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Sensitivity of CSM-CERES-Maize model to soil available water and impact on rainfed maize grown in the Brazilian Cerrado

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***ABSTRACT.** The response of maize to variations in soil available water (AW) is a function of the interactions among plant, soil and weather conditions. We studied the sensitivity of a previously calibrated CSM-CERES-Maize model and the response of rainfed maize grain yield to soil AW. The study was conducted for conditions in southeast Brazil. The model was set for weekly sowings, from August to September, for a total of 52 sowing dates. At each sowing date, six scenarios of soil AW using field capacity estimated at -4 kPa, -6 kPa, -10 kPa, -20 kPa, -33 kPa and determined in situ, were used. For each sowing date, the model was also set for rainfall reductions of 10%, 20%, 30%, 40% and 50%. The simulated results showed the sensitivity of the model to soil AW, which in turn affected grain yield of maize among sowing dates. For the highest yielding sowing date, a reduction of 48.3% in average grain yield was simulated with soil AW using FC at -4 kPa and FC at -33 kPa. Additionally, our simulations indicated significant correlation between grain yield and total crop evapotranspiration and between grain yield and maximum leaf area index. Scenarios of low rainfall had little effect on yield with high soil AW. Therefore, our simulations indicate that accurate information on FC is needed for the simulation of maize grown under rainfed conditions. Our simulations also indicate that the best sowing window for maize in southeastern Brazil ranges from Oct 17 to Nov 28.*

***Keywords.** Corn, Available Water, Crop yield, Modeling, Zea mays L.*

INTRODUCTION

Maize (*Zea mays* L.) stands out in Brazilian agriculture. In 2017, maize was planted in 17 million hectares during two cropping seasons. Currently, Brazil is the third largest maize producer in the world, with an estimated production of 97.7 million tons of grain. The state of Minas Gerais (MG) is one of the largest maize producer in the country, representing 19% of the volume produced nationally in the summer season (CONAB, 2017). Due to its economic importance worldwide, maize has been widely studied in Brazil and abroad. In rainfed maize production, soil-water availability is among one of the most important yield-limiting factors. According to Bergamaschi and Matzenauer (2014), maize is sensitive to water deficit, and is one of the most affected crops by rainfall intensity and distribution in Brazil.

Water is essential to plants (Reichardt and Timm, 2012), and its availability is driven by soil available water (AW). The soil AW is the difference between field capacity (FC) and permanent wilting point (PWP). The latter refers to the water held in the soil at -1,500 kPa (Brady and Weil, 2008; Reichardt and Timm, 2012), while the former is usually the water held at -33 kPa, but it is dependent on multiple factors, such as soil texture and structure; therefore, limitations on its accurate determination are evident.

In field experiments, many variables interact and cannot be controlled, making difficult to isolate their effects on crops growth. In addition, field experiments require availability of time and resources (Anothai et al., 2013). Modeling can help lessening these issues. The Decision Support System for Agrotechnology Transfer (DSSAT) (Jones et al., 2003) is a suite of programs, including crop models, that facilitate simulating the dynamics of water and nutrients in the soil, as well as the simulation of different crop management scenarios. The CSM-CERES-Maize model (Jones and Kiniry, 1986) of DSSAT has been used worldwide to assist research and the decision making of maize producers (Pereira et al., 2010). This is attributed, in part, to its detailed simulation of growth and development of the maize plant. In addition, the CSM-CERES-Maize model uses the concept of genotype-specific coefficients, allowing for the quantitative differentiation between cultivars. The objectives of this study were to evaluate the sensitivity of CSM-CERES-Maize model simulations to changes in soil available water and its impact on rainfed maize grown in the Brazilian Cerrado.

METHODS

The study was conducted for conditions of the Brazilian Cerrado biome, represented by the county of Sete Lagoas, Brazil (19° 30' S, 44° 12' W and elevation of 739 m). The DKB390PRO transgenic single hybrid maize genotype was used to simulate maize growth under no-tillage. The process of adjusting the genotype-specific coefficients was previously performed using data from trials conducted under optimum conditions of growth at two locations: Sete Lagoas and the Embrapa´s maize breeding program experimental network in Minas Gerais, Brazil (Andrade et al., 2016).

Data Collection

Soil data

The soil data representing the location of the study was characterized as a typical Cerrado biome Ferralsol. Undisturbed samples were collected at Embrapa Maize and Sorghum (19° 29' S 44° 10' W) at 0-0.05, 0.05-0.1, 0.1-0.3, 0.3-0.5, 0.5-0.7, 0.7-0.9 and 0.9-1.1 m; each layer corresponded to a composite sample of nine sub-samples. Then, a soil file was created using SBuild, a DSSAT tool to facilitate the manipulation of soil profile information and its preparation in a specific format (Table 1).

The field capacity (FC; Table 1) was determined at field according to Embrapa (1979). A 9 m^2 basin was built and covered with plastic to avoid loss of water via evaporation. The delimited area was previously saturated up to 1.20 m depth. Soil potential and soil water content were monitored daily at depths of 0.05, 0.1, 0.3, 0.5, 0.7, 0.9 and 1.1 m by using tensiometers for the former and the gravimetric method and a neutron probe for the latter. We considered that the soil water content reached FC when the water flux at the bottom of the rooting zone layer was lower than the daily reference evapotranspiration for dry season. In addition, undisturbed soil samples were taken to the laboratory to determine the soil water retention curve (SWRC), using a tension table for matric potentials at -6 and -10 kPa, and the Richard's chamber for potentials at -30, -100, -500 and -1,500 kPa. The root growth factor was determined following a qualitative evaluation of the root system distribution in the experimental field. Other soil data were obtained according to the Soil Analysis Methods Handbook (Embrapa, 2017). We adjusted the Van Genuchten model (1980) with Mualem restriction [$m = 1 - (1 / n)$] to SWRC data, using the RetC software (Van Genuchten et al., 1991) according to Equation 1:

Table 1. Soil characteristics required by the model.

Depth	Wilting point	Field capacity	Saturation	Root growth factor	Bulk density	Organic carbon	Clay	Silt	Nitrogen	pH-H_2O
(m)	(m^3 m^{-3})	(m^3 m^{-3})	(m^3 m^{-3})		(Mg m^{-3})	(%)	(%)	(%)	(%)	
0-0.05	0.311	0.378	0.568	0.9	1.05	2.01	63	19	0.12	6.07
0.05-0.1	0.309	0.366	0.577	1.0	1.02	2.01	63	22	0.12	6.03
0.1-0.3	0.306	0.374	0.561	1.0	1.07	1.87	68	20	0.10	5.93
0.3-0.5	0.292	0.362	0.599	0.6	0.96	1.60	71	13	0.08	5.40
0.5-0.7	0.260	0.352	0.611	0.3	0.93	1.50	72	13	0.06	5.03
0.7-0.9	0.246	0.340	0.627	0.1	0.89	1.37	79	7	0.06	5.03
0.9-1.1	0.233	0.329	0.631	0.1	0.87	1.26	73	13	0.05	5.07

$$\theta = \theta_r + \frac{\theta_s - \theta_r}{[1 + (\alpha|\Psi m|)^n]^m} \qquad (1)$$

where θ = water content (m^3 m^{-3}); θ_r = residual water content (m^3 m^{-3}); θ_s = saturated water content (m^3 m^{-3}); Ψ = soil water potential (cm); α = empirical parameter (cm^{-1}); m, n = empirical parameters. For each depth, the parameters m, n, α, θ_s and θ_r were obtained, and the coefficient of determination (R^2) of the model adjustment was obtained (Table 2).

Table 2. Parameters of the Van Genuchten model and R^2 of the model adjustment, for each soil layer.

Depth (m)	m	n	α	θ_s	θ_r	R^2
0-0.05	0.077	1.083	2.160	0.568	0.125	0.994
0.05-0.1	0.167	1.200	0.405	0.577	0.252	0.991
0.1-0.3	0.128	1.146	0.901	0.561	0.222	0.995
0.3-0.5	0.150	1.176	0.736	0.599	0.218	0.995
0.5-0.7	0.147	1.172	5.335	0.611	0.201	0.998
0.7-0.9	0.226	1.293	1.110	0.627	0.223	0.998
0.9-1.1	0.311	1.451	0.247	0.631	0.223	0.998

Meteorological data

Daily minimum, maximum and average temperature, solar radiation and rainfall over a period of 33 years (1981-2013) were obtained from the Embrapa Maize and Sorghum Meteorological Station, in Sete Lagoas, MG, Brazil.

Simulated scenarios

The CSM-CERES-Maize model version 4.6.1.0 (Hoogenboom et al., 2015), was used to simulate rainfed maize growth and yield for conditions in Sete Lagoas, Brazil. We used the DSSAT seasonal analysis tool to evaluate the effects of meteorological conditions on maize yield during the 33-yr period. The model was set to run weekly sowing dates for rainfed maize; from August 1 to July 24, totaling 52 dates. Thus, for each week, 33 values of grain yield were generated and corrected to 13% grain moisture.

Five soil water content levels were used (eq. 1) to obtain FC (m^3 m^{-3}) at matric potentials equivalent to -4, -6, -10, -20 and -33 kPa. The soil available water (AW; mm m^{-1}) was calculated as the difference between FC and permanent wilting point (PWP; m^3 m^{-3}). The latter consisted to soil water content at -1,500 kPa (Table 1). The sixth criterion was the soil AW obtained from FC determined *in situ*, and the PWP was the same as in the other scenarios (Table 3).

In DSSAT, it is also possible to make modifications in the historical series of meteorological data. Thus, we set the model to change the rainfall data for daily reductions of 10%, 20%, 30%, 40% and 50%, as compared to the observed data. Then, the soil AW scenarios were used in all rainfall scenarios.

Table 3. Soil available water from soil water content at fixed PWP and different FC strategies.

Scenario	Soil AW (mm m^{-1})
FC at -4 kPa	120
FC at -6 kPa	105
FC at -10 kPa	89
FC at -20 kPa	70
FC at -33 kPa	58
FC *in situ*	65

For all simulated scenarios, we assumed a row spacing of 0.7 m, with a plant population of 68,000 per ha. We simulated the sowing depth at 0.06 m and 2,000 kg ha^{-1} of straw left on the soil surface by the previous crop, *Brachiaria spp*. The fertilization at sowing consisted of 40 kg ha^{-1} of nitrogen, in the form of urea; 140 kg ha^{-1} of P_2O_5, as single superphosphate and 80 kg ha^{-1} of K_2O as potassium chloride.

The average of the 33 years of simulated yield from each sowing date, was used. The sowing window was set to 10% maximum grain yield reduction taking as reference the date of the highest yield (Amaral et al., 2009), according to Equation 2:

$$Ps = \left(1-\frac{Ys}{Ymax}\right)*100 \quad (2)$$

where Ps = grain yield break (%) at sowing date “s”; Ys = grain yield (kg ha^{-1}) at sowing date “s”; Ymax = maximum grain yield (kg ha^{-1}) among all sowing dates.

The statistical analysis was performed with R software (R Core Team, 2015). Grain yield at each sowing date for 33 years was subjected to Lilliefors normality test, analysis of variance at 5% probability, and mean comparison using Scott-Knott test at 5%.

RESULTS AND DISCUSSION

Climate conditions

According to Köppen (1936), the climate of the region is classified as Cwa, with dry winters and average temperature of the coldest month below 19°C. The annual average temperature is 22.4°C and the thermal amplitude is 5.1°C. The average annual rainfall is 1,382 mm, with a well-defined rainy season, with maximum average value of 312 mm in December and minimum of 8 mm in July (Figure 1). The winter season (Jun-Aug) accounted for about 2% of the total annual rainfall, supporting results provided by Ferreira and Souza (2011), who described the climate of Sete Lagoas.

Effect of sowing date and soil available water on grain yield

The distribution of rainfall (Figure 1) was the driving factor of the high variation in the average grain yield among the sowing dates (Figure 2). For all scenarios of soil AW, the best sowing window was from Oct 17 to Nov 28, with the highest average yield obtained in October 31. The last sowing date coincides with the beginning of the rainy season in the county (Ferreira and Souza, 2011). The differences among the scenarios at each sowing date can be directly related to soil AW (Table 3). Our simulated results are supported by field research demonstrating that water availability is the most important factor affecting rainfed maize production in Brazil (Bergamaschi and Matzenauer, 2014).

The highest average yields obtained corresponded to 8,301, 8,009 and 7,496 kg ha^{-1}, for FC at -4 kPa, -6 kPa and -10 kPa, respectively. For FC at -20 kPa, -33 kPa and in situ, the highest average yields were, respectively, 6,541, 4,289 and 6,379 kg ha^{-1} (Figure 2). Thus, increases in soil AW led to substantial increase in crop yield, as long as there were favorable weather conditions.

Among the scenarios with the highest (FC at -4 kPa) and lowest soil AW (FC at -33 kPa), the reduction in maximum yield was 48%. Paixão et al. (2016), using a modeling approach to simulate rainfed maize yield in 20 counties in Minas Gerais, reported an average yield of 6,853 kg ha^{-1} for Sete Lagoas on a soil with high water retention capacity (clayed soil). For a soil with low retention capacity (sand soil), the same authors obtained an average yield of 3,408 kg ha^{-1}, which represented a reduction of 50% in crop yield.

The response of maize to soil AW on the highest yielding date was obtained using maize yield from the treatment based on *in situ* FC (Figure 3), an approach that has been proven useful in previous studies (Reichardt, 1996; Andrade et al., 1998; De Jong van Lier, 2000).

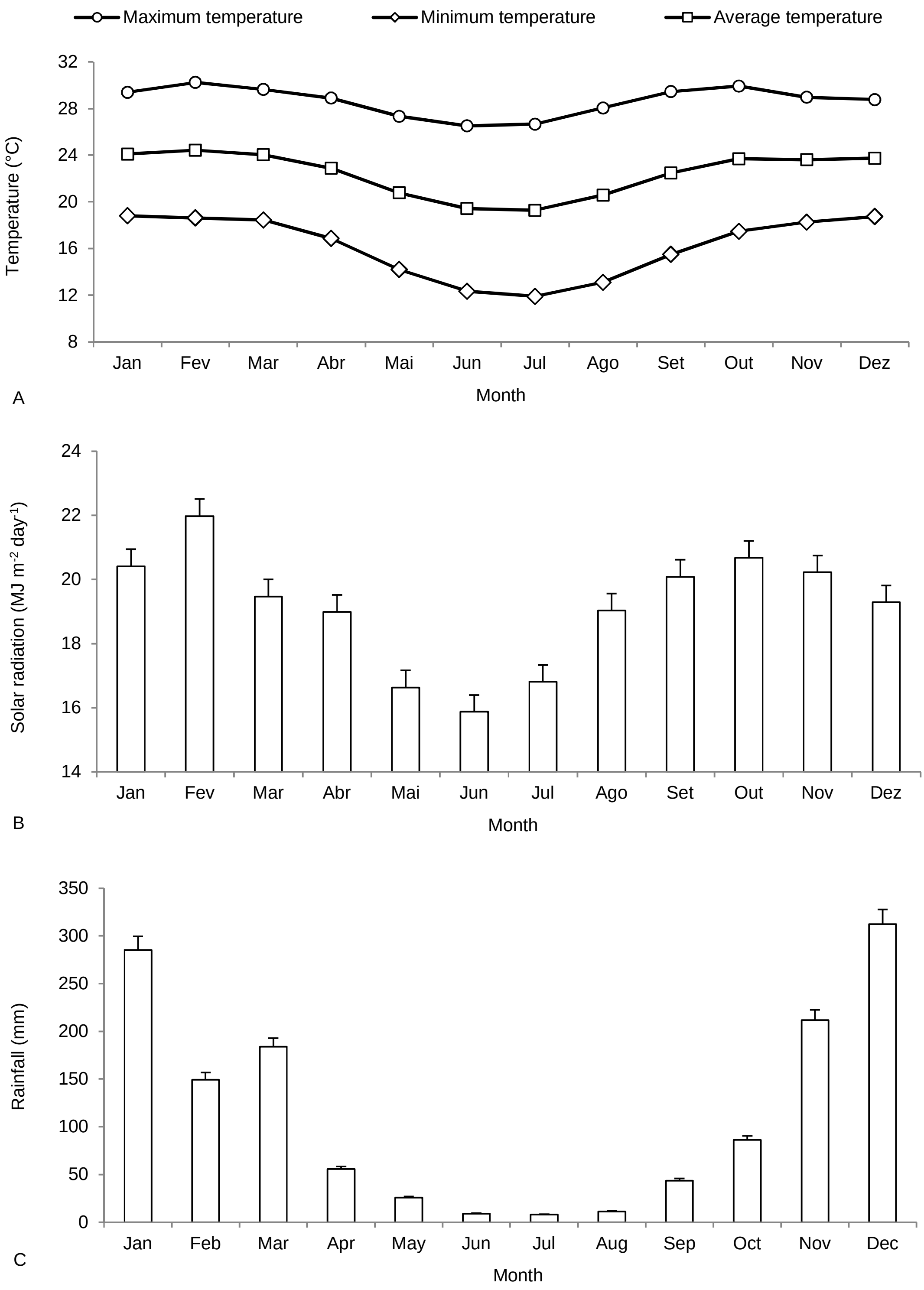

Figure 1. Monthly averages of air temperature (A), solar radiation (B) and rainfall (C).

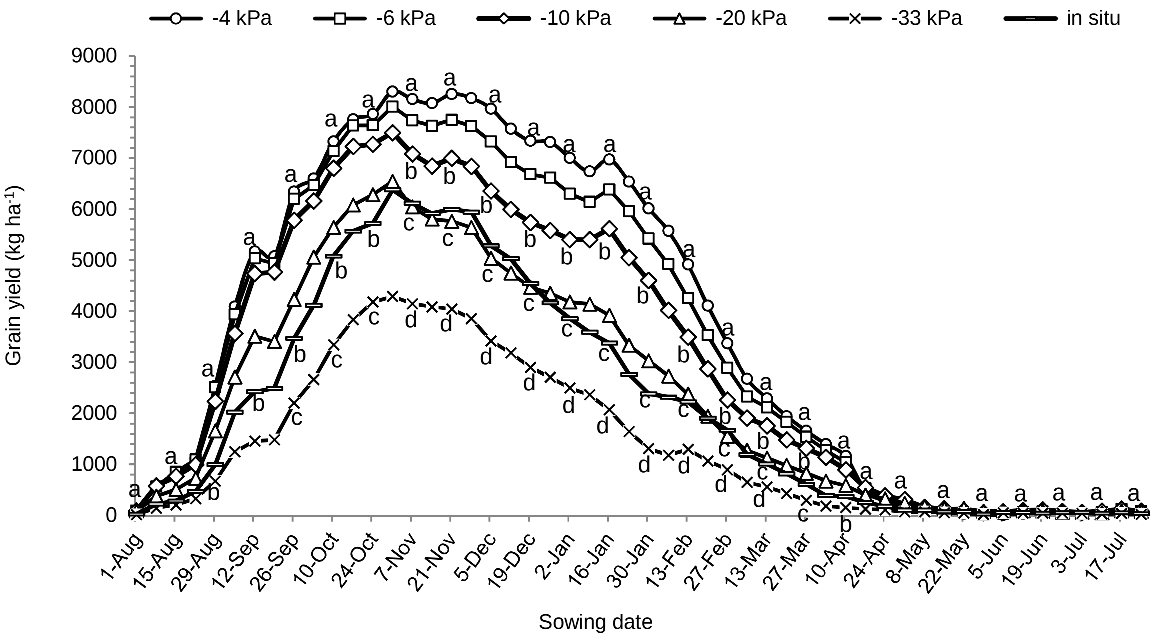

Figure 2. Average yield for different sowing dates and soil AW scenarios. At each date, same letters mean no-difference, at 5%.

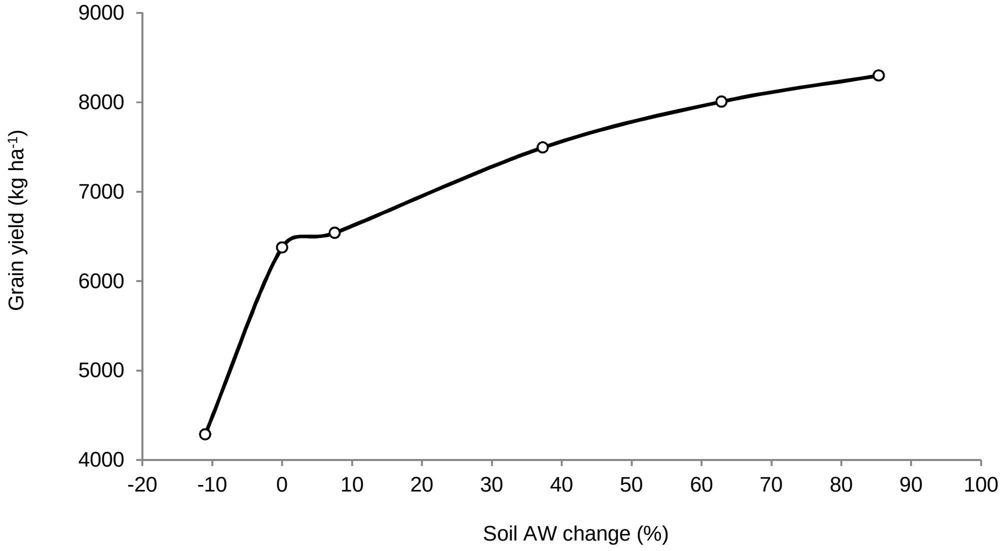

Figure 3. Average yield as a function of changes in soil AW.

A reduction of 11% in soil AW implied a break of 2,090 kg ha^{-1} in grain yield. On the other hand, for 85% increase in soil AW, the yield increased 1,922 kg ha^{-1} (Figure 3). Therefore, the sensitivity of maize to soil AW is much higher when the field capacity is underestimated as compared to *in situ* FC. Our results evidence the capacity of the model to properly simulate the sensitivity of the maize plant to soil available water. Our simulated results are supported by field research results reported by Bergamaschi et al. (2006). For scenarios of positive changes in soil AW, the grain yield of maize tended to increase at small rates, suggesting that genetic limitations of the maize plant response to changes in soil available water.

Effect of soil available water on sowing window

For all soil AW scenarios, decreases in yield were highly variable, even during the rainy season, but yield reductions were lower when maize was sowed from October 17 to November 28 (Figure 4).

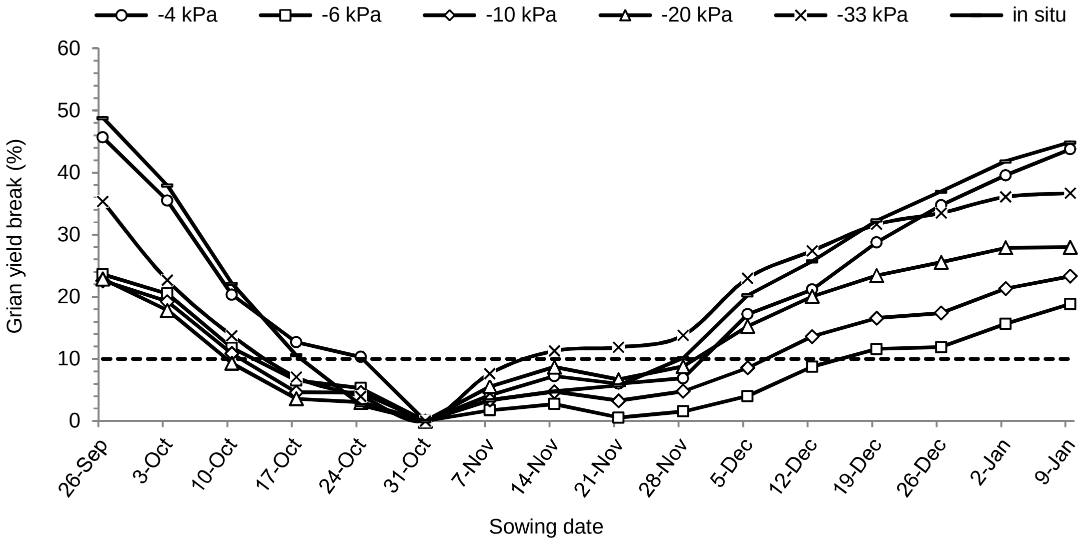

Figure 4. Average reduction on yield for different sowing dates of the rainy season, for each scenario of soil AW.

Accepting a maximum decrease of 10% on yield, we verified that the different soil AW shifted the sowing window, which also affected its duration. For FC at -4 kPa and *in situ*, the sowing window extended from October 24 to November 28, lasting 36 days. For FC at -6 kPa, the sowing window vary from October 17 to December 12, with duration of 57 days. For FC at -10 kPa and -20 kPa, the sowing window was from October 17 to December 5 and from October 10 to November 28, respectively, both lasting 50 days. Finally, for FC at -33 kPa, the sowing window extended from October 24 to November 28, lasting only 22 days (Figure 4).

Our simulated results are in agreement with those used in the Climate Risk Zoning (CRZ) of the Brazilian Ministry of Agriculture, Livestock and Supply, MAPA (Brasil, 2017), which reports that the local sowing window for DKB 390PRO in the last summer season (2017-18) extends from October 10 to December 31, totaling 83 days. Paixão et al. (2013), using a similar approach in the same region found that simulated sowing windows were also narrower than those proposed by the CRZ. However, the modeling approach has advantages over the CRZ of MAPA, since the user can establish its own admitted risk level and get an estimate of the expected yield (Amaral et al., 2014).

Effect of soil available water on crop physiology

Low soil-water availability implies stomatal closure and decreased leaf area, reducing photosynthesis and crop evapotranspiration, among other effects (Floss, 2011). In order to determine if the model was capable of simulating these effects, we performed a linear regression between grain yield and cumulative crop evapotranspiration and between grain yield and maximum leaf area index (LAI) for each treatment. All regressions between grain yield and cumulative crop evapotranspiration (Etc) were significant at 1% level. In contrast, the regressions for LAI were significant at 1% level for FC at -33 kPa and for FC determined *in situ*, while they were significant at 5% for FC at -6 kPa and at -10 kPa, and not significant for FC at -4 kPa and at -20 kPa ($p>0.05$). For all regressions, the Pearson coefficient of correlation (r) was positive, indicating that the yield increased with the increase of Etc and LAI. Strong associations ($0.7<|r|<0.9$) were observed between grain yield and crop evapotranspiration for FC at -10 kPa, at -20 kPa and FC*in situ*, and between yield and leaf area index for FC at -33 kPa, while the other associations were moderate ($0.5<|r|<0.7$) or negligible ($|r|<0.3$) (Table 4).

The relation between water stress and plant growth and development involves various physiological processes that are influenced by soil available water (Pegorare et al., 2009). The CSM-CERES-Maize model was able to simulate many of these processes and effects, suggesting that accurate estimations of field capacity are needed to ensure the proper performance of the model.

Maize response to soil available water

Maize grain yield decreases as rainfall decreased, for all soil AW scenarios. As an example, the response of maize to water (rainfall) is shown in Figure 5 for the highest yielding sowing date; this trend was similar for other sowing dates.

For the scenario of the highest soil AW (FC at -4 kPa), the reduction in grain yield was 24% as rainfall decreased 50%. On the other hand, for the scenario of the lowest soil AW (FC at -33 kPa), the reduction in grain yield for the same change in rainfall was as high as 72%. Assuming a grain yield break of 10%, maize production would be recommended up to 30% of decrease in rainfall for FC at -4 kPa (7.9% of yield break), up to 20% for FC at -6 kPa (8.5% of yield break) and without reduction in rainfall for FC at -10 kPa (10% of yield break). For the other soil AW scenarios, the grain yield break was higher than 10% in all conditions (Figure 5). In simulations with the CSM-CERES-Maize model under similar conditions in Brazilian Cerrado, Magalhães (2017) observed that a grain yield break greater than 10% was reached when decreases in rainfall were 25% or more. Therefore, management strategies should consider soil conservation measures, directed to increase soil available water.

Table 4. Linear regression and Pearson correlation coefficient between cumulative crop evapotranspiration along the cycle (mm) and yield (kg ha^{-1}) and between maximum leaf area index (m^2 m^{-2}) and yield (kg ha^{-1}) for each scenario of soil AW.

	-4 kPa	-6 kPa	-10 kPa	-20 kPa	-33 kPa	*in situ*
	y = grain yield, x = cumulative evapotranspiration					
a	0.0185	0.0206	0.0228	0.0217	0.0192	0.0243
b	426.23	401.78	374.43	365.90	363.85	349.21
r	0.64	0.69	0.72	0.70	0.69	0.84
p-value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
	y = grain yield, x = maximum leaf area index					
a	0.00003	0.00008	0.0001	0.0002	0.0005	0.0005
b	4.4838	4.076	3.492	2.570	0.0007	0.1579
r	0.25	0.39	0.43	0.34	0.76	0.69
p-value	0.158	0.023	0.012	0.054	<0.001	<0.001

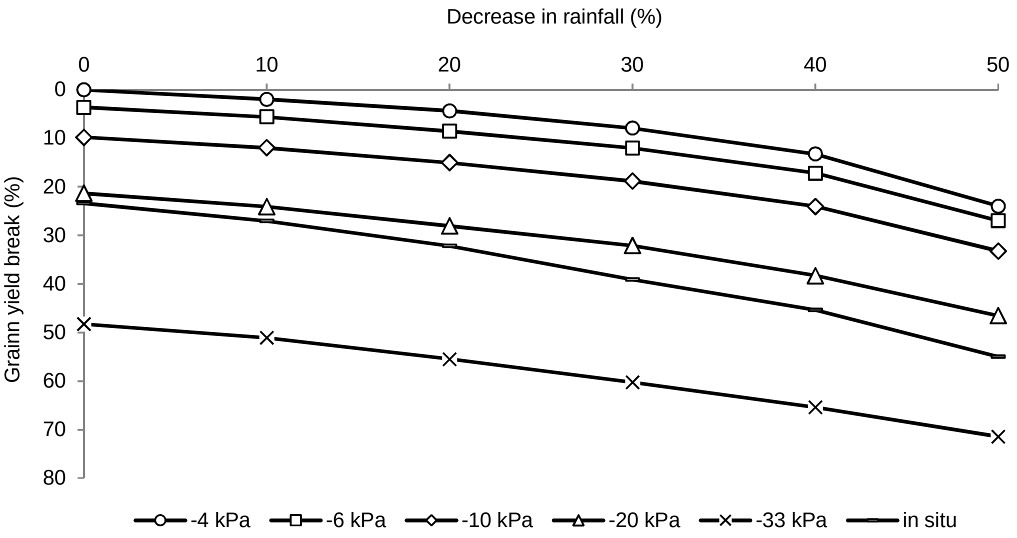

Figure 5. Grain yield break as a function of reductions in rainfall depths under six scenarios of soil AW.

CONCLUSIONS

The CSM-CERES-Maize model is sensitive to changes in soil available water, which in turn affects grain yield of rainfed maize grown in the Brazilian Cerrado.

Soil available water is the cause of high variation in the average grain yield of rainfed maize within sowing dates.

The model is capable to satisfactorily simulate the effects of water deficit on crop evapotranspiration and leaf area index.

For scenarios with greater soil AW, rainfall reductions seem to have little effect on grain yield break.

Our simulated results indicate the importance of detailed determination of the field capacity for the proper performance of the CSM-CERES-Maize model under rainfed conditions.

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