

Article

Assessment of Sowing Dates and Plant Densities Using the CSM-CROPGRO-Soybean Model Under Cerrado Climatic Conditions

Felipe Puff Dapper ¹, Rafael Battisti ^{1,*}, Elvis Felipe Elli ², Maxuel Fellipe Nunes Xavier ¹, Alisson Neves Harmyans Moreira ¹, Rilner Alves Flores ¹, Henrique Fonseca Elias de Oliveira ³, Marcos Vinícius da Silva ⁴, Jeffer Andrey Quintero Garcia ¹, Maria Lucia Jaimel Verjel ¹, Camilla de Souza Correia ⁵ and Marcio Mesquita ^{1,*}

- ¹ Escola de Agronomia, Universidade Federal de Goiás, Goiânia 74690-900, GO, Brazil; felipe.pdapper@gmail.com (F.P.D.); maxuel_xavier@discente.ufg.br (M.F.N.X.); alisson.harmyans@ufg.br (A.N.H.M.); rilner@ufg.br (R.A.F.); quinterojeffer@discente.ufg.br (J.A.Q.G.); luciajaimel@discente.ufg.br (M.L.J.V.)
 - ² Department of Crop, Soil, and Environmental Sciences, University of Arkansas Division of Agriculture, Fayetteville, AR 72701, USA; eelli@uark.edu
 - ³ Cerrado Irrigation Postgraduate Program, Goiano Federal Institute, GO-154, Km 03, Ceres 76300-000, GO, Brazil; henrique.fonseca@ifgoiano.edu.br
 - ⁴ Centro de Ciencias Agrarias e Ambientais (CCAA), Universidade Federal do Maranhão, BR-222, Km 04, Boa Vista, Chapadinha 65500-000, MA, Brazil; mv.silva@ufma.br
 - ⁵ Programa de Pós-Graduação Stricto Sensu em Engenharia Agrícola (PPGEA), Universidade Estadual de Goiás, Rodovia BR 153, N° 3105, Fazenda Barreiro do Meio, Anápolis 75132-400, GO, Brazil; camilla.correia@aluno.ueg.br
- * Correspondence: battisti@ufg.br (R.B.); marcio.mesquita@ufg.br (M.M.)

Abstract

Crop management strategies are essential to achieve maximum crop yields. In this context, crop models can be used to understand yield variability. The aim of this study was to evaluate historical yields based on the sowing date and plant density. Field experiments were conducted during two growing seasons at two locations using a maturity group 7.6 cultivar, with distinct sowing dates and plant densities (10 to 50 plants m⁻²). After calibration, the model was applied to historical weather data (1990–2022) for nine locations across the Cerrado biome. The CSM-CROPGRO-Soybean model simulated soybean development with biases for physiological maturity of +8 and −7 days for calibration and evaluation, respectively. The relative root mean square error for yield was below 14%. Similar trends were observed for the leaf area index (LAI) across plant densities, while biomass partitioning proved to be a limiting component, mainly for stem biomass. The optimal plant population ranged from 20 to 30 plants m⁻², whereas a low density (10 plants m⁻²) resulted in higher yield losses under late sowing. Therefore, the use of crop simulation models is an effective tool to understand and optimize sowing dates and plant densities under historical climatic conditions in the Cerrado.



Academic Editor: Gianni Bellocchi

Received: 23 June 2026

Revised: 17 July 2026

Accepted: 18 July 2026

Published: 21 July 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

Keywords: agrometeorological modeling; climate risk; crop management; attainable yield

1. Introduction

Brazil is responsible for 39% of the world's soybean production, which represents 152.14 million tons [1]. The Central-West Region of Brazil, which largely comprises the Cerrado biome, accounts for 49% of the national production, corresponding to 145 million tons [2]. Despite the favorable edaphoclimatic conditions for crop growth and development,

yields can still be increased through more efficient management practices [3]. While adjusting the plant population density for specific sowing dates can favor productivity due to the more efficient use of solar radiation [4], the interactive effects of these agronomic management prescriptions for the studied region remain unclear, and this knowledge gap needs to be addressed.

In this context, to explore the maximum potential yield, population adjustment is essential. The determination of the soybean plant density in the Cerrado biome has been based on recommendations from other regions, resulting in yield losses under specific environmental conditions [3], mainly when there are changes in the sowing date due to the delayed onset of rainfall [4].

Considering the extensive territory of the Cerrado biome, soybean is grown across a wide range of photoperiods, which directly influences the daylight duration, solar radiation, rainfall, and temperature [5]. Thus, estimating the attainable yield based on plant density adjustments for each sowing date can help to optimize soybean productivity by maximizing the solar radiation use efficiency [5]. Accordingly, incorporating plant population adjustment into management practices can contribute to reducing yield gaps associated with suboptimal management, ensuring the more efficient use of climatic resources [6].

According to the Köppen–Geiger climate classification, the Cerrado biome predominantly presents the Aw climate type, featuring rainy summers and dry winters [7]. Although the rainy period is well defined (October to March), there is large variability in rainfall distribution; thus, the sowing date can be adjusted to coincide with the period of lowest losses caused by water deficits [8]. Furthermore, the wide diversity in soil texture can influence the attainable crop yield [9], since the clay loam or coarser soils common in the Cerrado biome have low water retention capacity [10].

The influence of the plant density and sowing date under the cultivation conditions of the Cerrado biome in Brazil has not yet been fully elucidated [4]. Therefore, the hypothesis of this study was that the CSM-CROPGRO-Soybean model can be used to optimize the attainable yield as affected by the plant density and sowing date. Based on this, the objectives of this study were (a) to calibrate and validate the performance of the CSM-CROPGRO-Soybean model in simulating soybean development, growth, and yield as a function of the plant density and sowing date, using a cultivar belonging to maturity group 7.6, widely used in the region, and (b) to identify the combinations of plant density and sowing date that provide the highest yield based on seasonal analysis and long-term climatic history for a maturity group 7.6 variety across nine representative locations of the Cerrado biome.

2. Materials and Methods

2.1. Field Experiment

The study was carried out in the state of Goiás, Brazil, with field experiments conducted in the municipalities of Itaberaí and Silvânia (Lat: -16.706 , Long: -48.571 , 701 m; Lat: -16.203 , Lon: -49.765 , 877 m) (Figure 1). The climate is classified as Aw according to Köppen's climate classification, characterized by rainy summers and dry winters [7]. The cultivar used was Brasmax Tormenta CE, belonging to maturity group 7.6, with sowings conducted on 23 October and 25 November 2022 and 5 October and 1 December 2023, in Itaberaí and Silvânia, respectively.

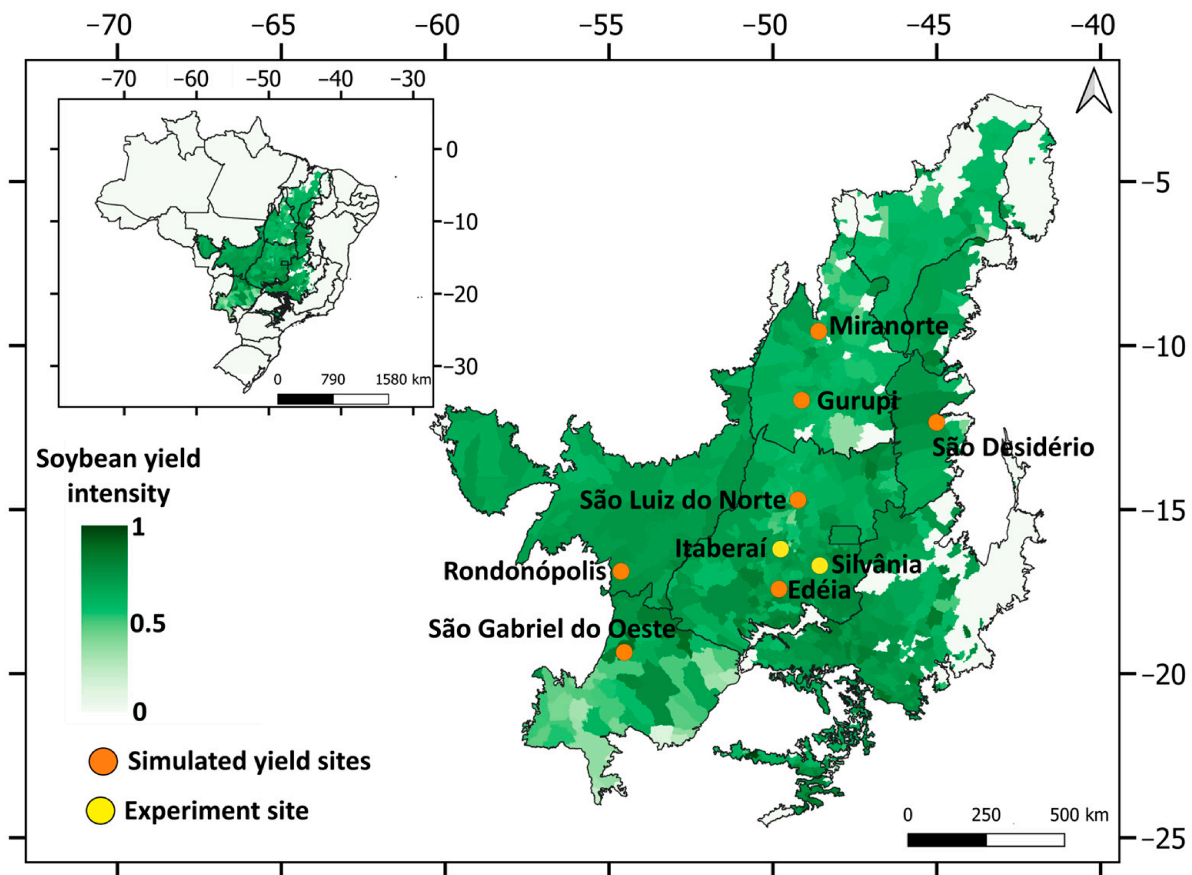


Figure 1. Brazilian states (top left), locations where calibration and evaluation experiments were conducted, and sites used for long-term simulated yield study, with colors indicating soybean production intensity by municipality across the Brazilian Cerrado biome, adapted from [2].

The experimental units consisted of plots of 5 m in length and 4 m in width, containing 8 planting rows. A completely randomized design in a 5×2 factorial scheme was used in each growing season, with factors including the plant density (10, 20, 30, 40, and 50 plants m^{-2}) and location (Itaberaí and Silvânia), for the growing seasons of 2022/23 and 2023/24. The plant density of 50 plants m^{-2} was applied only in the 2023/24 growing season. Sowing was carried out using a planter in a no-till system with 53 seeds per square meter, while plant population adjustments in each treatment were made by thinning plants 12 days after emergence to obtain the target plant density treatments. Crop management followed local high-yield farmer practices, aiming to minimize interference from limiting factors on crop growth and yield.

2.2. Soil, Weather, and Crop Data

Soil physical attributes were determined by collecting intact soil structure samples in the field using a volumetric ring to quantify the water content at saturation (SAT), field capacity (FC) and permanent wilting point (PWP), soil bulk density (BD), and saturated hydraulic conductivity (KSAT) (Table 1). FC and PWP were quantified using the Richards pressure chamber method at 10 and 1500 kPa, respectively [11].

Table 1. Soil layer, clay, sand, and organic matter (OM) content; soil water content at saturation (SAT), at field capacity (FC), and at permanent wilting point (PWP); soil bulk density (BD); saturated hydraulic conductivity (KSAT); and root growth factor in the soil (SRGF) in Itaberaí and Silvânia.

Soil Layer	Clay	Sand	OM	SAT	FC	PWP	BD	KSAT	SRGF
cm	%		g kg ⁻¹		m ³ m ⁻³		Mg m ⁻³	mm h ⁻¹	
Itaberaí									
0–10	45	47	23	0.53	0.46	0.25	1.51	18	1
10–20	45	47	13	0.53	0.44	0.25	1.67	18	0.75
20–40	46	46	8	0.50	0.42	0.22	1.60	13	0.40
40–60	48	44	8	0.50	0.42	0.23	1.58	13	0.30
60–130	48	44	8	0.50	0.42	0.23	1.58	13	0.1
Silvânia									
0–10	34	58	16	0.56	0.25	0.21	1.22	20	1
10–20	34	58	10	0.57	0.25	0.23	1.16	20	0.75
20–40	36	56	8	0.56	0.22	0.23	1.18	14	0.40
40–60	36	56	8	0.52	0.23	0.23	1.19	14	0.30
60–130	36	56	8	0.52	0.23	0.23	1.19	14	0.1

The daily weather data were obtained from the NASAPOWER digital platform, using the Power Data Access Viewer (<https://power.larc.nasa.gov/data-access-viewer/>) (accessed on 15 January 2025), validated in [12], including the daily maximum and minimum air temperature and total solar radiation, with precipitation obtained from a weather station installed at the experimental sites during the periods of the field experiments.

Phenological stages were monitored weekly, recording the date on which at least 50% of the plants in the plot reached the phenological characteristics described in [13], including the dates of sowing, emergence, first flower, first seed, and physiological maturity. The total aboveground biomass partitioned into the stem, leaf, pod, and grain, as well as the leaf area index and canopy height, was measured four to six times during the crop cycle—on average, at 25, 60, 75, and 90 days after sowing—by sampling five consecutive plants from the central rows of each experimental unit. Root samples were collected using the monolith method, which enables the complete recovery of the root system biomass. Dry biomass was obtained by drying the samples at 70 °C to a constant mass. The leaf area index was determined by digitizing the entire leaf area using the software ImageJ, version 1.46c (National Institutes of Health, Bethesda, MD, USA) [14]. At the end of the season, the grain yield, grain number per area, grain number per pod, and grain weight were measured, and the harvest index was calculated as the grain yield divided by the total aboveground dry biomass.

2.3. DSSAT Model Calibration and Evaluation

Calibration was performed using development and growth data collected during the 2022/23 growing season, and evaluation was performed using data from the 2023/24 growing season. The soil root growth factor (SRGF) (Table 1) was obtained from [4]. The initial soil water content was set at 50% of the difference between FC and PWP, with the simulation initiated 30 days prior to the sowing date.

The generic parameters for maturity group 7 from the ecotype and cultivar file in DSSAT-CROPGRO-Soybean software, version 4.7.5 (DSSAT Foundation, Gainesville, FL, USA) [15], were used as the initial set of cultivar parameters for calibration, following the value ranges described in [13]. The first step was to calibrate the phenological coefficients, including the first flower (EM-FL), first pod (FL-SH), first seed (FL-SD), and beginning of maturity (SD-PM) [16], in combination with the critical short-day length (CSDL) and the slope of the relative development response to photoperiod (PPSEN).

Growth parameters were calibrated in sequence, including the maximum leaf photosynthesis rate (LFMAX), specific leaf area of the cultivar under normal growth conditions (SLAVR), maximum fully expanded leaf size (three leaflets) (SIZLF), interval between first flower (R1) and end of leaf expansion (FL-LF), maximum seed weight (WTPSD), seed-filling duration for a set of pods under normal growth conditions (SFDUR), average number of seeds per pod under normal growth conditions (SDPDV), duration for the cultivar to reach the final pod load under optimal conditions (PODUR), and threshing percentage (THRSH) between grains and pods.

The calibration procedure combined the generalized likelihood uncertainty estimation (GLUE) method [17], implemented in the DSSAT platform, with a manual calibration step. The GLUE procedure generated 15,000 parameter [18] sets through Monte Carlo sampling within the predefined minimum and maximum ranges of the cultivar coefficients [13]. The performance of each parameter set was evaluated using the Gaussian likelihood function implemented in DSSAT, which accounts for the differences between simulated and observed variables relative to their assumed error variances. Likelihood values across observations were combined multiplicatively and normalized to obtain posterior probability weights. All parameter sets producing valid simulations were used to construct posterior distributions, and the complete parameter vector associated with the maximum posterior probability was selected as the GLUE-calibrated parameter set. This set was subsequently refined manually to improve the agreement between the simulated and observed crop growth time series, verifying the consistency with other calibrations and with the characteristics of maturity groups in the model database. The general model performance was evaluated using bias, the root mean square error (RMSE), and scatter plots between the measured and simulated results [19].

2.4. Long-Term Simulation: Sowing Date and Plant Density Interaction

Crop management was simulated using the DSSAT Seasonal Analysis software, version 4.7.5 (DSSAT Foundation, Gainesville, FL, USA) [15], considering the sowing dates and plant densities for nine locations, namely São Gabriel do Oeste, MS; Itaberaí, GO; Silvânia, GO; Rondonópolis, MT; Edéia, GO; São Luiz do Norte, GO; Gurupi, TO; São Desidério, BA; and Miranorte, TO (Figure 1). Daily meteorological data were obtained for the period from 1 January 1990 to 31 December 2022 from [20]. The management strategy evaluated included five population densities of 10, 20, 30, 40, and 50 plants m^{-2} for maturity group 7.6, as well as 10-day intervals between sowing dates for each location, defined based on the agroclimatic zoning risk [21]. The soil type and texture by location were obtained from [22], while soil hydraulic properties were obtained from [4]. The simulation was initiated three months prior to each sowing date, assuming initial soil water content at 50% of the difference between FC and PWP, thereby stabilizing the soil water content before each planting date in each growing season. The output used was the attainable grain yield at 13% grain moisture, defined as the maximum crop yield achievable under local soil and climate conditions with the best management practices, without limitations regarding pests, weeds, diseases, nutrition, and lodging [3].

3. Results

3.1. Weather Conditions in the Field Experiments

Considerable seasonal climatic variability was observed across the different locations, growing seasons, and sowing dates. The mean air temperatures (maximum and minimum) were 24.05 °C (20.01 and 28.63 °C) and 26.28 °C (21.13 and 22.08 °C), respectively, for the 2022/23 and 2023/24 growing seasons. The mean daily solar radiation was 23.18 and 21.80 $\text{MJ m}^{-2} \text{ day}^{-1}$ for the 2022/23 and 2023/24 growing seasons, respectively. The

cumulative water deficit during the 2022/23 growing season was 101 mm and 71 mm at the Itaberaí and Silvânia sites, respectively. During the 2023/24 growing season, the cumulative water deficit increased to 209 mm in Itaberaí and 117 mm in Silvânia.

3.2. Calibration and Evaluation

The calibration process, following [16], began with the adjustment of the parameters CSDL and PPSEN for predicting the occurrence of the first flower, followed by the calibration of EM-FL, FL-SH, FL-SD, and SD-PM (Table 2). Subsequently, FL-LF, SLAVR, and SIZELF were modified to improve the simulation of the leaf area index, for which parameter adjustment was necessary to enhance the performance at the lowest plant density. FL-LF was altered due to the indeterminate growth habit of the studied cultivar. LFMAX was adjusted to increase biomass production, since this parameter increases the plant photosynthetic rate; it was modified from 1.03 to 1.035 $\mu\text{mol m}^{-2} \text{s}^{-1}$. The final alterations involved parameters related to the duration of pod and grain growth to improve yield simulation (Table 2).

Table 2. Parameter acronyms, descriptions, and default (D) and calibrated (C) values in the CSM-CROPGRO-Soybean model for soybean crop maturation group 7.6.

Acronym	Description	Values	
		D	C
#ECO	Code for the ecotype to which the cultivar belongs	SB0801	SB0801
CSDL	Critical short-day length below which reproductive development progresses with no daylength effect (for short-day plants) (h)	12.58	12.02
PPSEN	Slope of the relative response of development to photoperiod with time (positive for short-day plants) (1/h)	0.311	0.330
EM-FL	Time between plant emergence and flower appearance (R1) (photothermal days)	20.2	15.2
FL-SH	Time between first flower and first pod (R3) (photothermal days)	9.0	7.0
FL-SD	Time between first flower and first seed (R5) (photothermal days)	16.8	12.8
SD-PM	Time between first seed (R5) and physiological maturity (R7) (photothermal days)	35.6	29.65
FL-LF	Time between first flower (R1) and end of leaf expansion (photothermal days)	18.00	21.00
LFMAX	Maximum leaf photosynthesis rate at 30 °C, 350 vpm CO ₂ and high light (mg CO ₂ m ⁻² s)	1.03	1.035
SLAVR	Specific leaf area of cultivar under standard growth conditions (cm ² g ⁻¹)	375	385
SIZLF	Maximum size of full leaf (three leaflets) (cm ²)	180	199.0
XFRT	Maximum fraction of daily growth that is partitioned to seed + shell	1.00	1.00
WTPSD	Maximum weight per seed (g)	0.18	0.18
SFDUR	Seed filling duration for pod cohort at standard growth conditions (photothermal days)	23.0	23.0
SDPDV	Average seed per pod under standard growing conditions (#/pod)	2.05	2.40
PODUR	Time required for cultivar to reach final pod load under optimal conditions (photothermal days)	10.0	10.0
THRSH	Maximum ratio of (seed/(seed + shell)) at maturity. Causes seeds to stop growing as their dry weights increase until shells are filled in a cohort (threshing percentage)	78.0	78.0
SDPRO	Fraction protein in seeds (g(protein)/g(seed))	0.400	0.350
SDLIP	Fraction oil in seeds (g(oil)/g(seed))	0.200	0.200
V1-JU	Time required from first true leaf to end of juvenile phase (thermal days)	6.0	6.0

The crop model showed biases of 0, 2, 6, and 8 days at calibration and 1, 2, −5, and −7 days at evaluation, respectively, for emergence, anthesis, first seed, and the onset of maturity (Table 3). No effects of the plant density on crop phenology were observed for the field and simulated data. The canopy height showed a difference mainly in the calibration step, with 0.93 and 0.61 m, respectively, for the measured and simulated data (Table 3). The maximum leaf area index (LAI) showed a relative root mean square error (rRMSE) of 0.43 in the calibration and 0.31 in the evaluation. The grain number per m² and per pod and

the grain weight performed better during calibration, whereas the bias, root mean square error (RMSE), and rRMSE increased during evaluation. The aboveground biomass showed rRMSEs of 0.32 and 0.33, respectively, in the calibration and evaluation, while the pod weight showed a considerably increased rRMSE from calibration to evaluation (Table 3).

Table 3. Measured (M) and simulated (S) values, bias, and absolute (RMSE) and relative root mean square error (rRMSE) values for phenology and growth variables during calibration and evaluation steps.

Variable	M	S	Bias	RMSE	rRMSE
Calibration					
Emergence day	6	6	0	-	-
Anthesis day	30	32	2	-	-
First seed day	55	61	6	-	-
Maturity day	107	114	8	-	-
Canopy height (m)	0.93	0.61	−0.32	0.92	0.99
Maximum LAI	4.29	3.91	−0.38	1.84	0.43
Grain number per m ²	2296	2685	389	775	0.34
Grain number per pod	2.46	2.61	0.15	0.66	0.27
Grain weight (g unit ^{−1})	0.185	0.189	−0.004	0.007	0.01
Top weight (kg ha ^{−1})	6078	7137	1059	1972	0.32
Pod weight (kg ha ^{−1})	6663	6228	−434	2630	0.39
Grain yield (kg ha ^{−1})	4377	4590	−213	606	0.14
Evaluation					
Emergence day	6	5	1	-	-
Anthesis day	30	28	2	-	-
First seed day	60	55	−5	-	-
Maturity day	114	106	−7	-	-
Canopy height (m)	0.69	0.61	−0.08	0.24	0.35
Maximum LAI	3.68	2.17	−0.51	1.14	0.31
Grain number per m ²	1242	2559	1317	1564	1.26
Grain number per pod	2.32	3.71	−1.39	1.91	0.82
Grain weight (g unit ^{−1})	0.143	0.355	0.211	0.617	4.30
Top weight (kg ha ^{−1})	6843	6099	−744	2292	0.33
Pod weight (kg ha ^{−1})	1125	4186	3061	3934	3.49
Grain yield (kg ha ^{−1})	3008	2823	−185	301	0.11

For the grain yield, the RMSEs were 606 and 301 kg ha^{−1} during calibration and evaluation, respectively (Table 2; Figure 2), with rRMSEs of 13 and 11%, respectively. The relationship between the measured and simulated values for the grain yield by plant density (Figure 2) shows the ability of the model to simulate different yield levels across plant densities (Figure 2a).

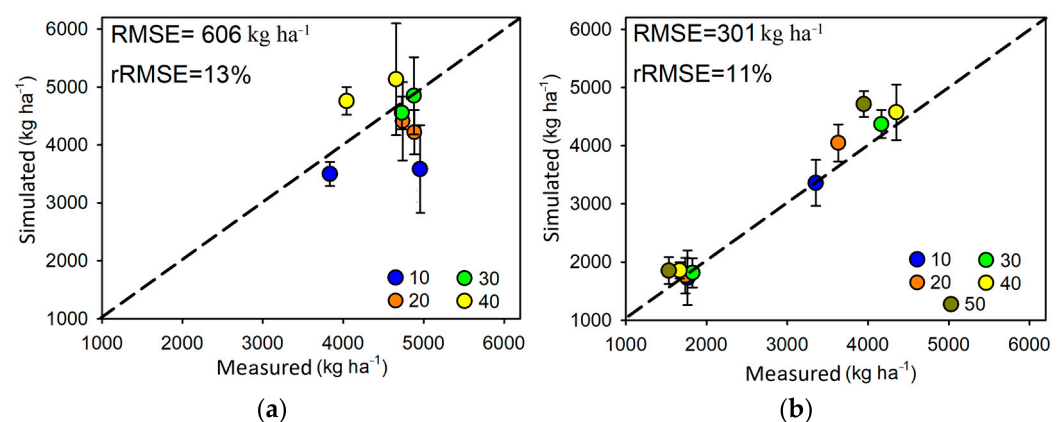


Figure 2. Relationship between the measured and simulated soybean yield during the calibration (a) and validation (b) processes at four (a) plant population densities (10, 20, 30, and 40 plants m^{−2}) for growing season 2022/23 and five (b) plant population densities (10, 20, 30, 40, and 50 plants m^{−2}) for growing season 2023/24 for a maturity group 7.6 cultivar. RMSE is the square root of the mean square error and rRMSE is the relative root mean square error.

The gradual increase in plant population density from 10 to 50 plants m^{-2} increased the LAI (Figure 3). However, the greatest difference in LAI occurred between the lowest population of 10 plants m^{-2} and the other populations. The smallest differences in LAI values were observed among the populations of 30, 40, and 50 plants m^{-2} (Figure 3). The simulated LAI values exhibited the same trend as the observed values for all population densities and sowing dates (Figure 3). The water deficit that occurred on the sowing date of 5 October 2023 in Itaberaí (Figure 3c) caused a drastic reduction in the LAI, with the CROPGRO-Soybean model proving efficient in estimating the LAI even under deficit conditions.

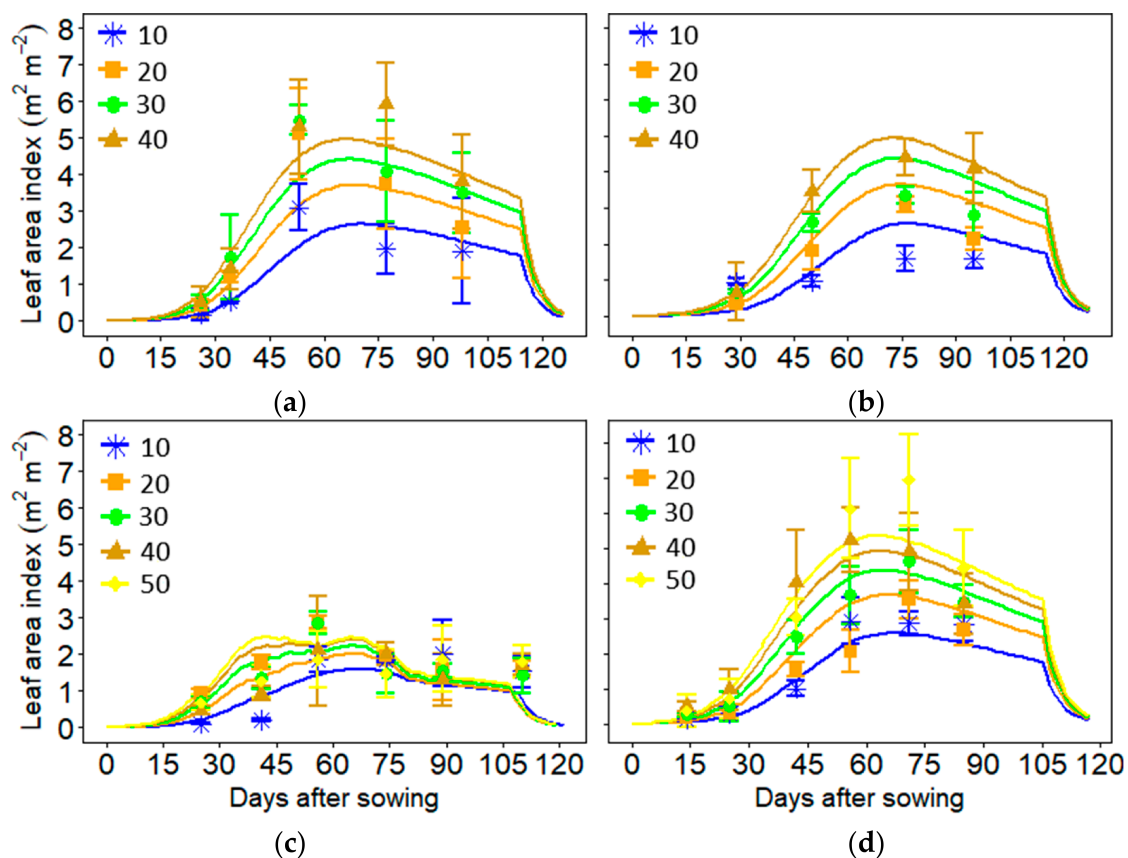


Figure 3. Leaf area index (LAI) measured (symbols) and simulated (lines) throughout the crop cycle for calibration (a,b) and validation (c,d) at four plant population densities (10, 20, 30, and 40 plants m^{-2}) for growing season 2022/23 and five plant population densities (10, 20, 30, 40, and 50 plants m^{-2}) for growing season 2023/24, with sowing on 23 October 2022 (a), 25 November 2022 (b), 5 October 2023 (c), and 1 December 2023 (d) in Itaberaí (a,c) and Silvanía (b,d).

Good agreement between the simulated and measured total dry mass values was observed (Figure 4), with model underestimation for the 5 October 2023 sowing date (Figure 4c) under the severe water deficit. Similarly, model underestimation was observed for the plant density of 10 plants m^{-2} on 23 October 2022 (Figure 4a). The leaf dry biomass showed a lower rate of increase for higher plant densities (above 40 plants m^{-2}) for all field experiment conditions (Figure 4e–h). For the 5 October 2023 (Figure 4e) and 25 November 2022 (Figure 4f) sowing dates, the lower plant density (10 plants m^{-2}) showed a sharper decline in the measured leaf dry mass than the model-simulated values.

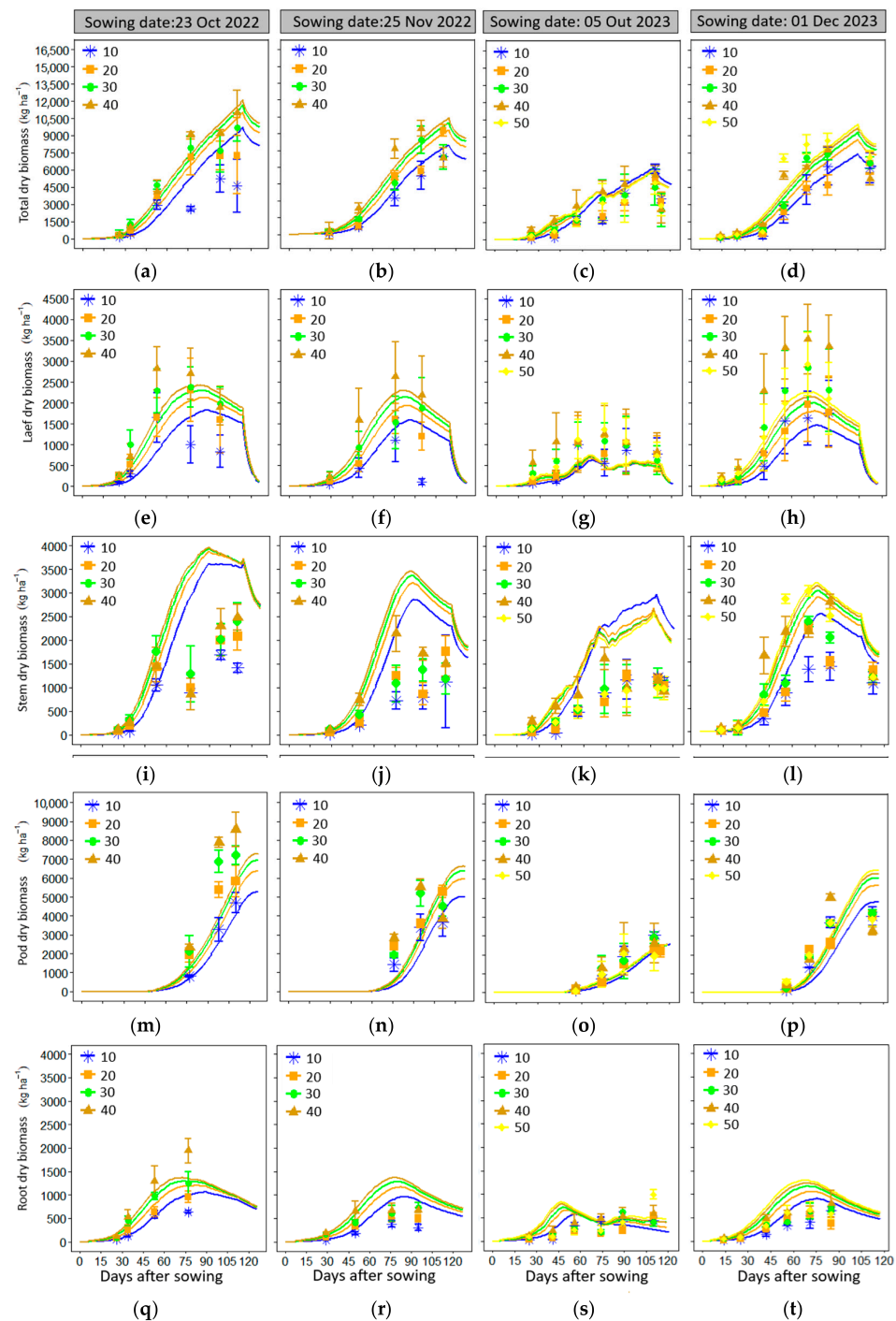


Figure 4. Measured (points) and simulated (lines) values of total (a–d), leaf (e–h), stem (i–l), pod (m–p), and root (q–t) dry biomass at four plant population densities (10, 20, 30, and 40 plants m^{-2}) for growing season 2022/23 and five plant population densities (10, 20, 30, 40, and 50 plants m^{-2}) for growing season 2023/24, with sowing dates on 23 October 2022 (a,e,i,m,q), 25 November 2022 (b,f,j,n,r), 5 October 2023 (c,g,k,o,s), and 1 December 2023 (d,h,l,p,t) in Itaberai (a,c,e,g,i,k,m,o,q,s) and Silvania (b,d,f,h,j,l,n,p,r,t).

The plant density of 50 plants m^{-2} showed lower measured leaf dry biomass than 40 plants m^{-2} for the sowing date of 1 December 2023 (Figure 4h), which was captured by the crop model. Stem dry mass showed the highest bias in simulated values (Figure 4i–l). The only exception was for a plant density above 30 plants m^{-2} for sowing on 1 December 2023 (Figure 4i). Both the measured and simulated values of pod dry biomass showed lower differences across plant densities (Figure 4m–p). The measured root dry biomass was

highly different across plant densities for the sowing date of 23 October 2022 (Figure 4q), with greater root biomass under higher plant densities due to early planting and a lower water deficit than on 5 October 2023. The simulated root dry mass values were consistent with the measured trends, but with less pronounced differences across plant densities. The crop model simulated intense root senescence under water deficit conditions (Figure 4s), suggesting that a substantial proportion of the root system became physiologically inactive under these stress conditions.

3.3. Sowing Dates and Plant Densities

The seasonal simulation analysis over 30 growing seasons showed that the greatest yield response was observed at an increase in plant density from 10 to 20 plants m^{-2} (+20%), followed by increases from 20 to 30 plants m^{-2} (+10%), 30 to 40 plants m^{-2} (+6%), and 40 to 50 plants m^{-2} (+4%) (Figure 5). The average yields across locations ranged from 2950 (Miranorte, Figure 5h) to 4260 kg ha^{-1} (São Gabriel do Oeste, Figure 5a). Sowing dates across October, November, and December resulted in average yields of 3034, 3470, and 3313 kg ha^{-1} , respectively (Figure 5), with greater interannual variability during the first and second ten-day periods of October (01/10 and 10/10).

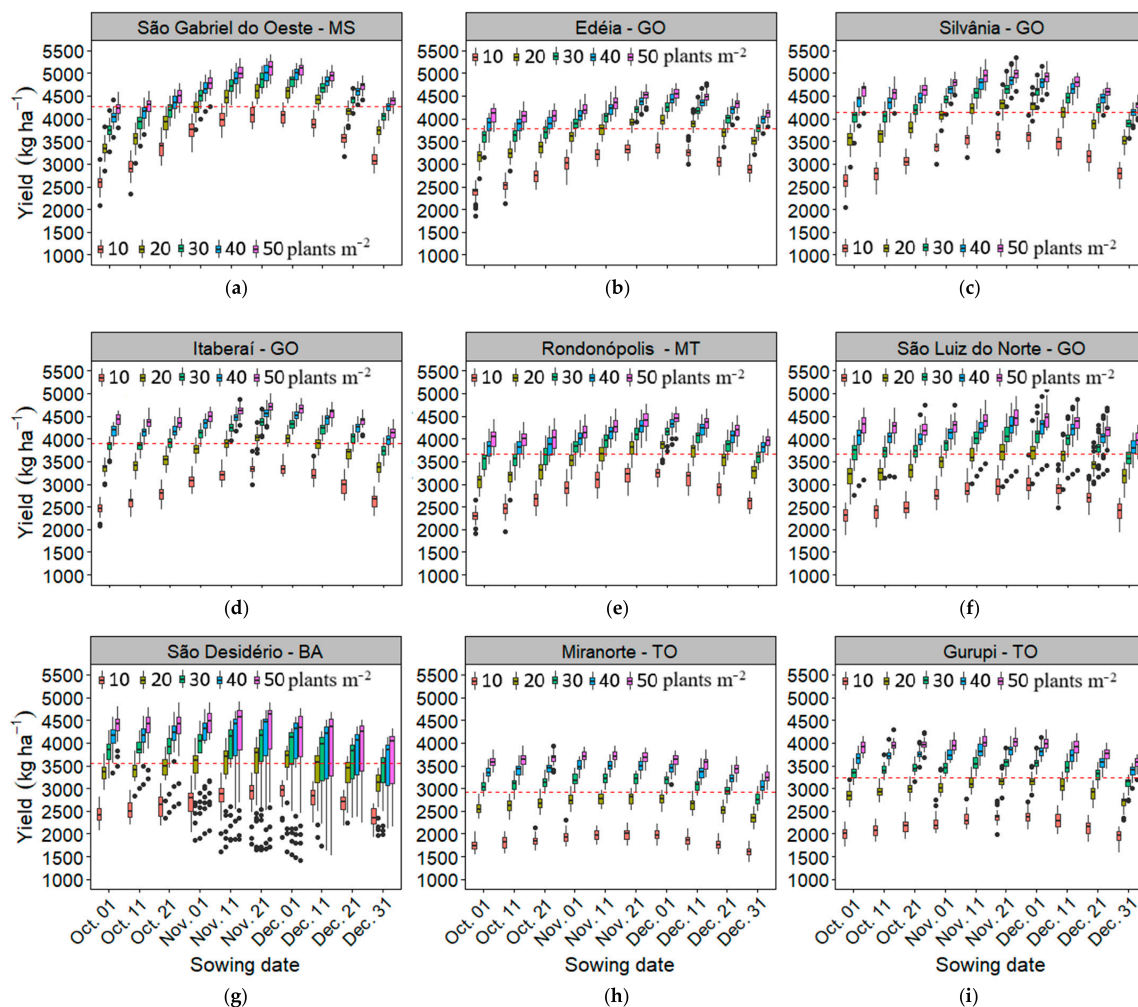


Figure 5. Simulated yield as a function of plant density (10, 20, 30, 40, and 50 plants m^{-2}) for ten sowing dates across nine locations in the Cerrado biome, including São Gabriel do Oeste—MS (a), Edéia—GO (b), Silvânia—GO (c), Itaberaí—GO (d), Rondonópolis—MT (e), São Luiz do Norte—GO (f), São Desidério—BA (g), Miranorte—TO (h), and Gurupi—TO (i). The red dotted line represents the simulated average yield; boxes represent the 25th, 50th (median), and 75th percentiles; whiskers represent the 5th and 95th percentiles; and black points represent outliers.

Yields above the average were observed for sowing dates ranging from 1 November to 21 December, with the highest yields on 21 November at 30 plants m^{-2} in São Gabriel do Oeste (Figure 5a) and Rondonópolis (Figure 5e). Edéia (Figure 5b), Silvânia (Figure 5c), and Itaberai (Figure 5d) showed patterns similar to those of São Gabriel do Oeste and Rondonópolis, but with 10 plants m^{-2} showing a larger difference relative to 20 plants m^{-2} . São Luiz do Norte (Figure 5f), Miranorte (Figure 5h), and Gurupi (Figure 5i) showed a longer sowing window with yields above average for 30 plants m^{-2} . São Desidério showed higher variability across year-to-year growing seasons, with the most promising sowing dates occurring until 1 December at 30 plants m^{-2} (Figure 5g).

4. Discussion

The CROPGRO-Soybean model was calibrated for a maturity group 7.6 cultivar with an indeterminate growth habit using high-resolution crop data. Although the calibration used two growing seasons, the 18 treatment combinations provided substantial variability in phenology, LAI, biomass and yield under contrasting water regimes. The breadth of data underscores the model's robustness [23], with cultivar-specific responses refined using a model validated for climate and soil extrapolation across the Cerrado.

The model showed low bias for the grain yield and an adequate capacity to represent crop growth and development. However, traits such as the pod weight ($\text{rRMSE} = 3.49$) and single-grain weight ($\text{rRMSE} = 4.30$) showed higher bias during model evaluation, suggesting that these traits are strongly influenced by the local conditions and are less mechanistically represented in the model. Nevertheless, the good performance observed for the grain yield indicates that compensatory effects among simulated crop growth parameters may have contributed to the adequate simulation of the final grain yield. These simulation patterns and performance metrics were similar to those reported in other studies using CSM-CROPGRO-Soybean [23,24].

Anthesis is strongly influenced by the air temperature during the vegetative phase of the crop [25]. Although this relationship is consistent with the variation observed in the emergence-to-flowering period of 27 to 32 days for model calibration and validation, the results indicate that temperature alone did not explain all observed variability. In addition, the crop model was able to represent later sowing dates, which were exposed to progressively shorter photoperiods, contributing to changes in the duration of the vegetative period [26,27].

Although the model showed good performance in simulating the total dry biomass, this agreement appears to result from compensatory effects among biomass components. The stem dry mass was consistently overestimated throughout the crop cycle, indicating that the model allocated a higher proportion of assimilates to vegetative structural growth than observed in the field. This overestimation may have compensated for the underestimation of the pod dry biomass, followed by smaller discrepancies in root and leaf biomass. In CROPGRO-Soybean, biomass partitioning is controlled by internal species-level functions, with limited flexibility for cultivar-specific calibration [13,27]. Thus, biases in the temporal allocation of dry matter, especially to stems and pods, indicate limitations in representing organ-level biomass dynamics [4], but with a limited impact on this study because the focus was the grain yield.

The greatest difference in the simulated yield was observed between densities of 10 and 20 plants m^{-2} . This pattern was related to the lower efficiency of solar radiation use in reduced populations, due to the lower leaf area index, which tends to reduce biomass accumulation and grain production [28]. Reduced plant densities provide lower leaf areas, which decreases light interception by the canopy, thereby reducing the photosynthetic rate and, consequently, the production of photoassimilates [29]. These results are con-

sistent with those described in [4], where the authors identified plant densities between 20 and 30 plants m^{-2} as most favorable for achieving high yields under the Cerrado biome conditions. In the present study, increasing the population beyond 40 plants m^{-2} did not result in further yield gains, suggesting the existence of a threshold beyond which a higher plant density restricts the partitioning of biomass allocated to grain filling, increasing the competition for light, water, and nutrients in higher populations [30,31].

The rainfall period in the Cerrado biome region occurs between the months of October and March. However, October exhibits considerable variability in the distribution of precipitation [8], which contributed to slightly lower yields for the first sowing dates. On the other hand, late sowing in December was associated with a shorter daylight duration. Thus, plants were exposed to lower amounts of solar radiation, and the growth cycle was accelerated due to the earlier flowering, which decreases biomass partitioning toward grain filling [32]. November consistently provided higher yields, therefore being the most promising sowing date period in the Cerrado biome, when considering optimal management. This coincides with the period presenting the longest photoperiod combined with water availability, favoring increased soybean productivity [33].

The results indicate that interannual yield variability resulted from the interaction among soil characteristics, precipitation distribution, and the atmospheric evapotranspiration demand throughout the growing seasons, indicating that, in environments with a low soil water storage capacity, management strategies related to the sowing date and plant population can mitigate yield losses [34,35]. These interactions shaped the attainable yield simulated by the crop model under different climate-risk conditions [3].

5. Conclusions

The CSM-CROPGRO-Soybean model showed low bias for the grain yield, with adequate representation of soybean growth and development, considering contrasting plant densities, sowing dates, and locations. Limitations were observed for the pod weight, single-grain weight, and stem and pod dry biomass, leading the model to compensate among these components. Planting soybeans in November with plant populations between 20 and 30 plants m^{-2} was the most promising agronomic management strategy to maximize the attainable seed yields. The plant density of 10 plants m^{-2} resulted in low yields, especially for late sowings performed in December due to the reduced cycle length. At plant densities above 40 plants m^{-2} , a slight increase in the attainable yield was observed under optimal management conditions, assuming no limitations from pests, weeds, diseases, nutrient availability, or lodging. However, this response should be interpreted cautiously, as higher plant densities may increase the risks of lodging and disease pressure under field conditions, potentially limiting the expected yield gains. Sowing dates should be carefully considered to reduce the risk of crop exposure to water deficits. Sowing during the first and second ten-day periods of October should be considered only when rainfall starts early in the growing season, ensuring adequate conditions for crop establishment.

Author Contributions: Conceptualization, F.P.D. and R.B.; methodology, F.P.D., J.A.Q.G., M.L.J.V., R.B. and E.F.E.; investigation, F.P.D., R.B., E.F.E., M.F.N.X., R.A.F., M.V.d.S., J.A.Q.G., M.L.J.V., C.d.S.C., H.F.E.d.O. and A.N.H.M.; writing—original draft preparation, F.P.D. and R.B.; writing—review and editing, F.P.D., R.B., E.F.E., M.F.N.X., M.V.d.S., H.F.E.d.O., A.N.H.M. and M.M.; supervision, R.B. and M.M.; project administration, R.B.; funding acquisition, F.P.D., R.B. and M.M. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), grant numbers 165096/2021–7 (1st author), 302834/2022–2 (2nd author), 312854/2023–4 (12th author), and 420516/2023–9 (12th author), and the Goiás State Research Foundation—FAPEG, grant number 202510267001850 (12th author).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors on request.

Acknowledgments: We would like to thank the DSSAT Foundation for providing the crop simulation platform used in this study. We also acknowledge the Brazilian Daily Weather Gridded Data (BR-DWGD) [24] for making high-quality meteorological data available for Brazil. Finally, we are grateful to the farmers who kindly provided the experimental areas and supported the field activities necessary for conducting this research.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. FAOSTAT. Food and Agriculture Data. Available online: <http://www.fao.org/faostat/en/#home> (accessed on 16 February 2025).
2. Instituto Brasileiro de Geografia e Estatística (IBGE). Produção Agrícola Municipal. Available online: <https://www.ibge.gov.br/estatisticas/economicas/agricultura-e-pecuaria/9117-producao-agricola-municipal-culturas-temporarias-e-permanentes.html?&t=resultados> (accessed on 16 February 2025).
3. Santos, E.F.; Santos, M.P.; Silva, R.A.; Marques, L.M.; Battisti, R. Soybean yield gap in integrated crop-forest, conventional, and no-tillage systems in sandy soil. *Pesqui. Agropecu. Trop.* **2026**, *56*, e84404. [\[CrossRef\]](#)
4. Sampaio, L.S.; Battisti, R.; Lana, M.A.; Boote, K.J. Assessment of sowing dates and plant densities using CSM-CROPGRO-Soybean for soybean maturity groups in low latitude. *J. Agric. Sci.* **2020**, *158*, 819–832. [\[CrossRef\]](#)
5. Tagliapietra, E.L.; Streck, N.A.; Rocha, T.S.M.; Richter, G.L.; Silva, M.R.; Cera, J.C.; Guedes, J.V.C.; Zanon, A.J. Optimum Leaf Area Index to Reach Soybean Yield Potential in Subtropical Environment. *Agron. J.* **2018**, *110*, 932–938. [\[CrossRef\]](#)
6. Corassa, G.M.; Amado, T.J.C.; Strieder, M.L.; Schwalbert, R.; Pires, J.L.F.; Carter, P.R.; Ciampitti, I.A. Optimum Soybean Seeding Rates by Yield Environment in Southern Brazil. *Agron. J.* **2018**, *110*, 2430–2438. [\[CrossRef\]](#)
7. Alvares, C.A.; Stape, J.L.; Sentelhas, P.C.; Gonçalves, J.L.M.; Sparovek, G. Köppen’s climate classification map for Brazil. *Meteorol. Z.* **2013**, *22*, 711–728. [\[CrossRef\]](#)
8. Soares, K.W.S.; Battisti, R.; Dapper, F.P.; Carvalho, A.P.M.; Silva, M.V.; Silva, J.L.B.; Oliveira, H.F.E.; Mesquita, M. Shifting Climate Patterns in the Brazilian Savanna Evidenced by the Köppen Classification and Drought Indices. *Atmosphere* **2025**, *16*, 849. [\[CrossRef\]](#)
9. Silva, R.B.M.; Francelino, M.R.; Moura, P.A.; Moura, T.A.; Pereira, M.G.; Oliveira, C.P. Relação solo/vegetação em ambiente de cerrado sobre influência do grupo Urucua. *Ciênc. Florest.* **2015**, *25*, 363–373. [\[CrossRef\]](#)
10. Medrado, E.; Lima, J.E.F.W. Development of pedotransfer functions for estimating water retention curve for tropical soils of the Brazilian savanna. *Geoderma Reg.* **2014**, *1*, 59–66. [\[CrossRef\]](#)
11. Teixeira, P.C.; Donagemma, D.G.; Fontana, A.; Teixeira, W.G. *Manual de Métodos de Análise de Solo*, 3rd ed.; Embrapa: Brasília, Brazil, 2018.
12. Battisti, R.; Silva, O.C.C.; Knapp, F.M.; Alves Júnior, J.; Mesquita, M.; Monteiro, L.A. Assessment of the reliability to use NASAPOWER gridded weather applied to irrigation planning and management in Brazil. *Theor. Appl. Climatol.* **2024**, *155*, 8287–8297. [\[CrossRef\]](#)
13. Boote, K.J.; Jones, J.W.; Batchelor, W.D.; Nafziger, E.D.; Myers, O. Genetic coefficients in the CROPGRO-soybean model. *Agron. J.* **2003**, *95*, 32–51. [\[CrossRef\]](#)
14. Rasband, W. *ImageJ*, version 1.46c; U.S. National Institutes of Health: Bethesda, MD, USA, 2011.
15. Hoogenboom, G.; Porter, C.H.; Shelia, V.; Boote, K.J.; Singh, U.; White, J.W.; Hunt, L.A.; Ogoshi, R.; Lizaso, J.I.; Koo, J.; et al. *Decision Support System for Agrotechnology Transfer (DSSAT)*, version 4.7; DSSAT Foundation: Gainesville, FL, USA, 2017.
16. Hunt, L.A.; Boote, K.J. Data for model operation, calibration, and evaluation. In *Understanding Options for Agricultural Production*; Tsuji, G.Y., Hoogenboom, G., Thornton, P.K., Eds.; Springer: Dordrecht, The Netherlands, 1998; pp. 9–39.
17. Makowski, D.; Wallach, D.; Tremblay, M. Using a Bayesian approach to parameter estimation: Comparison of the GLUE and MCMC methods. *Agronomie* **2002**, *22*, 191–203. [\[CrossRef\]](#)
18. Jones, J.W.; He, J.; Boote, K.J.; Wilkens, P.W.; Porter, C.H.; Hu, Z. Estimating DSSAT Cropping System Cultivator-Specific Parameters Using Bayesian Techniques. *Agron. Abstr.* **2011**, *2*, 365–393. [\[CrossRef\]](#)
19. Wallach, D.; Makowski, D.; Jones, J.W.; Brun, F. *Working with Dynamic Crop Models: Evaluation, Analysis, Parameterization, and Applications*, 1st ed.; Elsevier Science: Amsterdam, The Netherlands, 2006.
20. Xavier, A.C.; Scanlon, B.R.; King, C.W.; Alves, A.I. New improved Brazilian daily weather gridded data (1961–2020). *Int. J. Climatol.* **2022**, *42*, 8390–8404. [\[CrossRef\]](#)

21. Ministério da Agricultura e Pecuária (MAPA). Programa Nacional de Zoneamento Agrícola de Risco Climático (ZARC). Available online: <https://www.gov.br/agricultura> (accessed on 17 September 2025).
22. RADAMBRASIL. *Pesquisa de Recursos Naturais*; Ministério de Minas e Energia: Rio de Janeiro, Brazil, 1974; Volume 4.
23. Fensterseifer, C.A.; Streck, N.A.; Baigorria, G.A.; Timilsina, A.P.; Zanon, A.J.; Cera, J.C.; Rocha, T.S.M. On the number of experiments required to calibrate a cultivar in a crop model: The case of CROPGRO-soybean. *Field Crops Res.* **2017**, *204*, 146–152. [[CrossRef](#)]
24. Irene Filho, J.; Andrade Júnior, A.S.; Cuadra, S.V.; Silva, E.M.; Vieira, P.F.M.J. Calibração e avaliação do CSM-CROPGRO-soybean para cultura da soja no cerrado do sudoeste piauiense. *Rev. Caatinga* **2024**, *37*, 1–13. [[CrossRef](#)]
25. Tang, Y.; Lu, S.; Fang, C.; Liu, H.; Dong, L.; Li, H.; Su, T.; Li, S.; Wang, L.; Cheng, Q.; et al. Diverse flowering responses subjecting to ambient high temperature in soybean under short-day conditions. *Plant Biotechnol. J.* **2023**, *21*, 782–791. [[CrossRef](#)] [[PubMed](#)]
26. Ort, N.W.W.; Morrison, M.J.; Cober, E.R.; Samanfar, B.; Lawley, Y.E. Photoperiod affects node appearance rate and flowering in early-maturing soybean. *Plants* **2022**, *11*, 871. [[CrossRef](#)] [[PubMed](#)]
27. Battisti, R.; Sentelhas, P.C.; Boote, K.J. Sensitivity and requirement of improvements of four soybean crop simulation models for climate change studies in Southern Brazil. *Int. J. Biometeorol.* **2018**, *62*, 823–832. [[PubMed](#)]
28. Werner, F.; Silva, M.A.A.E.; Ferreira, A.S.; Zucareli, C.; Junior, A.A.B. Grain, oil, and protein production on soybean stems and branches under reduced densities. *Rev. Bras. Ciênc. Agrár.* **2021**, *16*, 1–9. [[CrossRef](#)]
29. Yokoyama, A.H.; Junior, A.A.B.; Zucareli, C.; Ribeiro, R.H. Índice de área foliar e SPAD durante o ciclo da soja em função da densidade de plantas e sua relação com a produtividade de grãos. *Rev. Ciênc. Agrovet.* **2018**, *17*, 531–538. [[CrossRef](#)]
30. Fernandes, R.D.M.; Melo, D.M.; Elli, E.F.; Battisti, R. Climate change impacts on rainfed and irrigated soybean yield in Brazil's new agricultural frontier. *Theor. Appl. Climatol.* **2022**, *147*, 803–816.
31. Klimek-Kopyra, A.; Baciór, M.; Lorenc-Kozik, A.; Neugschwandtner, R.W.; Zajac, T. Intraspecific competition as a driver for true production potential of soybean. *Ital. J. Agron.* **2021**, *16*, 1. [[CrossRef](#)]
32. Nória Júnior, R.S.; Sentelhas, P.C. Soybean-maize succession in Brazil: Impacts of sowing dates on climate variability, yields and economic profitability. *Eur. J. Agron.* **2019**, *103*, 140–151. [[CrossRef](#)]
33. Bossolani, J.W.; Meneghette, H.H.A.; Sanches, I.R.; Santos, F.L.; Parra, L.F.; Lazarini, E. Sowing date changes phenological development, plastochron index, and grain yield of soybeans under Cerrado conditions. *Braz. J. Agric. Environ. Eng.* **2022**, *26*, 488–494. [[CrossRef](#)]
34. Zhang, J.; Liu, J.; Yang, C.; Du, S.; Yang, W. Photosynthetic performance of soybean plants to water deficit under high and low light intensity. *S. Afr. J. Bot.* **2016**, *105*, 279–287. [[CrossRef](#)]
35. Nória Júnior, R.d.S.; Safanelli, J.L.; Souza, L.F.d.; Dourado Neto, D. Soybean yield monitoring system for Brazil with FAO-AEZ crop model. *Agrometeoros* **2024**, *32*, e027580. [[CrossRef](#)]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.