMG1288	CRIXÁ	FTR4182	TMG2286
BRS9280	TMG2179	DESAFIO	FTR4280	ULTRA
BRSGM8.7	TMG2182	DM80I79	GRATA	
CDGM8.2	TMG2185			

To assess the robustness of the DSSAT CSM-CROPGRO-Soybean model, using yield data obtained from the 2016-2017, 2017-2018, 2018-2019, and 2019-2020 crop seasons, the data obtained and measured for soil, climate, plant growth, and grain yield values were used to create an experiment in DSSAT using the XBuild module, incorporating the same soil parameters and cultivar coefficients that had previously been adjusted to the model during the calibration process.

To analyze the models performance in the calibration and evaluation stages, the Pearson correlation (r), root mean square error (RMSE), and Willmott concordance index, d-Stat (WILLMOTT, 1982) were considered. The data for the statistical procedure of the correlation analysis between simulated yield and observed yield was presented as a graph prepared in the R statistical program, version 4.2.1 (R CORE TEAM, 2022).

RESULTS AND DISCUSSION

Model calibration

Table 6 shows the genetic coefficients, with the parameters of the adjusted cultivars file (SBGRO.CUL), used in the calibration process for the BRS 8980, Domínio, Extrema, and Bonus cultivars. The calibration process consisted of first adjusting the parameters of the cultivars associated with the phenology of the crop in comparison with the observed data from the main phenological stages (R1, R3, R5, and R7) and then calibrating the coefficients associated with the allocation of photoassimilates and crop growth. Climate data was entered into the platform using the Weatherman computer package (JONES et al., 2003; HOOGENBOOM et al., 2019b; HOOGENBOOM et al., 2021). Phenology and biomass data were used to analyze the simulations using the *GBuild* module.

Table 6. Final values of the cultivar coefficients calibrated with data from the experiment in Bom Jesus-Pi for BRS 8980 (MG 8.9), Domínio (MG 8.4), Extrema (MG 8.1), and Bonus (MG 7.9).

Characteristics	Definition	Unit	BRS	DOM	EXT	BON
CSDL	Critical length of day below which reproductive development progresses without the effect of photoperiod	hours	12.07	12.07	12.07	12.07
PPSEN	Slope of the relative response of development to photoperiod	hours	0.330	0.330	0.330	0.330
EM-FL	Time between plant emergence and the appearance of flowers (R1)	photothermal days	39.0	33.0	32.0	30.0
FL-SH	Time between first flower and first pod (R3)	photothermal days	10.0	10.0	10.0	10.0
FL-SD	Time between first flower and first seed (R5)	photothermal days	29.0	13.0	15.5	13.5
SD-PM	Time between first seed (R5) and physiological maturity (R7)	photothermal days	26.2	36.0	29.5	27.5
FL-LF	Time between the first flower (R1) and the end of leaf expansion	photothermal days	39.0	36.0	30.0	30.0
LFMAX	Maximum rate of leaf photosynthesis at 30 °C, 350 vpm CO2 and high luminosity	mg $CO_2/m^2/s$	1,030	1,030	1,030	1,030
SLAVR	Specific leaf area of the cultivar under standard growing conditions	cm^2/g	300	385	220	230
SIZLF	Maximum extended leaf size (trifoliolate leaf)	cm^2	170	180	180	180
XFRT	Maximum fraction of daily growth that is partitioned to seed+seedling	g/g	1.0	1.0	1.0	1.0
WTPSD	Maximum weight per seed	g	0.15	0.16	0.16	0.16
SFDUR	Duration of seed filling under normal growing conditions	photothermal days	25.0	19.0	19.0	19.0
SDPDV	Average number of seeds per pod under normal growing conditions	#/pod	2.20	2.20	2.20	2.20
PODUR	Time needed for the cultivar to reach potential pod growth	photothermal days	10	10	10	10
THRSH	Threshing percentage	seed/(seed + shell)	78	78	78	78
SDPRO	Protein fraction in seeds	g(protein)/g (seed)	0.4	0.4	0.4	0.4
SDLIP	Oil fraction in seeds	g(oil)/g (seed)	0.2	0.2	0.2	0.2

BRS= BRS 8980, DOM= BM8486 BRASMAX Domínio, EXT= BM8181 BRASMAX Extrema and BON= BM8579 BRASMAX Bônus.

During the soybean cycle, total rainfall was 1053.6 mm for the BRS 8980 cultivar and 1122.8 mm for the Domínio, Extrema, and Bonus cultivars. There was no water deficit, considering the cultivars' water requirements. However, it is important to note that this amount of rain was not evenly distributed throughout the soybean plant cycle, resulting in periods of drought that caused a water deficit at certain stages of development, partly explaining the cultivars productivity reduction.

The accumulated water retention in the soil during the cultivation periods, considered as the evapotranspiration volumes plus the final value stored in the soil, was estimated at 618.5 mm, 569.6 mm, 533.2 mm, and 537.7 mm for the BRS 8980, Domínio, Extrema, and Bonus cultivars, respectively. The crop evapotranspiration calculated by the model was 485.1 mm, 464.6 mm, 451.00 mm, and 452.8 mm for the same cultivars, respectively.

Rainfall revealed water use efficiency (WUE) was higher than 0.3 kg m^{-3} for all sowing dates. The WUE values obtained with rainfall for each sowing date were 0.725, 0.529, 0.473, and 0.393 kg m^{-3} for the BRS 8980, Domínio, Extrema, and Bonus cultivars, respectively (Figure 2). This means that to achieve these levels of dry mass production, 1000 liters of water are needed with the rainfall on the first, second, and third sowing dates, respectively.

When analyzing the effects of water deficit on soybean yield, Wijewardana et al. (2018) found that water deficiency can lead to an increase in small and shriveled seeds, negatively affecting yield. This study shows that rainfall during the first sowing season (cultivar BRS 8980) maintained the water balance in the soil within the appropriate range for soybean cultivation, considering the soil and climate conditions of the Cerrado in the Southwestern region of Piauí. Therefore, the combination of this sowing date and the rain during the period resulted in higher grain yields for this cultivar.

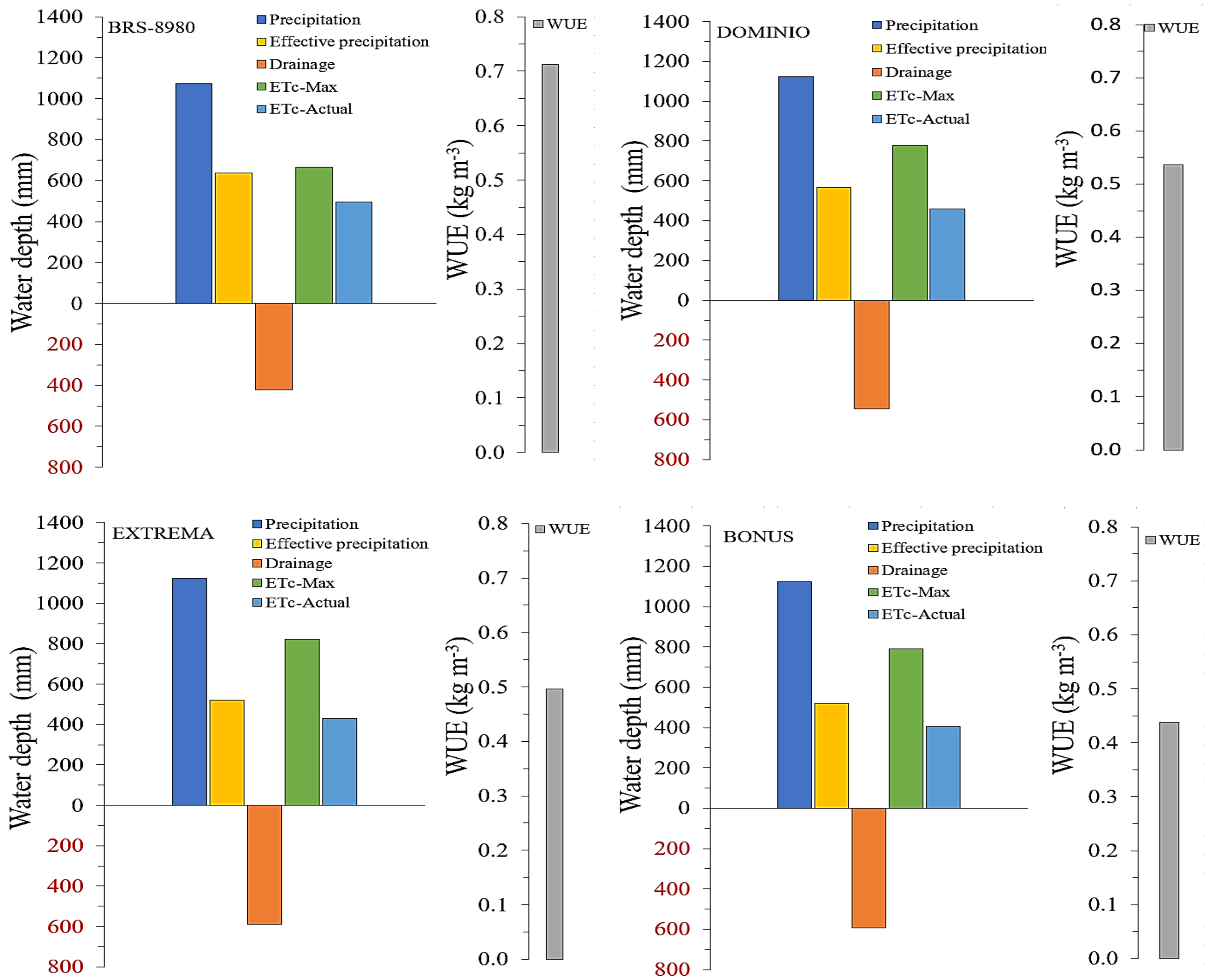

Figure 2. Soil water balance according to the rainfall during the cycle of cultivars.

It should also be noted that these cultivars were harvested earlier due to pest infestation problems, such as whitefly. These infestations tend to occur more frequently in later sowings, which limits the crop's maximum yield potential. In this sense, Vasconcellos et al. (2023) report that late crops usually suffer from high whitefly infestations, as the frequency of insect migration from areas sown at the beginning of the sowing window is very high.

For total shoot biomass, all the simulations performed satisfactorily. It is important to note that despite the different weights of shoot biomass depending on the cultivars and sowing dates, the calibrations showed good accuracy of the simulated values concerning the values observed in the field experiments, with coefficients of determination (R^2) equal to 0.92, 0.88, 0.81, and 0.95, for the BRS 8980, Domínio, Extrema, and Bonus cultivars, respectively (Figures 3A to 3D). According to Battisti, Sentelhas, and Boote (2017), it is important to consider the calibration of the model not only for yield but also for taking into account biomass observations since errors in the calibrations can lead to a process of compensation, whereby a good yield prediction can occur, but based on physically wrong simulations.

The model used coherently reflected the biomass gain obtained in the crops, with the best results obtained in the simulation with the BRS 8980 cultivar. Battisti, Sentelhas, and Boote (2017) found that the DSSAT model underestimated the total shoot biomass of soybeans under rainfed conditions in a simulation for soybean cultivation in the southern region of Brazil. Therefore, despite the general consistency of the model used in this study, it is important to consider that there are differences and peculiarities between simulation models and specific growing conditions, which can lead to discrepancies in the results obtained.

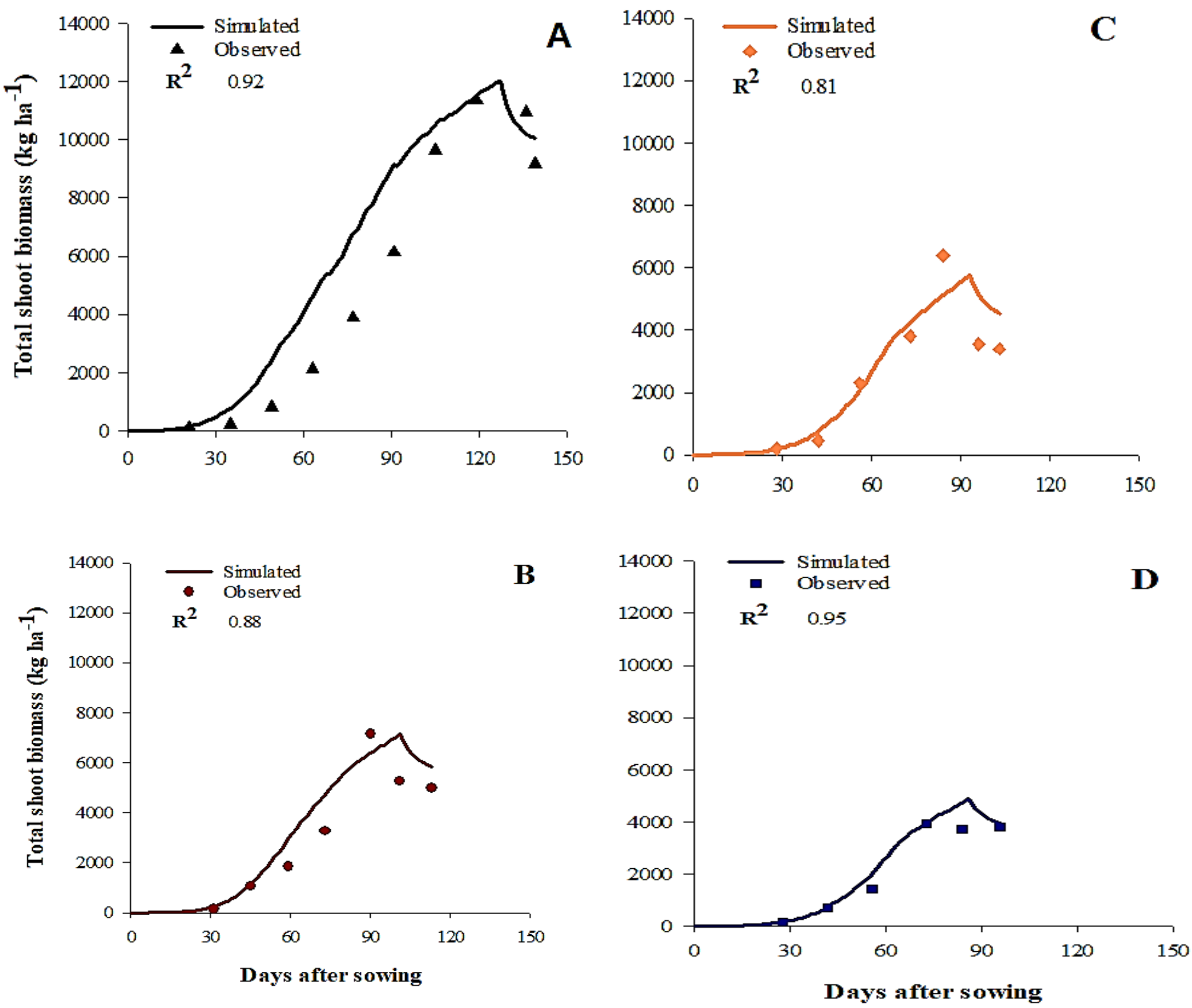

Figure 3. Total shoot biomass throughout the cycle observed (symbols) and simulated (lines) according to the sowing dates and cultivars: (A) sowing on 11/29/2019 (BRS 8980), (B) sowing on 01/14/2020 (Domínio), and (C and D) sowing on 01/30/2020 (Extrema and Bonus).

The results show a satisfactory fit of the DSSAT CSM-CROPGRO-Soybean model with the soybean crop in the Cerrado of the Southwestern region of Piauí. This adjustment was achieved after calibrating the genetic coefficients, showing a development and growth pattern similar to the data collected and statistics obtained in other studies (Table 7). These results corroborate Reis et al. (2020), who, when assessing the influence of climate variability on soybean yield, concluded that the DSSAT CSM-CROPGRO-Soybean model showed good predictive capacity, confirmed by the statistical parameters, indicating high applicability for the environmental conditions of the MATOPIBA region.

Table 7. Statistical parameters evaluated for total shoot biomass in the calibration process of the CSM-CROPGRO-Soybean model at the end of the cultivars cycle.

Parameter	BRS 8980	Domínio	Extrema	Bônus
		Total shoot biomass (kg)		
R^2	0.92	0.88	0.81	0.95
RMSE	1694.00	1089.10	914.32	481.15
d-Stat	0.96	0.94	0.94	0.97

As for the accuracy of the model in estimating the grain yield of soybean cultivars, the water supply associated with the genetics of the cultivars and the phytosanitary management adopted provided an observed yield of 3516.0 kg ha^{-1} for the cultivar sown in the first sowing date (BRS 8980), 2456.06 kg ha^{-1}, for the cultivar sown in the second sowing date (Domínio), and 2133 kg ha^{-1} and 1781.08 kg ha^{-1} for the cultivars sown in the third sowing date (Extrema and Bonus, respectively). The simulated yields were 4117 kg ha^{-1}, 2847 kg ha^{-1}, 2378 kg ha^{-1}, and 2120 kg ha^{-1} for BRS 8980, Domínio, Extrema, and Bonus, respectively.

The model overestimated grain yield for all the sowing dates evaluated by 14.59%, 13.73%, 10.30%, and 15.99% for BRS 8980 (first sowing date), Domínio (second sowing date), Extrema (third sowing date), and Bonus (third sowing date), respectively (Figure 4). However, the model consistently captured the effects of periods of water deficiency, especially for later sowings, consistent with the sowing window indicated for the region (31/01/2020) by the ZARC (Ordinance nº. 116/2021-MAPA). It was also observed that the later sowing of soybeans, concerning the sowing date recommendations for the region, led to a reduction in grain yield, followed by the simulated data (Figure 4).

The highest simulated (4117.0 kg ha^{-1}) and observed (3516.0 kg ha^{-1}) grain yields were obtained with the BRS 8980 cultivar. This result is probably due to the influence of genetic differences between the cultivars, the different genetic coefficients adjusted, or even the fact that it was sown in November. This conclusion is supported by the results obtained by Reis et al. (2020), who found that the highest grain yields in the regions of Balsas, MA, and Uruçuí-PI were obtained when soybeans were sown in November.

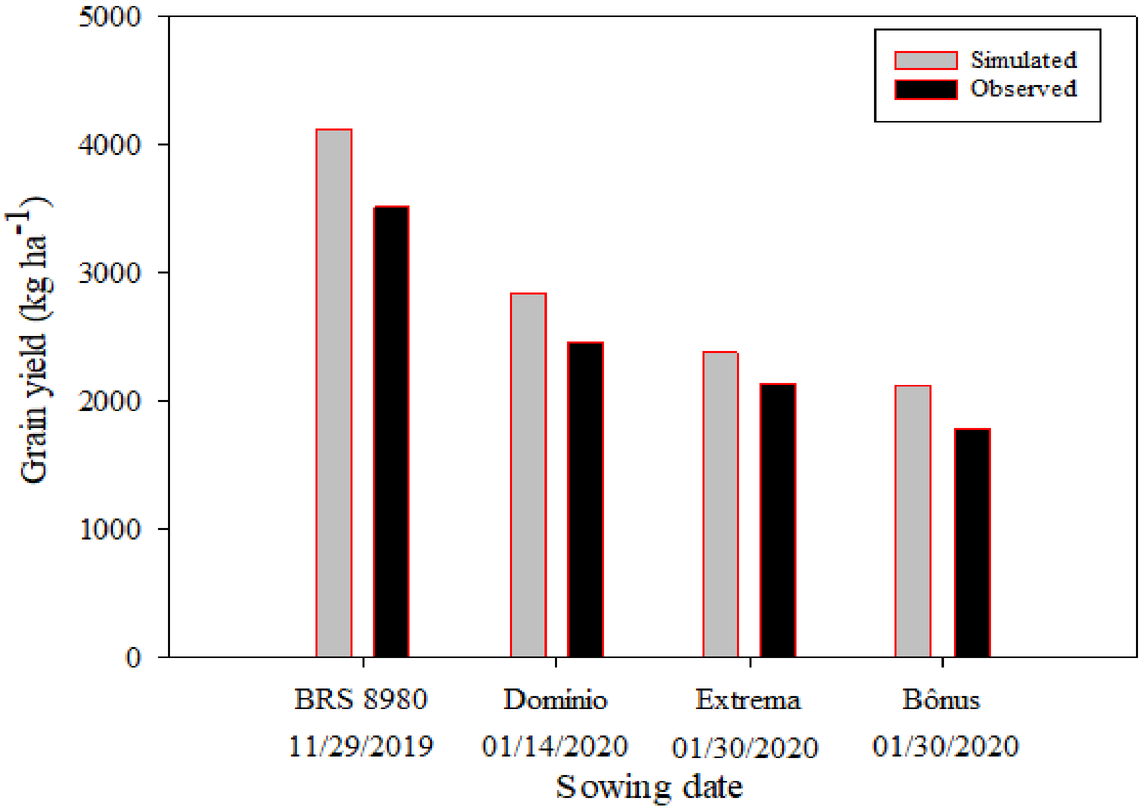

Figure 4. Grain yield variable of the BRS 8980, Domínio, Extrema, and Bonus cultivars, represented by gray (simulated) and black (observed) bars.

Model evaluation

The evaluation of CSM-CROPGRO-Soybean in the simulation of grain yield, according to the methodology developed by Shimakura (2006), which establishes a classification system for the Pearson coefficient, showed a strong correlation between the measured and predicted grain yield for the 2018-2019 crop season, with a Pearson coefficient (r) value of 0.74. A moderate correlation was observed in the 2017-2018 and 2019-2020 crop season, with r values of 0.52 and 0.56, respectively. However, for the 2016-2017 crop season, a weak correlation was identified between measured and predicted grain yield, with a r value of -0.21, which means there is a strong relationship between the variables, but it is not linear. The correlation is therefore low (Figure 5).

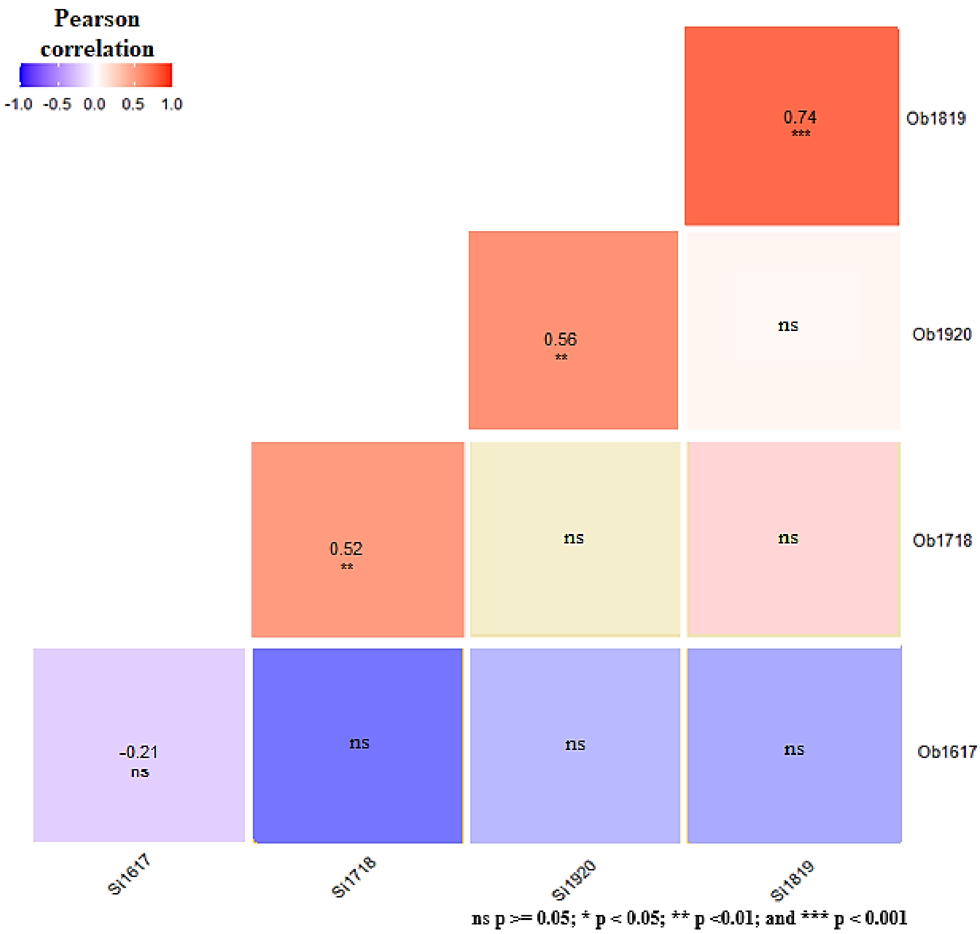

Figure 5. Pearson correlation between observed (Obs) and simulated (Si) performance (evaluations in 2016/2017, 2017/2018, 2018/2019 and 2019/2020 crop seasons).

The highest correlation coefficient was observed in the 2018-2019 crop season, while the lowest was in the 2016-2017 crop season. The Pearson correlation for the first was positive, while for the second, it was negative. These differences can be explained by the number of genotypes evaluated in each crop season, 29 for 2018/2019 and 22 for 2016/2017. This suggests that the 2018-2019 crop season had a higher correlation value due to the greater number of genotypes evaluated.

Reis et al. (2020), to statistically evaluate the performance of the DSSAT CSM-CROPGRO-Soybean model in four different locations in the MATOPIBA region, conducted an analysis based on three statistical measures, considering the estimation of soybean crop yield during the period between the 1980/1981 and 2012/2013 crop seasons. The results obtained corroborate the effectiveness of the simulations conducted by the model, showing a coherent estimate of soybean yield. However, the correlation coefficients achieved by the authors were slightly higher than those achieved in this study, with values ranging from 0.78 to 0.98 in wet and dry scenarios.

During the soybean cycles, the cultivars received 585.96 mm (2016/2017), 1013.7 mm (2017/2018), 1053.4 mm (2018/2019), and 874.8 mm (2019/2020) of rain in an inhomogeneous manner, resulting in periods of water deficit during the crop cycle and differentiation in the cultivars yield potential.

The evaluation of the DSSAT CSM-CROPGRO-Soybean model in the simulation of grain yield for soybean cultivars of determinate and indeterminate growth types showed a similar distribution between the observed and estimated grain yield in all the crop seasons evaluated (Figure 7). The results showed that, on average, the model overestimated grain yield by 19.83%, 2.93%, and 2% for the 2016-2017, 2017-2018 and 2019-2020 crop seasons, respectively; however, there was an underestimation of 2.86% for the 2018-2019 crop season. However, the values indicated a similar behavior throughout the crop seasons between the estimates and observed values of the model (Figures 7A, B, C, and D).

In the first crop season (2016-2017), they had the lowest average yield measured (3211.4 kg ha^{-1}) and consequently simulated (4006.0 kg ha^{-1}) since the model was able to simulate the values measured in the field with good accuracy (Figure 7). Thus, taking into account that the varieties grown were sown during the recommended period for the region, the reduced grain yield during the 2016-2017 crop season, as shown in both the observed and simulated results, may probably have been due to the lower volume of rainfall during the period (585.9 mm), in contrast to the conditions recorded in the other crop seasons under evaluation (Figure 6).

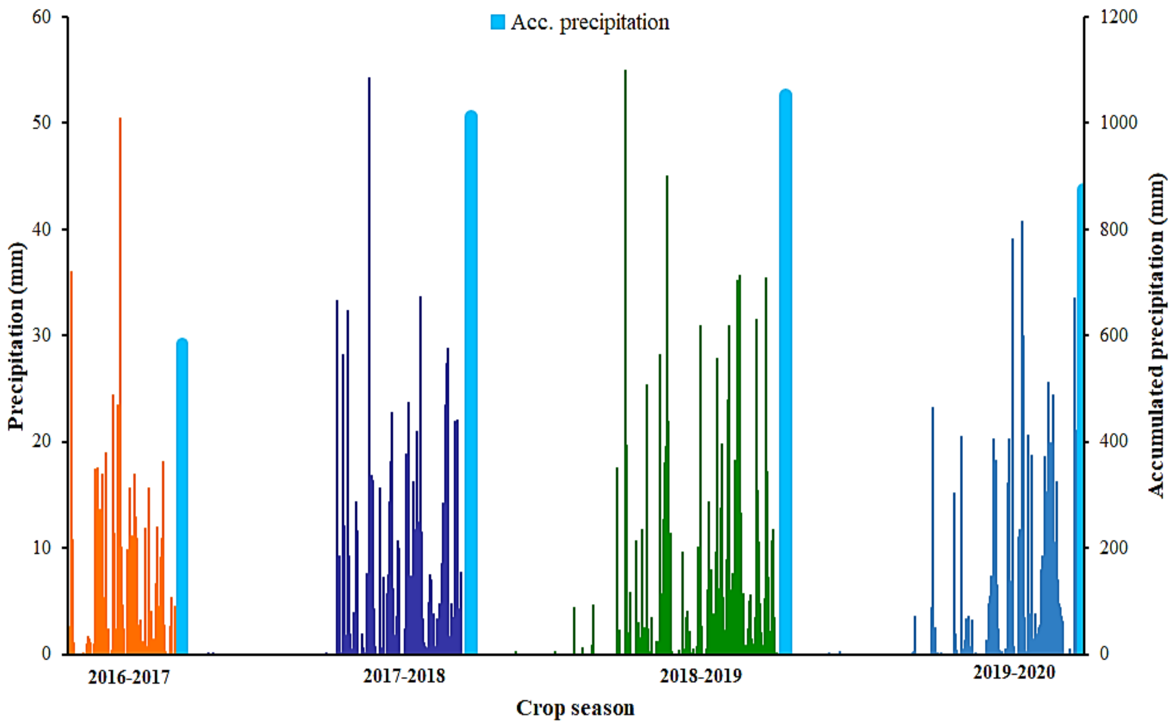

Figure 6. Measured (thin bars) and accumulated (thick bars) rainfall in the experimental areas in the 2016-2017, 2017-2018, 2018-2019, and 2019-2020 crop seasons.

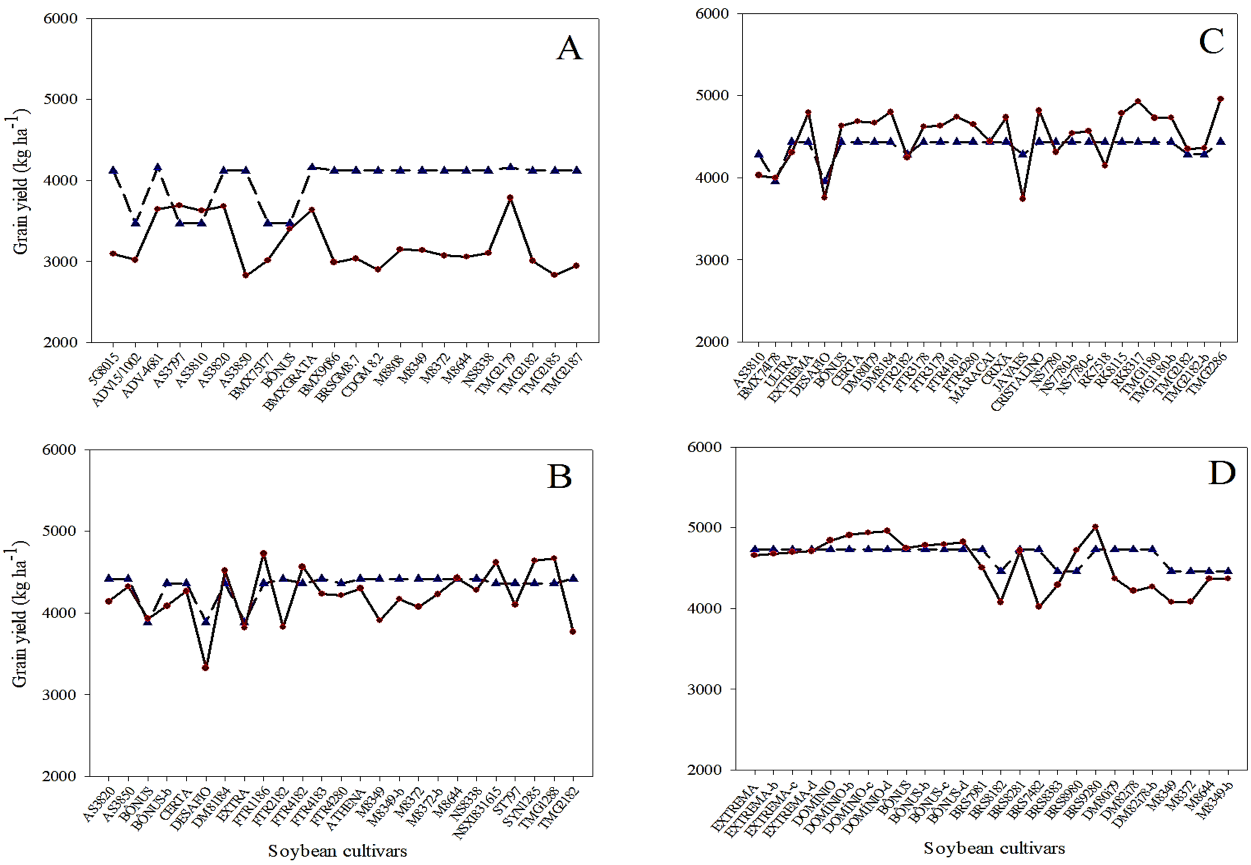

Figure 7. Observed and simulated grain yield for soybean cultivars of determinate and indeterminate growth habits in the 2016-2017 (A), 2017-2018 (B), 2018-2019 (C), and 2019-2020 (D) crop seasons.

The statistical indexes obtained to assess the models performance showed values equal to d-Stat = 0.64, 0.80, 0.89, and 0.88; RMSE = 924.59, 306.46, 276.20, and 298.59 kg ha^{-1} for the 2016-2017, 2017-2018, 2018-2019, and 2019-2020 crop seasons, respectively. These values reflect the correspondence quality between the models predictions and the observed data. It should be noted that although the model tended to overestimate yield in some crop seasons, the estimates were generally close to the observed values. The statistical indexes indicate a reasonable correspondence between the model predictions and observed data.

The concordance indexes achieved for grain yield, ranging from 0.64 to 0.89, were generally higher than the values obtained by Talacuece et al. (2016) when calibrating and validating the CROPGRO-Soybean model to estimate the growth, development, and yield of two soybean cultivars. The authors achieved "d" index values of 0.68 and 0.71 for the cultivars Tgx 1740-2F and Tgx 1908-8F, respectively. It should be noted that that work only considered two cultivars and the same cultivars used in the calibration were used to evaluate the model. Thus, the "d" index values presented in this study are higher since the model evaluation used several cultivars of determinate and indeterminate growth types grown on a soybean farm in the region.

It should also be noted that this yield response to the parameterization conducted for the soil and climatic conditions of this study region may be due mainly to the coefficients adjusted in the model to substantially capture the estimates of soybean yield for the Cerrado of Piauí. However, there are cases where the model patterns are considered sufficient to predict grain yield.

Boote et al. (2018), when evaluating the sensitivity of grain yield modeling to high temperature, reported that no modifications were deemed necessary for the DSSAT/ CROPGRO-Soybean model after evaluation concerning soybean data in sunlit and controlled environment experiments. On the other hand, Yan et al. (2020) made a small change (±5%) to each model parameter and observed, based on various statistical parameters, that the DSSAT model can adequately simulate the crop yield for all the treatments evaluated. However, it is crucial to note that these studies were conducted under different climatic conditions. While the first was conducted at high temperatures, the second was conducted in a temperate climate, with an average annual temperature of around 7 ºC to 8 ºC.

It is worth noting that the model evaluated in this study proved promising and can be applied to predict soybean yields in the Cerrado region of Piauí in situations of both low and high rainfall during the growing season. Silva et al. (2021) observed that applying full irrigation to soybeans resulted in grain yields of 3290 kg ha^{-1}, while for the treatment with 50% of total water requirements, grain yield was 1379 kg ha^{-1}, indicating that the model was able to successfully simulate a similar response to water deficit with a decrease in total crop weight and grain yield.

The model generally overestimated the observed grain yield values in the soil and climate conditions characteristic of the Cerrado of the Southwestern region of Piauí. According to Battisti, Bender, and Sentelhas (2019), the yield simulated directly by the model when calibrated through experiments under ideal management conditions and without considering losses other than those derived from climatic factors (attainable yield), as in this case, is expected to overestimate the yield, since it represents the maximum yield that the crop can achieve under rainfed conditions. In this sense, when evaluating soybean crop management adaptations using the DSSAT/CROPGRO-Soybean model, Sciarresi et al. (2020) emphasize that increasing the intensity and quality of soil data collection in agronomic trials would help reduce the model's uncertainty in calibrations with regional data.

This study is the first to simulate soybean productivity for soil and climate conditions at different sowing dates in the Cerrado of the Southwestern region of Piauí. We suggest continuing to evaluate the model to improve this important tool to help producers and professionals working in the area plan and manage annual grain crops in the region.

CONCLUSION

The statistical indexes showing the efficiency of the calibration process were more favorable for the BRS 8980 (first sowing date) and Bônus (third sowing date) cultivars. The total biomass production showed high agreement with the measured values, capturing the decrease in production satisfactorily based on the sowing date, with later dates showing greater exposure to water deficit and lower growth. Concerning yield, the model consistently overestimated the values, a pattern similar to that obtained in other studies. However, the model captured the variability depending on the planting dates satisfactorily, with a similar pattern for biomass and the yield for simulations of four other crop seasons, independent of the crop season in which the model was calibrated and several different cultivars. As for the efficiency of the DSSAT CSM-CROPGRO-Soybean model, it satisfactorily simulated the evolution of biomass and the yield of soybeans under the conditions of the Cerrado of the Southwestern region of Piauí.

REFERENCES

ANDRADE JÚNIOR, A. S. et al. Classificação climática e regionalização do semi-árido do Estado do Piauí sob cenários pluviométricos distintos. **Revista Ciência Agronômica,** 36: 143-151, 2005.

BARBIERI, J. D. et al. Simulação da produtividade e de épocas de semeadura para soja e milho em eventos de El niño Oscilação Sul no estado de Mato Grosso. **Acta Iguazu,** 9: 45-66, 2020.

BATTISTI, R.; BENDER, F. D.; SENTELHAS, P. C. Assessment of different gridded weather data for soybean yield simulations in Brazil. **Theoretical and Applied Climatology,** 35: 237-247, 2019.

BATTISTI, R.; SENTELHAS, P. C.; BOOTE, K. J. Inter-comparison of performance of soybean crop simulation modelsand their ensemble in southern Brazil. **Field Crops**

Research, 200: 28-37, 2017.

BOOTE, K. J. et al. Modeling sensitivity of grain yield to elevated temperature in the DSSAT crop models for peanut, soybean, dry bean, chickpea, sorghum, and millet. **European Journal of Agronomy**. 100: 99-109, 2018.

HOOGENBOOM, G. et al. Decision support system for agrotechnology transfer v3.5. In: HOOGENBOOM, G.; WILKENSP, W.; TSUJI, G. Y. 1999, University of Hawaii, Honolulu, Hawaii. **DSSAT version 3**, vol. 4, 1999. p. 1-36.

HOOGENBOOM, G. et al. The DSSAT crop modeling ecosystem. In: BOOTE, K. J. (Eds.) **Advances in Crop Modeling for a Sustainable Agriculture**. Cambridge: Burleigh Dodds Science Publishing, 2019a. v. 1, cap. 7, p. 173 -216.

HOOGENBOOM, G. et al. **Decision Support System for Agrotechnology Transfer (DSSAT) Version 4.7.5 (https://DSSAT.net)**. DSSAT Foundation, Gainesville, Florida, USA, 2019b.

HOOGENBOOM, G. et al. **Decision Support System for Agrotechnology Transfer (DSSAT) Version 4.8 (DSSAT.net)**. 2021. DSSAT Foundation, Gainesville, Florida, USA. Disponível em: DSSAT.net - Official Home of the DSSAT Cropping Systems Model. Acesso em: 23 ago. 2023.

JONES, J. W. et al. The DSSAT cropping system model. **European Journal of Agronomy**, 18: 235-265, 2003.

JONES, J. W. et al. **Decision Support System for Agrotechnology Transfer Version 4.0**. Volume 4. DSSAT v4.5: Crop Model Documentation. University of Hawaii, Honolulu, HI, 2010.

LI, Z. T. et al. Evaluation of the DSSAT-CSM for simulating yield and soil organic C and N of a long-term maize and wheat rotation experiment in the Loess Plateau of Northwestern China. **Agricultural Systems**, 135: 90-104, 2015.

NASA - National Aeronautics and Space Administration. **The data was obtained from the POWER Project's**. Geos 5.12.4 (FP-IT) 0. x 0.5 Degree Daily Averaged. Version on, accessed on 07/06/2023: PODER DA NASA | Previsão de Recursos Energéticos Mundiais.

PERONDI, D. et al. Crop season planning tool: Adjusting sowing decisions to reduce the risk of extreme weather events. **Computers and Electronics in Agriculture**, 156: 62-70, 2019.

PRAGANA, R. B. et al. Characterization of yellow latosols (oxisols) of serra do quilombo, in Piauí state savanna woodlands – Brazil. **Revista Caatinga**, 29: 832-840, 2016.

R CORE TEAM. R: A language and environment for statistical computing. 2022. **R Foundation for Statistical Computing**, Vienna, Austria. Disponível em: https://www.r-project.org//>. Acesso em: 31 out. 2022.

REIS, L. et al. Influence of Climate Variability on Soybean Yield in MATOPIBA, Brazil. **Atmosphere**, 1130: 1-24, 2020.

RITCHIE, J. T. Soil water balance and plant water stress. In: TSUJI, G. Y.; HOOGENBOOM, G.; THORNTON, P. K. (Eds.). **Understanding Options for Agricultural Production. Systems Approaches for Sustainable Agricultural Development**. Dordrecht, the Netherlands: Kluwer Academic Publishers, 1998. v. 7, cap. 3, p. 41-54.

RICHETTI, J.; JOHANN, J. A.; OPAZO, M. A. U. Crop modeling with less data: the FAO model for Soybean yield estimation. **Engenharia Agrícola**, 41: 196-203, 2021.

SCIARRESI, C. et al. Evaluating short-season soybean management adaptations for cover crop rotations with a crop simulation model. **Field Crops Research**, 250: 1-16, 2020.

SILVA, E. H. F. M. et al. Performance of the CSM-CROPGRO-soybean in simulating soybean growth and development and the soil water balance for a tropical environment. **Agricultural Water Management**, 252: 378-3774, 2021.

SHIMAKURA, S. E. **Interpretação do coeficiente de correlação**. 2006. Disponível em: http://leg.ufpr.br/~silvia/CE003/node74.html. Acesso em: 16 ago. 2023.

SOUZA, J. M. H. et al. Análise de Sensibilidade dos Coeficientes Genéticos do Modelo Canegro/DSSAT. **Anuário do Instituto de Geociências** – UFRJ, 2: 47-52, 2017.

TALACUECE, M. A. D. et al. Modeling of Soybean under Present and Future Climates in Mozambique. **Climate**, 4:1-14, 2016.

VASCONCELLOS, M. C. et al. Estratégias de controle de pragas em soja e suas implicações na comunidade de artrópodes e na rentabilidade da cultura. **Nativa**, 11: 28-43, 2023.

XAVIER, A. C. et al. New improved Brazilian daily weather gridded data (1961–2020). **International Journal of Climatology**, 42: 8390–8404, 2022.

WIJEWARDANA, C. et al. Quantifying soil moisture deficit effects on soybean yield and yield component distribution patterns. **Irrigation Science**, 36: 241–255, 2018.

WILLMOTT, C. J. Some comments on the evaluation of model performance. **Bulletin American Meteorological Society**, 63:1309-1313, 1982.

YANG, J. M. et al. An evaluation of the statistical methods for testing the performance of crop models with observed data. **Agricultural Systems**, 127: 81–89, 2014.

YAN, W. et al. Simulating and predicting crop yield and soil fertility under climate change with fertilizer management in northeast China based on the Decision Support System for Agrotechnology Transfer Model. **Sustainability**, 12: 1-20, 2020.