

Environment

Using the CSM-CROPGRO-Soybean model to estimate soybean sowing dates in the Cerrado of Piauí, Brazil

Utilização do modelo CSM-CROPGRO-Soybean para estimar épocas de semeadura da soja no cerrado piauiense, Brasil

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ABSTRACT

Soybean cultivation is one of the main agricultural activities in Piauí, particularly in the Cerrado biome region. It is a rainfed crop, so the soybean sowing date is crucial to its good yield performance. This study aimed to make an evaluation using the CSM-CROPGRO-Soybean model to simulate soybean grain yield for the Cerrado region of southwest Piauí according to the different sowing dates. The CSM-CROPGRO-Soybean model and historical climate data were used to simulate scenarios for rainfed soybean, sowing dates for eight municipalities in the southwest region of Piauí. Two soybean cultivars were considered: BRS 8980 IPRO (BRS 8980) and the BMX 84I86 cultivar (Dominio). The simulated yield results were analyzed regarding frequency distribution and yield breaks. Sowings made in the first ten days of November had longer cycles, while later, sowings resulted in shorter cycles. This difference in duration was 16.4% for the BRS 8980 cultivar and 13.1% for the Dominio cultivar. The process of assessing the consistency of soybean yield variability concerning simulated yields, was carried out by comparing simulated and measured yields on a commercial soybean production farm in the municipality of Bom Jesus. The best sowing dates were observed for the second and third ten-day period of November and the first 10-day period of December, while the worst date was the third 10-day period of January for all the municipalities evaluated. Choosing the best sowing date for the region can vary according to the risk level the producer is willing to assume. It was concluded that sowings made in the first 10-day period of November had longer cycles, while later sowings resulted in shorter cycles. The use of the DSSAT CSM-CROPGRO-Soybean simulation model proved to be a suitable tool to help make decisions regarding soybean cultivation in the Cerrado region of southwest Piauí.

Keywords: Agricultural modeling; Sowing date; Climate risk

RESUMO

O cultivo da soja se destaca como uma das principais atividades agrícolas do Piauí, particularmente na região do bioma Cerrado. Por ser uma cultura de sequeiro, a época de semeadura da soja é crucial para o seu bom desempenho produtivo. O objetivo deste estudo foi avaliar a utilização do modelo CSM-CROPGRO-Soybean para simular o rendimento de grãos de soja para a região do cerrado do Sudoeste Piauiense com diferentes épocas de semeadura. Utilizou-se o modelo CSM-CROPGRO-Soybean, juntamente com dados históricos de clima, para simular cenários de épocas de semeadura da soja em regime de sequeiro, para oito municípios da região Sudoeste do Piauí. Considerou-se duas cultivares de soja, BRS 8980 IPRO (BRS 8980) e a cultivar BMX 84186 (Domínio). Os resultados de produtividade simulados foram analisados em termos de distribuição de frequência e de quebra da produtividade. As semeaduras realizadas no primeiro decênio de novembro apresentaram ciclos mais longos, enquanto as semeaduras mais tardias resultaram em ciclos mais curtos. Essa diferença de duração foi de 16,4% para a cultivar BRS 8980 e de 13,1% para a cultivar Domínio. O processo de avaliação da consistência da variabilidade da produtividade de soja em relação aos rendimentos simulados foi realizado através da comparação entre os rendimentos simulados e medidos em uma fazenda de produção comercial de soja no município de Bom Jesus. As melhores datas de semeadura foram observadas para o segundo e terceiro decênio de novembro e primeiro decênio dezembro, enquanto a pior data foi o terceiro decênio de janeiro, para todos os municípios avaliados. A escolha da melhor data de semeadura para a região pode variar de acordo com o nível de risco que o tomador de decisão está disposto a assumir. A utilização do modelo de simulação DSSAT CSM-CROPGRO-Soybean mostrou-se como uma ferramenta valiosa para auxiliar na tomada de decisões relacionadas ao cultivo de soja na região do cerrado do Sudoeste Piauiense.

Palavras-chave: Modelagem agrícola; Época de plantio; Risco climático

1 INTRODUCTION

With production growing by 23.2% between the 2022 and 2023 crop seasons, Brazil has become the world's largest soybean producer, surpassing the United States, Argentina, and China. In the 2023 crop season, Brazil produced 147,240,376 tons of soybeans (IBGE, 2023). Its importance has been growing in all regions of the country. According to Bohn et al. (2016), in the state of Piaui, the considerable yield levels achieved by soybean cultivation in the Cerrado, combined with the prospect of improved infrastructure and economic incentives, make the region one of the most promising for crop in Brazil.

According to Wu et al. (2018), soybean production is driven by the continuous growth of global demand, resulting from population increase and the multiple uses of

this crop, including human and animal nutrition as well as biodiesel production. The Cerrado of Piauí produced 3,258,861 tons of soybeans in the 2023 crop season in an area of 939,435 ha, with an average yield of 3491.00 kg ha⁻¹ (IBGE, 2023).

Although soybean yield is growing at a steady pace due to (I) the use of technologies, (II) the adoption of genotypes with higher yield potential, (III) the use of soil management practices, and (IV) the higher qualification of producers, there have been fluctuations in the yield (Reis et al., 2020). Producers should, therefore, sow their soybeans according to the Agricultural Climate Risk Zoning (ZARC) (Brasil, 2023), as it is an efficient agroclimatic risk management tool recognized by the National Monetary Council.

The ZARC is a set of techniques that aims to indicate to the producer what, where, and when to plant in an attempt to avoid adverse climatic events, such as drought and excessive rain, considering the characteristics of the plant, as well as soil and climate conditions, based on a methodology validated by Embrapa (Brasil, 2023).

Climate variability is a main factor that makes farming a high-risk activity (Barbieri et al., 2020). The choice of sowing date is one of the cheapest and most efficient ways to mitigate the effect of water deficiency in rainfed crops, and one of the ways to recommend sowing dates is through the use of simulations.

The simulation of crop behavior according to the variability of a region's soil and climate can be carried out using biophysical models, such as those present in the Decision Support System for Agrotechnology Transfer (DSSAT) simulation platform (Hoogenboom et al., 2019). However, simulation models need to be calibrated and evaluated when applied to a production environment other than the one in which the model was previously validated, or when simulating cultivars that have not previously been calibrated. The system modular platform includes a soil module, a crop module (which can simulate different crops by setting specific parameters for each species), a weather generator module (WGEN), and a module that simulates competition for resources (e.g., light, water) by crops within the soil-plant-atmosphere system (Cuadra et al., 2018).

Agricultural climate risk zoning helps to inform the formulation of new public policies aimed at increasing the sustainability of soybean cultivation in the Cerrado biome (Melo et al., 2020). Soybean yield simulations based on a recommended sowing window for the region (from November 1 to January 31) can be made to identify the patterns of water deficit that affect the crop in different parts of the Cerrado of southwest Piauí. In this way, a comparison can be made between the different sowing dates, analyzing the variations in yield and identifying the most favorable dates for sowing when the climatic risks are lowest.

In this sense, the progress made in agricultural zoning studies is evident, contributing significantly to the sustainability of agricultural activity; however, it is necessary to improve the current recommendation system for soybean cultivation to keep up with recent changes in climatic, agricultural, and socioeconomic scenarios (Melo et al., 2020).

Given the above, this study aimed to evaluate the use of the CSM-CROPGRO-Soybean model to simulate soybean grain yield for the Cerrado region of southwest Piauí with different sowing dates.

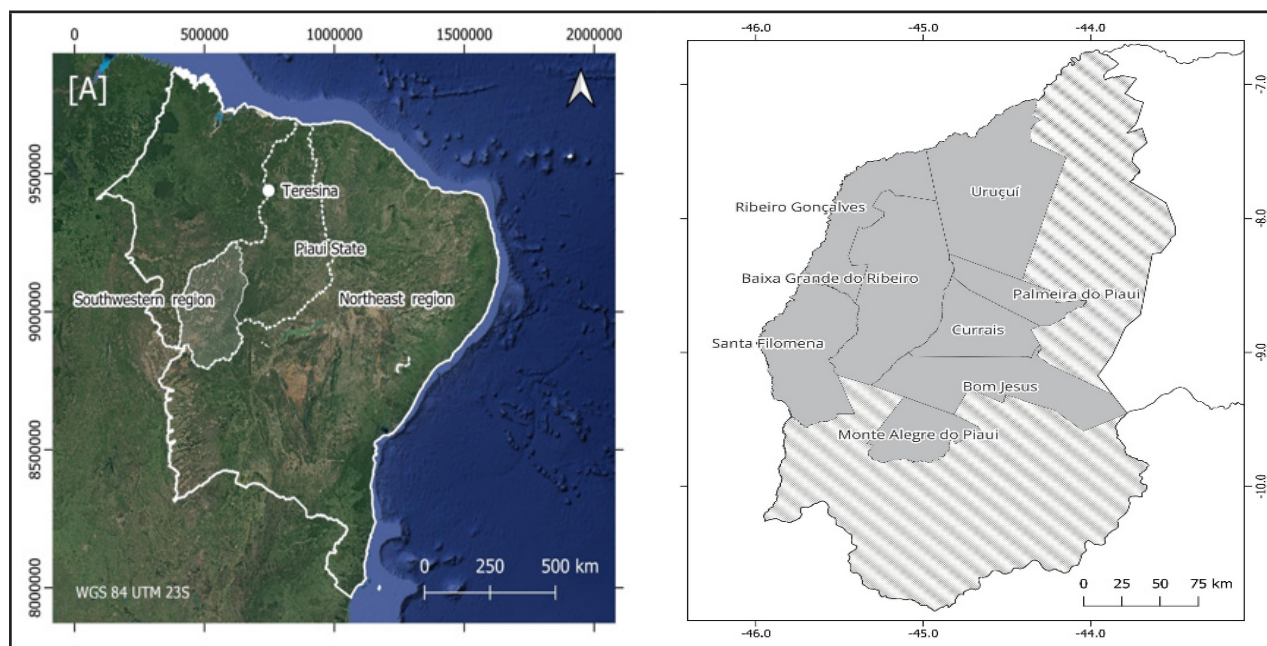
2 MATERIAL AND METHODS

The CSM-CROPGRO-Soybean model was used from the DSSAT v4.7.5 (Decision Support System for Agrotechnology Transfer) package, which is a set of programs for simulating growth, development, and yield, according to the soil-plant-atmosphere dynamics (Jones et al., 2010), previously calibrated and evaluated, to simulate the grain yield of soybeans sown on different dates under rainfed conditions in eight municipalities in the southwest region of the state of Piauí (Figure 1).

The geographical coordinates of the municipalities are shown in Table 1. The model seasonal analysis tool was used, along with historical daily weather data for the Piauí municipalities of Baixa Grande do Ribeiro, Bom Jesus, Currais, Monte Alegre do Piauí, Palmeira do Piauí, Ribeiro Gonçalves, Santa Filomena, and Uruçuí to simulate sowing season scenarios for the 1989/1990 to 2019/2020 crop seasons,

allowing 30 crop seasons to be simulated. The meteorological data used in this study was obtained from the daily database of Xavier et al. (2022), comprising rainfall (mm), air temperature ($^{\circ}\text{C}$), relative air humidity (%), wind speed (m s^{-1}), and solar radiation ($\text{MJ m}^{-2} \text{day}^{-1}$).

Figure 1 – Location of the soybean growing area highlighting the municipalities evaluated



Source: Authors (2023)

The Cerrado of Piauí has a great deal of soil variability, which affects the soil's chemical and physical attributes. Different physical attributes lead to different water storage capacities in the soil. Therefore, to make it possible to compare the municipalities, three basic soil types were adopted (0.40 , 0.66 , and 1.21 mm cm^{-1} of available water - AW) in all the locations to represent the great diversity of soils in the Cerrado of Piauí. For risk analysis in Agricultural Climate Risk Zoning, these soils are classified as AD1, AD3, and AD5, respectively, according to SPA/MAPA Normative Instruction N^o 1 of June 21, 2022 (MAPA, 2022), based on classification criteria established by Teixeira et al. (2021). The soil profiles required by the crop simulation model were built based on the data from the soil profile used in the model calibration, classified as a Latossolo Amarelo Distrófico argissólico (Pragana et al., 2016).

Table 1 – Municipalities in the Southwest of Piauí evaluated in the simulations, with their respective geographical coordinates (latitude, longitude, and altitude)

Municipalities	Geographical Coordinates		
	Latitude	Longitude	Altitude
Baixa Grande do Ribeiro	8°37'30.0" S	45°07'30.0" W	459 m
Bom Jesus	9°07'30.0" S	44°37'30.0" W	476 m
Currais	8°52'30.0" S	44°37'30.0" W	528 m
Monte Alegre do Piauí	9°37'30.0" S	45°07'30.0" W	472 m
Palmeira do Piauí	8°37'30.0" S	44°22'30.0" W	520 m
Ribeiro Gonçalves	7°52'30.0" S	45°22'30.0" W	400 m
Santa Filomena	8°52'30.0" S	45°37'30.0" W	458 m
Uruçuí	7°52'30.0" S	44°37'30.0" W	417 m

Source: *Google Earth* (2023)

Two soybean cultivars were evaluated: BRS 8980 IPRO (BRS 8980 - determinate growth habit) and BMX 84186 (Dominio - indeterminate growth habit), whose genetic coefficients were previously calibrated and validated for the Cerrado region of Piauí, registered in the model following all the technical guidelines related to crop management, phytosanitary control, and fertilization recommended for soybeans in the region. Thus, the difference in simulated soybean yields for the different sowing dates was due to weather conditions.

The CROPGRO-Soybean model was used to simulate the achievable yields and the cycle of the cultivars. The attainable yield was used because most soybeans are grown under rainfed conditions, and the yield is linked to the water deficit in the production regions, as Battisti & Sentelhas (2019) emphasized.

The management was programmed in the XBuild module of the DSSAT model, with the option of simulating soybean yields for automatic sowings, selecting the best sowing date within each 10-day period of November, December, and January for each year evaluated, following the soybean sowing window recommended for the region by the Agroclimatic Risk Zoning of the Ministry of Agriculture, Livestock, and Food Supply (MAPA, 2021).

When determining the nomenclature of the treatments, three types of soil were considered: Soil type 1 (0.40 mm cm⁻¹ AW), Soil type 2 (0.66 mm cm⁻¹ AW), and Soil type 3 (1.21 mm cm⁻¹ AW). The sowing dates for each 10-day period were defined as 1 Nov,

2Nov, and 3Nov for the 1st, 2nd, and 3rd 10-day period of November; 1Dec, 2Dec, and 3Dec for the 1st, 2nd, and 3rd 10-day-period of December; 1Jan, 2Jan, and 3Jan for the 1st, 2nd, and 3rd 10-day period of January, respectively.

The simulated grain yield values were plotted as a frequency distribution for each sowing date. The average cycle time of the evaluated cultivars was also used to determinate the behavior of the cycle according to the sowing dates, making it possible to establish different levels of risk that the producer would be willing to take.

Subsequently, the soybean yields obtained by the model were compared to average yield data obtained from a commercial soybean farm in the region, located in the Serra do Quilombo in the municipality of Bom Jesus, Piauí, at São Carlos Farm (9°17'02.0" S, 44°44'42.7" W, and altitude of 633 m), which has been growing soybeans in the Cerrado region of Piauí for over 20 years.

3 RESULTS AND DISCUSSION

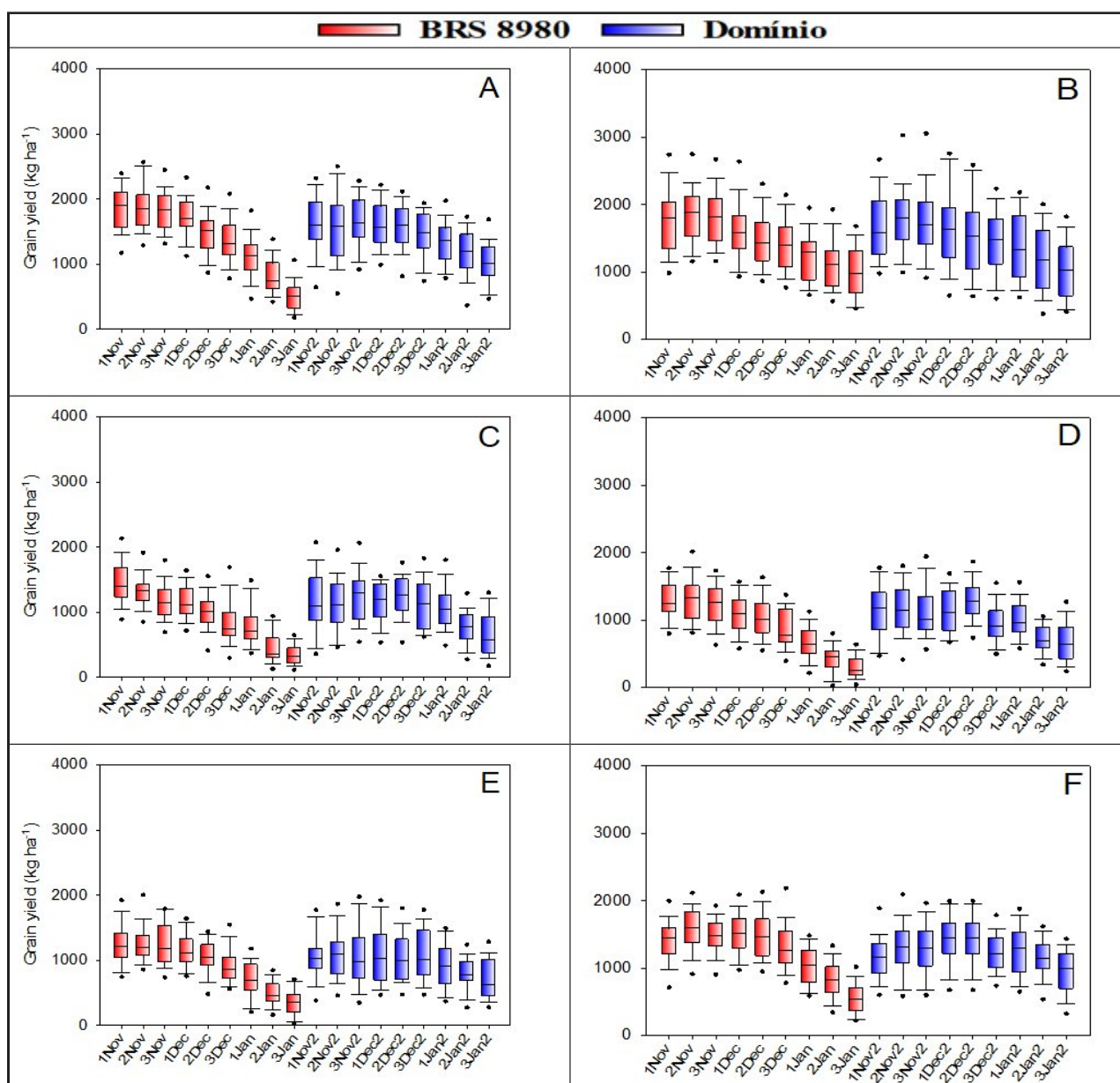
For Soil type 1, the results generally show that in the frequency distribution of soybean yields, the two cultivars follow roughly the same behavior in all the municipalities evaluated (Figure 2), with higher grain yield values in sowings made at the beginning of the period indicated for the region by the ZARC (Ordinance No. 116/2021-MAPA).

Due to the variability found in cultivation under rainfed management conditions, it can be inferred that this is due to variations in water availability caused by the occurrence of drought periods, which generally occur in January, corroborating Báez et al. (2020), who observed a drop in soybean grain yield due to an increase in the level of water deficit in the soil.

It was noted, however, that there were changes in grain yield values for all municipalities, with considerable variations between maximum and minimum yields on all sowing dates, indicating that water availability significantly affects crop yields. This was also observed by Pham et al. (2023) when they evaluated how climate variation affects soybean yield, highlighting that water deficiency significantly affected soybean

growth and development, affecting yield. Similarly, when studying soybean crops grown under heat and water stress, Ergo et al. (2018) concluded that water deficit reduced soybean yield and its components (grain number and weight).

Figure 2 – Frequency distribution of soybean grain yield for Soil type 1 conditions with minimum, maximum, median, and percentile values for different sowing dates under rainfed conditions



Legend: A= Baixa Grande do Ribeiro, B= Bom Jesus, C= Currais, D= Monte Alegre do Piauí, E= Palmeira do Piauí, F= Ribeiro Gonçalves, G= Santa Filomena, and H= Uruçuí.

Source: Authors (2023)

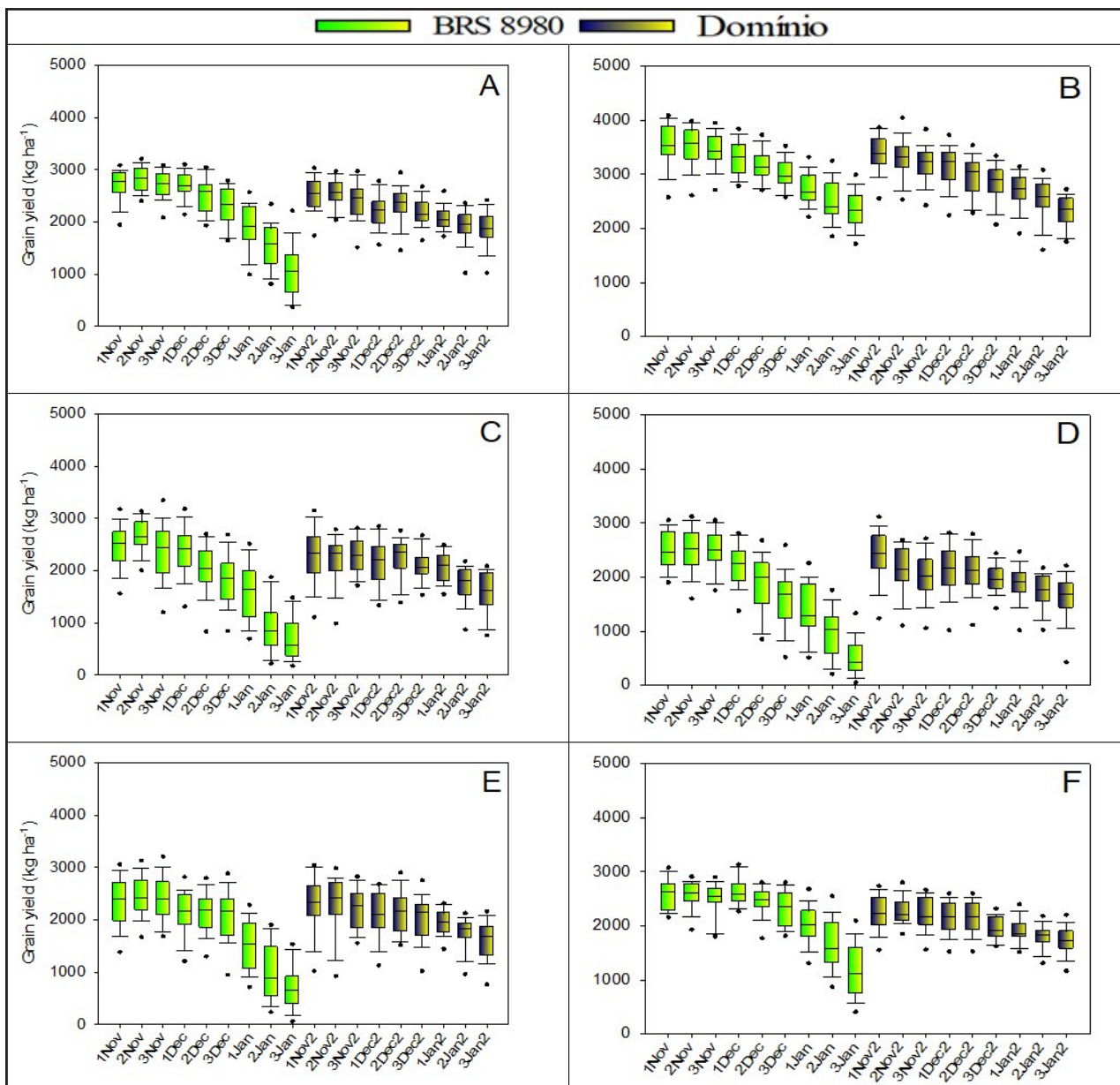
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It is worth noting that the sowing dates assessed comprise the region's rainy season, and the variability observed in yields is due to droughts in a given year or the poor distribution of rainfall throughout the crop cycle. It can be seen that the variability between the sowing dates is very considerable, showing the predominance of the influence of rainfall on soybean grain yield to the detriment of other factors, considering that this is Soil type 1 with less water availability for the crop.

Figure 3 shows the frequency distributions of simulated soybean yields, considering Soil type 2 conditions, over 30 years for different sowing dates in rainfed management in the eight municipalities evaluated. As for Soil type 1, soybean yields ranged considerably lower than Soil type 2 conditions in all the municipalities evaluated. The average yield values for the BRS 8980 cultivar ranged from 57.00 to 4,102.00 kg ha⁻¹, while for the Dominio cultivar, they varied from 366.00 to 4,184.00 kg ha⁻¹. The municipality of Bom Jesus had the highest grain yields for both cultivars (Figure 3B), while the municipality of Monte Alegre had the lowest (Figure 3D).

Except for the municipality of Bom Jesus, where yield for the two cultivars showed slight variation, all the other municipalities showed similar levels of yield and variability (Figure 3), considering the soil conditions and the type of growth of the cultivars used in the simulations. However, the results make it clear that weather conditions within the same municipality have significantly impacted soybean yields since they are affected by the same meteorological phenomena.

Figure 3 – Frequency distribution of soybean grain yield for Soil type 2 conditions with minimum, maximum, median, and percentile values for different sowing dates under rainfed conditions



Legend: A= Baixa Grande do Ribeiro, B= Bom Jesus, C= Currais, D= Monte Alegre do Piauí, E= Palmeira do Piauí, F= Ribeiro Gonçalves, G= Santa Filomena, and H= Uruçuí.
 Source: Authors (2025)

Considering the characteristics of the inputs used in the simulations and the use of the maturity group of cultivars adapted to various Brazilian regions, Battisti & Sentelhas (2019), when characterizing Brazil’s soybean-producing regions by water deficit

patterns, also identified that regions with similar characteristics showed great variability in soybean yield within the same state, as a result of the climatic conditions observed. In the same vein, Eulenstein et al. (2017), estimating soybean yield trends in climate change scenarios through simulations with the CROPGRO-Soybean model, concluded that the impact of climate scenarios on soybean grain yield was directly influenced by location.

It can also be seen that sowings made in November showed higher grain yields and stability for the two cultivars analyzed (Figure 3). This justifies the recommended period for sowing soybeans in the Southwest region of Piauí, which has a climate Aw-type, tropical savannah classification, according to the Köppen system. The average annual rainfall in the region is between 700 and 1,200 mm, and the rainy season is from November to May, according to Andrade Júnior et al. (2005).

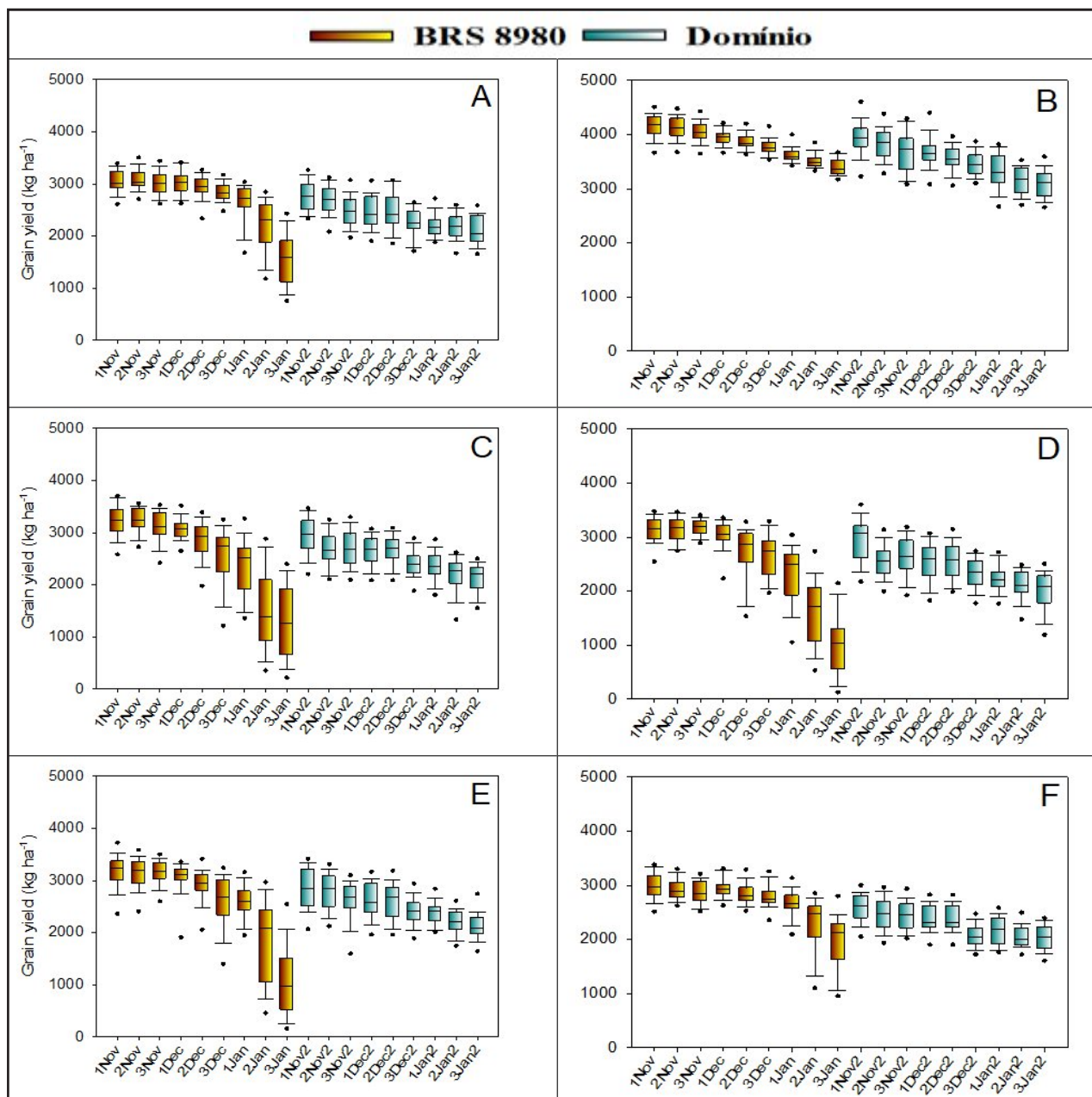
On the other hand, sowing in January showed a considerable decrease in grain yield, possibly due to lower rainfall at the end of the rainy season. Although the region has a well-defined rainy season, there is a great deal of variability in the rainfall distribution during the soybean growing season, generating droughts that can damage grain yields.

The data evidence that soybean yield in Soil 3 had less variation between sowing dates in all the municipalities evaluated due to the soil's higher available water capacity (Figure 4). In this sense, the variations in risk concerning sowing dates were significantly reduced compared to the results observed in Soils 1 and 2. It was found that there were higher variations in the BRS 8980 cultivar only in sowings carried out in the second and third 10-day periods of January, while for the Dominio cultivar, these variations only occurred in Currais, Monte Alegre, and Palmeira do Piauí but to a lesser extent.

The results of the simulations showed that Bom Jesus, PI, in Soil type 3, had the highest soybean yields for the two cultivars on all sowing dates. Considering all the sowing dates for this municipality, the grain yield ranged from 3,153.00 kg ha⁻¹ (third 10-day period of January) to 4,554.00 kg ha⁻¹ (first 10-day period of November) for the cultivar with determinate growth habit and from 2,573.00 kg ha⁻¹ (first 10-day period of January) to 4,944.00 kg ha⁻¹ (first 10-day period of November) for the cultivar with indeterminate

growth habit. It is important to note that even in the simulations carried out later, the grain yield in Bom Jesus was higher than in the other municipalities evaluated.

Figure 4 – Frequency distribution of soybean grain yield for Soil 3 conditions with minimum, maximum, median, and percentile values for different sowing dates under rainfed conditions



Legend: A= Baixa Grande do Ribeiro, B= Bom Jesus, C= Currais, D= Monte Alegre do Piauí, E= Palmeira do Piauí, F= Ribeiro Gonçalves, G= Santa Filomena, and H= Uruçuí.

Source: Authors (2023)

In fact, according to Battisti et al. (2018a), there is great variability in soybean yields between Brazilian farms, even in the same region, as observed by these authors in a study estimating the difference in soybean yields between 200 farms in Brazil. Therefore, the results obtained in this study are relevant for improving cultivation techniques and increasing soybean yield in the region.

A possible explanation for the small difference in grain yield between the sowing dates for this type of soil is the greater capacity of water available, which increased water availability to the plants, especially when there was insufficient rainfall. Alves et al. (2021), evaluating the growth and yield of a new soybean variety subjected to different soil water deficiency conditions, concluded that the treatments with the least water restriction were responsible for the greatest plant growth and yield.

Figure 4 shows greater asymmetry at the bottom. Discrepant data was found, especially for the BRS 8980 cultivar, with lower soybean yield values. It is important to note that climatic variations significantly impact yield and can either increase or decrease it. For example, we can mention the adjacent towns of Bom Jesus (Figure 4B) and Currais (Figure 4C), which show quite different levels of variability. This phenomenon can be attributed to the amount and distribution of rainfall in each location.

For all the municipalities evaluated, considering the three types of soil, sowings made in November and December resulted in higher yields. On the other hand, the last 10-day period of January showed significant yield losses in all the municipalities and years analyzed.

Therefore, the different ways the cultivars grow resulted in different yield levels in the three types of soil simulated in all the municipalities surveyed. It was observed that the Dominio cultivar (indeterminate growth habit) had the highest yields, which can be explained by its longer pod issuing time. This cultivar has a distinctive characteristic; until flowering begins, only about half the plants' final height is reached. Therefore, after this stage, the plant continues to grow significantly, with the production of nodes on the main stem, which makes it possible to double its height until maturity (Embrapa, 2021).

The simulation of the cycle of the BRS 8980 cultivar revealed a similar pattern of shortening of the soybean cycle in all the municipalities evaluated (Table 2), although there were slight differences between the municipalities. Sowings made in the first 10-day period of November were found to have longer cycles, while later sowings resulted in shorter cycles.

Table 2 – Cycle length of the BRS 8980 soybean cultivar, simulated according to sowing dates, in the Piauí municipalities of Baixa Grande do Ribeiro, Bom Jesus, Currais, Monte Alegre do Piauí, Palmeira do Piauí, Ribeiro Gonçalves, Santa Filomena, and Uruçuí

Municipality	Soil type	Sowing – 10-day period								
		November			December			January		
		1°	2°	3°	1°	2°	3°	1°	2°	3°
Duration of the Soybean Cycle (days)										
Baixa Grande do Ribeiro	S1	152	150	148	145	141	137	134	130	127
	S2	151	149	146	144	140	136	133	130	125
	S3	150	148	146	144	141	138	136	131	126
Bom Jesus	S1	154	153	150	146	142	140	136	133	131
	S2	151	149	147	144	141	138	134	131	128
	S3	150	149	147	143	140	138	135	132	129
Currais	S1	158	155	151	149	145	140	138	133	133
	S2	156	153	150	148	142	139	136	131	129
	S3	155	152	150	147	143	140	138	131	128
Monte Alegre do Piauí	S1	154	152	148	146	140	137	134	130	127
	S2	152	149	147	144	138	135	132	127	123
	S3	150	149	147	144	139	136	133	128	123
Palmeira do Piauí	S1	157	155	152	149	145	141	138	135	132
	S2	153	152	150	147	143	140	135	132	128
	S3	153	152	150	147	143	140	137	133	126
Ribeiro Gonçalves	S1	150	148	146	144	140	137	133	129	126
	S2	148	146	144	142	139	136	133	128	125
	S3	147	146	144	142	139	137	134	130	127
Santa Filomena	S1	151	148	146	143	139	135	132	128	124
	S2	149	147	144	142	138	135	133	126	123
	S3	148	147	143	142	138	136	133	128	124
Uruçuí	S1	152	150	148	145	141	137	135	130	130
	S2	149	147	146	144	139	137	134	129	125
	S3	149	146	145	143	140	137	134	130	127

Legend: S1= Soil type 1 (0,40 mm cm⁻¹ of AW), S2= Soil type 2 (0,66 mm cm⁻¹ of AW), and S3= Soil type 3 (1,21 mm cm⁻¹ of AW)

Source: Authors (2023)

On average, the cycle was reduced by 16.4% across all municipalities. For example, in Currais, sowing in the first 10-day period of November resulted in a cycle of 158 days, while in Santa Filomena, sowing in the third 10-day period of January resulted in a cycle of 123 days. In addition, it was observed that the soil type also influenced the cycle length, with longer cycles in Soil type 1 compared to Soil types 2 and 3 in most sowing 10-day periods and very close cycles when comparing Soil types 2 and 3 (as shown in Table 2).

It is important to note that environmental factors directly impact plant growth and can vary in different ways throughout the crop development phases. In this sense, Souza et al. (2018) emphasize that the decrease in soybean yield in late sowings can be attributed to the lower availability of natural resources, such as water and nutrients, during crucial periods for plant development. Hence, It is essential to understand the interaction between climatic elements and agriculture to maximize production and minimize risks.

The simulation of the cycle length for the Dominio cultivar also showed the effects of sowing date and soil type on the soybean cycle in all the municipalities evaluated and the differences among the municipalities themselves (Table 3). Like the BRS 8980 cultivar, the Dominio cultivar had longer cycles when sowings were made in the first 10-day period of November, with the cycle shortening as sowings were delayed, resulting in shorter cycles when sowings were made later. However, the longest and shortest cycles of the Dominio cultivar were considerably shorter than those of the cultivar with determinate growth habit (BRS 8980).

The longest cycle for the Dominio cultivar was observed in Currais, where sowing in the first 10-day period of November lasted 133 days, while in Monte Alegre and Santa Filomena, sowing in the third 10-day period of January resulted in a cycle of 110 days.

The cultivar with determinate growth habit had a longer cycle, resulting in a longer period to reach physiological maturity. However, when they were sown at the end of the region sowing window, both cultivars had their cycles shortened. This trend was observed in all the soil scenarios evaluated, and the municipalities analyzed. This information is relevant for producers, as it can help them make decisions, especially when planning

two crops in the same agricultural year (off-season). In addition, this data can also help agencies responsible for planning and financing formulate new public policies to promote the sustainability of soybean cultivation in the Cerrado of southwest Piauí.

Table 3 – Cycle length of the Dominio soybean cultivar, simulated according to sowing dates, in the Piauí municipalities of Baixa Grande do Ribeiro, Bom Jesus, Currais, Monte Alegre do Piauí, Palmeira do Piauí, Ribeiro Gonçalves, Santa Filomena, and Uruçuí

Municipality	Soil type	Sowing - 10-day period								
		November			December			January		
		1°	2°	3°	1°	2°	3°	1°	2°	3°
		Duration of the Soybean Cycle (days)								
Baixa Grande do Ribeiro	S1	130	128	126	125	124	120	118	114	111
	S2	129	127	126	124	124	120	119	114	113
	S3	128	127	125	125	124	120	119	116	114
Bom Jesus	S1	131	130	127	124	122	121	118	115	112
	S2	129	128	126	124	121	120	117	114	112
	S3	129	128	126	124	122	120	117	115	113
Currais	S1	133	130	129	127	128	121	119	115	113
	S2	131	129	128	126	126	121	119	115	112
	S3	132	129	128	127	127	123	120	116	114
Monte Alegre do Piauí	S1	130	129	127	126	125	119	117	113	110
	S2	129	128	125	124	124	119	117	112	110
	S3	130	128	126	125	124	119	118	114	111
Palmeira do Piauí	S1	132	130	127	127	127	122	119	116	113
	S2	130	129	126	126	126	122	119	115	113
	S3	131	129	127	126	126	122	120	117	115
Ribeiro Gonçalves	S1	128	125	124	124	124	119	117	115	111
	S2	126	124	123	123	123	119	117	115	111
	S3	126	124	123	123	123	119	117	116	113
Santa Filomena	S1	128	126	124	124	121	118	117	113	110
	S2	128	126	124	123	120	118	117	113	111
	S3	128	126	124	123	121	119	117	114	112
Uruçuí	S1	129	127	126	125	124	120	118	114	112
	S2	128	126	124	124	123	119	118	115	111
	S3	127	126	125	124	123	119	118	116	113

Legend: S1= Soil type 1 (0,40 mm cm⁻¹ of AW), S2= Soil type 2 (0,66 mm cm⁻¹ of AW), and S3= Soil type 3 (1,21 mm cm⁻¹ of AW).

Source: Authors (2023)

The relationships between climatic elements and agricultural production are quite complex, with a direct effect of environmental factors on the growth and development of plants in different ways and at different stages of the crop (Souza et al., 2018). In this way, the reduction in yield observed in late sowings may be a consequence of the shortening of the cultivar cycle, negatively impacting grain yield. These results corroborate those obtained by Battisti et al. (2018b), who stated that the longer cycles resulted in higher yields than the shorter cycles in all the climate scenarios studied. These conclusions were reached when evaluating crop management strategies aimed at improving the resilience of soybeans to climate change in the southern region of Brazil.

The consistency of the variability of observed soybean yields concerning the simulated yields was assessed by comparing the simulated yields for the municipality of Bom Jesus with the yields observed on a commercial soybean farm located in the Serra do Quilombo, in the same municipality. There was a moderate correspondence between measured and simulated soybean yields when considering Soil Types 1 and 2 (Figure 5). It should be noted that the lowest yields were associated with Soil Type 1, while the highest yields were related to Soil Type 2.

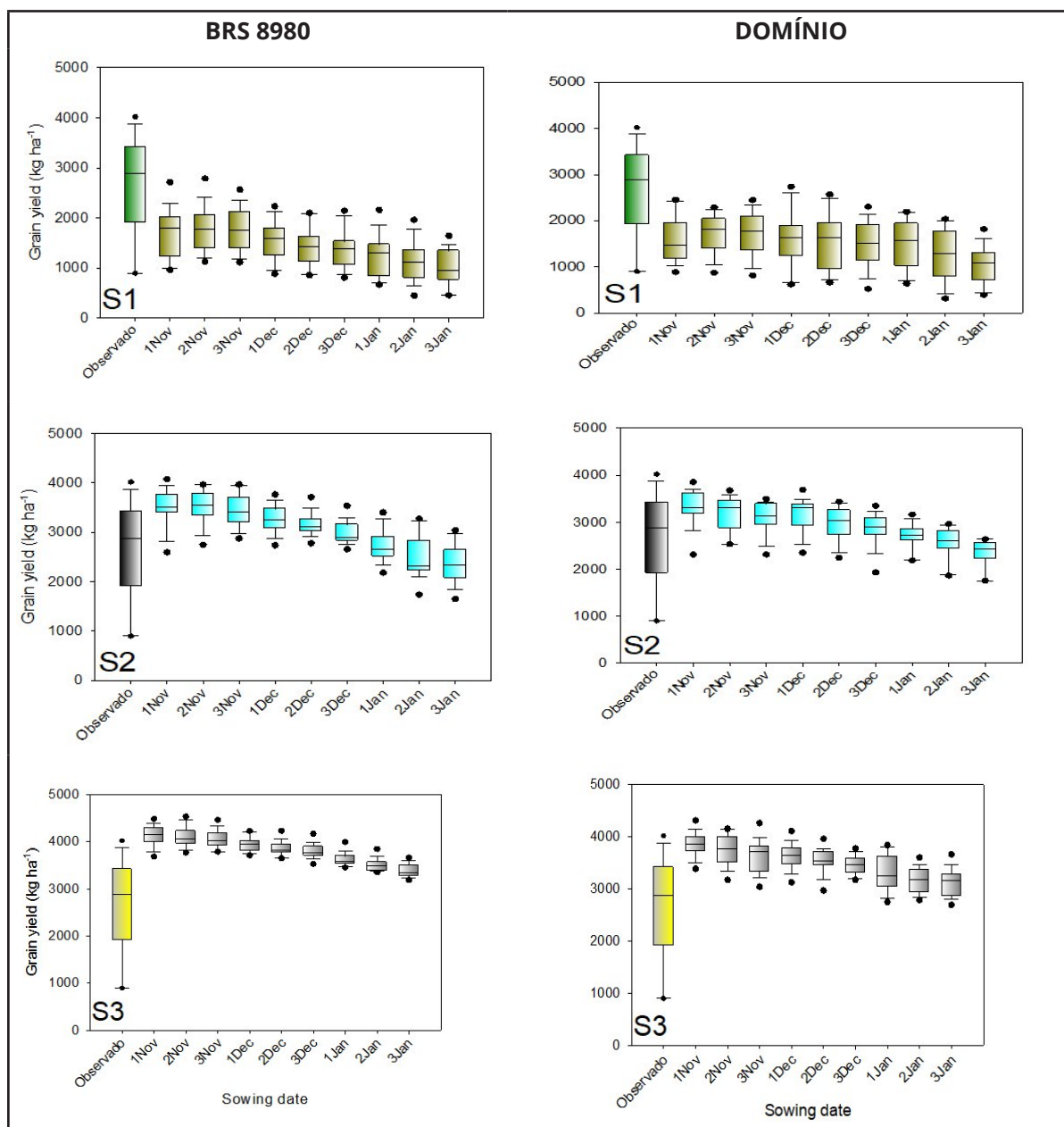
This result is evidenced by the physical characteristics of Cerrado soils, which have a high depth and porosity, allowing for a high water infiltration capacity. However, despite this high infiltration rate, there is limited water storage capacity, as reported by Sena et al. (2021).

Based on the soybean yields (average) obtained over seventeen years for the municipality of Bom Jesus - PI (Figure 5), it was observed that in the Soil Type 3, the simulated yield values were overestimated with the observed values, especially when sowing in November and December.

Furthermore, there was less variability in the simulated yield values for this type of soil, which can undoubtedly be attributed to the greater water availability. A study by Melo et al. (2020), which dealt with climate risk zoning for soybean cultivation in

the Cerrado, confirmed this relationship by concluding that soils with a higher water retention capacity are less likely to suffer from water deficit. This capacity guarantees an adequate water supply for the crop over a prolonged period.

Figure 5 – Frequency distribution of the average soybean yield observed by the producer in Serra do Quilombo and the simulated average soybean yield for the municipality of Bom Jesus, PI, during 17 crop seasons



Legend: S1= Soil type 1 (0.40 mm cm⁻¹ of AW), S2= Soil type 2 (0.66 mm cm⁻¹ of AW), and S3= Soil type 3 (1.21 mm cm⁻¹ of AW). Rendimento observado: e Rendimento simulado:

Source: Authors (2023)

Similarly, Santos et al. (2021), when estimating the potential yield (PoY) and attainable yield (AtY) using a crop growth model calibrated for high soybean productivity levels under the conditions of the Cerrado biome in central Brazil, concluded that the simulations indicated that water deficit significantly reduces yield at different levels.

The highest soybean yield measured by the farm in the seventeen years evaluated was in the 2018 crop season at 4,020.00 kg ha⁻¹, and the lowest was observed in the 2016 crop season at 895.2 kg ha⁻¹. This difference meant that the variability between the measured yields was much greater than the simulated variability over this period. However, for Soil Types 1 and 2, the simulated yield values for both cultivars were within this range of values measured on the farm, corroborating the results presented in this study.

In general, it was found that the model used could consistently capture the soybean yield compared to the measurements taken by the producer. This result was especially notable for Soil Type 2, which has similarities with the soil on the commercial soybean farm used in the evaluation, classified as AD3 according to SPA/ MAPA Normative Instruction No. 1 of June 21, 2022 (MAPA, 2022). Therefore, despite the general consistency of the model used in this study, it is important to consider differences and peculiarities between the specific growing conditions, which can lead to discrepancies in the results obtained, as was observed in Soil Type 3.

There is a need to develop alternative methods to monitor the considerable increase in soybean yields in the Cerrado region of southwest Piauí and possible reductions in yield due to climatic fluctuations. For example, the adoption of soybean cultivars with greater drought tolerance in regions with more pronounced water deficits, as recommended by Battisti & Sentelhas (2015) in a study evaluating this trait in Brazilian cultivars, conducted through simulation using a simple agrometeorological model.

In this context, agroclimatic modeling emerges as the most promising alternative since it is a tool capable of generating assumptions and providing information on the influence of climatic variations on crops over the years. The results presented here

demonstrate the potential of this tool since simulating soybean yields at different sowing dates enabled an assessment of yield variability in a wide range of scenarios.

Considering the above, availability and adequate distribution of water throughout the crop cycle are crucial factors for determining the best sowing dates to raised crops. According to Nória Júnior & Sentelhas (2019), both early and late sowing of soybeans results in yield losses. By analyzing the best sowing dates for soybean-corn succession in various producing regions of Brazil, these researchers concluded that the sowing date can vary according to the region.

Using the simulation model to evaluate soybean yields in rainfed cultivation made it possible to identify the most favorable sowing dates for each municipality and estimate the crop yield. These results suggest that the best sowing date for the region may vary according to the level of risk that the producer is willing to take, especially when considering the possibility of cultivating crops in the second-crop season in a given crop season. This approach allows for a more precise analysis of the best sowing dates, taking into account the specific characteristics of each municipality and the variability of crop yields.

4 CONCLUSIONS

Sowings made in the first 10-day period of November had longer cycles, while later sowings resulted in shorter cycles. This difference in duration was 16.4% for the BRS 8980 cultivar and 13.1% for the Dominio cultivar.

There was a discrepancy between the variability of soybean yields estimated by the simulation model and the data collected by a farmer in Bom Jesus - PI. However, the observed values were similar to the simulated values when considering Soil Types 1 and 2.

The DSSAT CSM-CROPGRO-Soybean simulation model is a suitable tool to help decide soybean cultivation in the Cerrado region of southwest Piauí.

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