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AGROMETEOROLOGY - Article

Longer crop cycle lengths could offset the negative effects of climate change on Brazilian maize

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ABSTRACT: Maize (*Zea mays*) is considered one of the most important crops for world food security. Globally, Brazil is the second largest maize producer and the fourth largest maize consumer. The climate variables is one of the main determining factors for crop yield. Given the possibility of future climate changes, our objective was to evaluate the impact of climate change on maize crop growth and development, assessed strategies to cope with the future crop and to quantify the impacts on various producing regions of Brazil. The DSSAT/CERES-Maize model was calibrated with field data and then used to simulate current and six future climate scenarios, according to the AgMIP protocols. We selected three regional climate circulation models (GCMs) and two representative concentration pathways (RCPs) for the period of 2040-2069. For most of the producing regions, the simulations showed a decreasing trend during both the summer and autumn sowing seasons, except the autumn crops in Southern Brazil. We found the air temperature rise as the main factor for yield decreasing, and this finding provides an adaptation option to cope with future climate, as the country has a great latitudinal range for crop management, meaning genotypes with extended cycles could compensate the climate change, and thereby avoid the yield loss for maize crops.

Keywords: crop modelling, food security, adaptation, *Zea mays*.

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INTRODUCTION

Global climate variability and change caused by natural processes and anthropogenic factors may result in major environmental issues that will affect the world during the 21st century. In Brazil, observations show a tendency for an increase in the frequency of extreme rainfall events in Southern Brazil (Groisman et al. 2005), while projections show tendencies for increasing extremes in both maximum and minimum temperatures, and high spatial variability for rainfall (Marengo et al. 2009). Maize (*Zea mays*) is considered one of the most important crops for world food security due to its chemical composition, nutritional value and its productive potential (Kresovic et al. 2014).

Climate has a major impact on crop yield, so uncertainties about the future climate generate ambiguities regarding national and global food security, especially when dealing with commodity crops and the exporting countries (Li et al. 2011; Holzkamper et al. 2015), since climate change can cause production frustrations, local food limitations and price increases over time (Waongo et al, 2015). Future agricultural scenarios based on future climate would lend direction to how farming systems can adapt, which would involve aspects of soil fertility and management, genetics and agronomic practices (Tao et al. 2014; Ma et al. 2017).

Process-based crop models are well recognised by the scientific literature for testing academic hypotheses and assessing future scenarios and the impacts of climate change on agriculture (Rosenzweig et al. 2013). The DSSAT/CERES-Maize model simulates complex management strategies for a wide range of soil conditions and is capable of analysing the interactions of these strategies with the environmental conditions (Jones et al. 1986; Farhangfar et al. 2015). After calibrating the model, simulations were run to examine the impact of climate change on the maize crop in Brazil, identify the main reasons for yield variations and offer insights on how to adapt the crop to the future climate. Our objective here was to evaluate the impact of climate change on maize crop growth and development, assessed strategies to cope with the future crop and to quantify the impacts on various producing regions of Brazil.

MATERIAL AND METHODS

Experimental data

Two experiments, one in autumn and another in summer, were carried out in the experimental area of Luiz de Queiroz College of Agriculture, University of São Paulo (ESALQ/USP), Piracicaba (SP), Brazil (lat 22°42'30" S, long 47°38'30" W, and 546 m alt). The autumn crop was sown in May 2016, and the summer crop was sown in October 2016. Each plot comprised four rows of 20 m length, with 0.45 m interrow spacing. Among the most commercialised by the producers of the region, the maize hybrid P4285YH was selected, due to its high yield potential in the selected region. The soil was prepared conventionally, by plowing at a depth of 30 cm, followed by drilling and levelling.

Analyses of physical and chemical characterization were performed in both experimental areas. Mineral fertilisation at planting and cover crop was applied based on the soil analysis, to avoid any crop nutritional deficiency. In order to estimate the values of permanent wilting point, field capacity and soil saturation point were estimated by the water retention curve. Both experiments included two treatments (irrigated and rainfed), with four replicates.

Five plants were randomly selected from each plot, for recording biometric data on leaf area index, plant height (every 7 days throughout the crop cycle), and dry mass of the vegetative part (leaves + stem) and dry matter (leaves + stem + ear + tassel) every 21 days throughout the crop cycle. The plant height was measured with the aid of a measuring tape as the distance (m) from the ground level to the point of insertion of the flag leaf. The results were expressed as the average height of five plants per plot. At physiological maturity (three months after planting), the ears were manually harvested, threshed with the aid of a thresher and the grains were weighed. The grain yield data was calculated on a dry basis and expressed as $kg \cdot ha^{-1}$.

Model calibration

The DSSAT/CERES-Maize model is composed of six parameters related to genetic characteristics of the maize crop. The genetic coefficients P1, P2 and P5 define the phenology of the crop, while the G2 and G3 define the grain yield. To decide which parameters to estimate, a targeted sensitivity analysis was first performed on the DSSAT/CERES-Maize model, to determine the dependency of simulated variables on changes in key parameters. In addition, a major decision about what parameters to optimise was based on the available measured information, to avoid adjusting parameters that were unrelated to these data. Also, no adjustments were made to other parameters whose values could be directly measured or were well-known. The model was manually calibrated, by visual fitting, to reduce the root-mean-square error (RMSE) between simulated and observed values. Table 1 provides the statistical results of the model calibration.

The RMSE, the model efficiency index (EF) (Nash and Sutclife 1970) and the d-index (Willmot et al. 1982) were used to evaluate the model performance in the calibration procedure. They were used for evaluating all crop measured variables, except for plant height and above ground biomass in the first crop.

Spatial extrapolation

Given the DSSAT/CERES-Maize model operates on a local scale and the operation requires relatively large computational resources, the number of simulation points was limited by following the approach for upscaling modelling simulation, provided by Van Wart et al. (2013). For the selection simulation zones, the yield data obtained from the Brazilian Institute of Geography and Statistics (IBGE) were used. Then, 10 locations of Brazilian maize production with a 30-year daily weather series, whose homogeneous zones accounted for more than 80% of the maize cultivation area in Brazil.

Future climate scenarios

The global climate models (GCMs) used in this study were obtained from the Agricultural Model Intercomparison and Improvement Project (AgMIP) database. Of the 20 available GCMs, three were evaluated for variation of the air temperature relative to the baseline, taking as reference: 1) the model with the highest increase in relation to the average temperature of the baseline; 2) the model with the lowest increment; and 3) the intermediate model regarding the future temperature variation. For the simulations of the future scenario projections, the atmospheric carbon dioxide (CO_2) concentrations of 526 and 628 ppm, epitomising the representative concentration pathway (RCP) scenarios RCP 4.5 and RCP 8.5, respectively, were used, making a total of six future examined scenarios. The baseline of the simulations was a CO_2 around 373 ppm, representing the mean value of the climatic series. The weather future scenarios were created for each selected site in Brazil, in 10 simulation points spread throughout the country, to cover the locations of importance for national maize production (Table 2).

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Table 1. Statistical analysis of the DSSAT/CERES-Maize model for the autumn and summer experiment, irrigate and rainfed in Piracicaba-SP, Brazil.

	Variable analyzed	Average		BIAS	RMSE	MAE	d	EF
		Observed	Simulated					
	IRRIGATED							
Autumn Experiment	Leaf area index	1.49	1.83	0.339	0.700	0.528	0.90	0.68
	Plant height	0.81	1.08	0,274	0.397	0.275	0.90	0.61
	Vegetative mass	3,185	2,824	-361.4	776.8	554.8	0.98	0.95
	Biomass	4,130	2,902	-1,228.3	2,319.0	1,421.6	0.91	0.77
	RAINFED							
	Leaf area index	0.77	0.87	0.099	0.234	0.223	0.96	0.88
	Plant height	0.56	0.52	-0.044	0.148	0.123	0.97	0.89
	Vegetative mass	1,506	1,713	207.1	430.2	254.1	0.98	0.92
	Biomass	1,800	1,734	-66.6	206.0	149.9	0.99	0.99
	IRRIGATED							
Summer Experiment	Leaf area index	3.54	3.58	0.037	0.452	0.377	0.99	0.96
	Plant height	1.36	1.17	-0.184	0.230	0.413	0.89	0.71
	Vegetative mass	6,800	6,902	102.4	1,481.7	1,300.2	0.98	0.93
	Biomass	11,487	8,409	-3,077.7	3,854.2	3,077.7	0.96	0.87
	RAINFED							
	Leaf area index	3.03	3.26	0.233	0.644	0.515	0.98	0.93
	Plant height	1.34	1.14	-0.200	0.575	0.480	0.86	0.66
	Vegetative mass	6,937	6,839	-97.6	1,883.2	190.9	0.97	0.87
	Biomass	11,366	8,409	-2,956.8	3,585.7	2,956.8	0.96	0.88

Table 2. Global circulation models (GCM) selected for each weather station regarding the air temperature variation in relation to the baseline.

Weather Station	Level of deviation in relation of air temperature of baseline	Global circulation model
Diamantino-MT	Maximum	CanESM2
	Mean	BNU-ESM
	Minimum	inmcm4
Rondonópolis-MT	Maximum	CanESM2
	Mean	BNU-ESM
	Minimum	inmcm4
Corumbaíba-GO	Maximum	CanESM2
	Mean	BNU-ESM
	Minimum	MRI-CGCM3
Porangatu-GO	Maximum	CSIRO-Mk3-6-0
	Mean	BNU-ESM
	Minimum	inmcm4
Guarapuava-PR	Maximum	CanESM2
	Mean	BNU-ESM
	Minimum	MIROC5
Londrina-PR	Maximum	CanESM2
	Mean	BNU-ESM
	Minimum	NorESM1-M
Barreiras-BA	Maximum	MIROC-ESM
	Mean	BNU-ESM
	Minimum	inmcm4
Bagé-RS	Maximum	IPSL-CM5A-MR
	Mean	BNU-ESM
	Minimum	MIROC5
Santa Maria-RS	Maximum	IPSL-CM5A-MR
	Mean	BNU-ESM
	Minimum	MIROC5
Antônio Carlos-SC	Maximum	CanESM2
	Mean	BNU-ESM
	Minimum	MRI-CGCM3

Crop model set-up for representative maize farming systems

For simulating both main maize seasons in Brazil, simulations were performed for crops on two different sowing dates: October 15th (summer) and February 15th (autumn). Simulations were set-up to assure similar nitrogen management to that usually applied by growers in Brazil, with two nitrogen applications during the crop cycles: the first at the sowing date, and the second when crops reached the V5 phenological state. To appraise the proportion of rainfall changes and air temperature variations responsible for crop development and growth changes in the future, all simulations were done for rainfed and fully irrigated crops.

RESULTS

In general, the results for the climatic scenarios pointed to temperature rise and rainfall decrease in maize producing →

areas in Brazil in 2050, compared to the baseline. This trend is especially relevant for summer crops, with estimates of increases between 2 to 16% in air temperature (an absolute increase of roughly 4.5 °C in the most extreme scenario) (Table 3). The scenarios also indicated a possible 24% reduction in rainfall volume in the most extreme scenario. Among the considered GCMs, the one with the highest temperature variation in relation to the baseline also showed the greatest rainfall variation compared to the baseline (Table 3); thus, it was assumed the most pessimistic scenario. Conversely, the GCM with the lowest temperature variation also had the lowest rainfall decrease changes in comparison to the baseline; therefore, producing the least pessimistic scenario for future crops.

In all analysed future scenarios, simulations revealed a reduction in average yield of summer crops in relation to the baseline. Overall, for RCP 4.5 and RCP 8.5, significant percentages of reduction were observed in the maximum GCM, with a pronounced increase in air temperature and a marked rainfall decrease, for most locations. For RCP 4.5 and RCP 8.5 scenarios, in summer crops, yields were respectively reduced by 4 to 42% for irrigated crops, and ranged from 5 to 55% for rainfed crops, with a larger yield reduction for RCP 8.5, the hottest climate scenario (Fig. 1).

The autumn simulations revealed a decrease in yields for RCP 8.5 in the maximum GCM, for both irrigated and rainfed crops (Fig. 2). In the RCP 4.5 scenario and minimum GCM, there was a slight increase in yields for both irrigated (+ 1%) and rainfed crops (+ 5%). However, in RCP 8.5, yields for irrigated crops did not change and increased only 2% for rainfed ones, respectively (Fig. 2). Thus, based on the comparison between rainfed and irrigated simulations, the main limiting factor in the future scenarios was not the rainfall decrease, but the air temperature increase.

Future scenarios signalled a slight decrease in rainfall for most autumn crops, except for the minimum GCM for RCP 4.5; however, mainly for RCP 8.5 in the maximum GCM. Air temperature increased between 3 to 17% (representing an absolute increase of about 2-3 °C in the most extreme scenario), except for the minimum GCM, which showed an

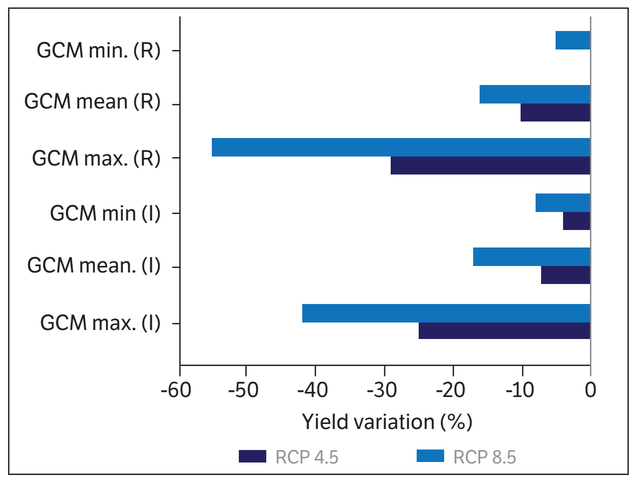

Figure 1. Relative variation of maize yield, referring to the summer season for irrigated (I) and rainfed (R) crops under different RCPs and GCMs.

Table 3. Relative and absolute variation of annual average values of the future climate scenarios in relation to the baseline for the summer season crop.

Season	Variation	GCM minimum			GCM medium			GCM maximum		
		PP (mm)	Tmax (°C)	Tmin (°C)	PP (mm)	Tmax (°C)	Tmin (°C)	PP (mm)	Tmax (°C)	Tmin (°C)
					RCP 4.5					
Summer	Relative variation (%)	-0.6	2.9	4.9	-10.7	6.4	7.6	-16.4	10.7	11.0
	Variation (mm or °C)	-0.2	0.8	1.0	-83.3	1.8	1.6	-119.9	3.1	2.3
					RCP 8.5					
	Relative variation (%)	-2.4	4.8	8.3	-11.0	8.7	11.1	-23.9	16.0	15.8
	Variation (mm or °C)	-19.5	1.4	1.7	-86.3	2.5	2.3	-182.7	4.5	3.2
					RCP 4.5					
Autumn	Relative variation (%)	5.9	3.0	6.1	-7.9	7.7	11.7	-15.0	13.4	17.2
	Variation (mm or °C)	34.6	0.8	1.1	-55.9	1.9	2.0	-97.7	3.5	3.0
					RCP 8.5					
	Relative variation (%)	5.9	3.0	6.1	-7.9	7.7	11.7	-15.0	13.4	17.2
	Variation (mm or °C)	34.6	0.8	1.1	-55.9	1.9	2.0	-97.7	3.5	3.0

increase in air temperature of around 3% to 6% (representing an increase of about 1 °C) (Table 3).

The climatic scenario and minimum GCM (the least pessimistic one) for RCP 4.5 suggested reductions of between 4 to 8% for irrigated crops and 0 to 5% for rainfed crops, respectively, for summer and autumn crops. Simulations for mean and maximum GCMs showed yield reductions ranging from 4 to 25% for irrigated crops and from 0 to 29% for rainfed ones, respectively, for the summer and autumn crops. For the RCP 8.5 scenario, the overall average of three GCMs implied future reductions of between 8 to 42% for irrigated crops and between 5 to 55% for rainfed, respectively, for summer and autumn crops (Fig. 1 and 2).

For the summer rainfed maize crop in Brazil, as temperature increased, evapotranspiration rates also rose, as all simulated

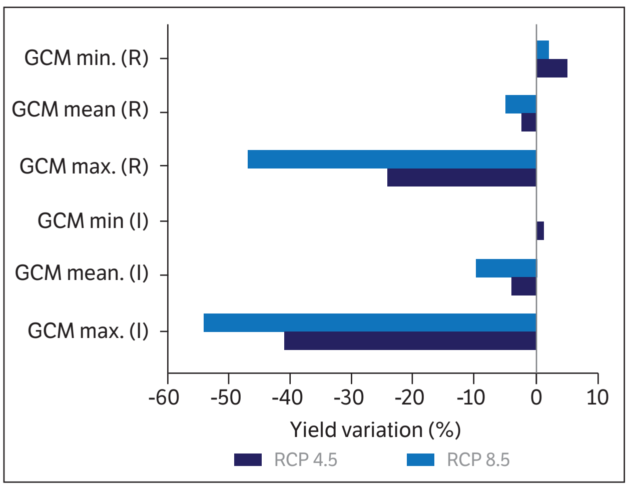

Figure 2. Relative variation of maize yield, referring to the autumn season crop for irrigated (I) and rainfed (R) crops under different RCPs and GCMs.

scenarios showed evapotranspiration increase for RCP 4.5 (Fig. 3a) and RCP 8.5 (Fig. 3b). In the most pessimistic scenario, there is a decrease of 5%, and a decrease of 2% for the most optimistic one, considering the baseline to 525-547 mm. An inverse relationship between maize crop yield and average air temperature during the cycle was observed in summer crops, which was also evidenced in the current paper for both RCP 4.5 (Fig. 4a) and RCP 8.5 (Fig. 4b) scenarios. As mentioned above, in addition to a slight increase in crop water stress, air temperature increase caused a decrease in the crop cycle by 6-22 days in RCP 4.5 (Fig. 4c) and 8-29 days in the most extreme stage, in RCP 8.5 (Fig. 4d).

Comparisons of rainfed and fully irrigated simulations (Figs. 1 and 2) showed that rainfall is not the main factor for yield reduction in future crops, but air temperature. This is attributed to the fact that, even under irrigation, projected crop yields were reduced to levels similar to rainfed simulated yields.

DISCUSSION

The water effect can be evaluated in the context of this study, considering that the soil moisture deficit results in reduction transpiration and stomatal closure, with a consequent decrease in crop yield (Crawford et al. 2012; Araya et al. 2017). The evapotranspiration reduction simulated in future climate scenarios (Fig. 3a, b) means that part of the energy to sustain the plant metabolic processes is used in others, affecting the physical environment of crops by modifying the energy balance of the system (Cunha et al. 1996).

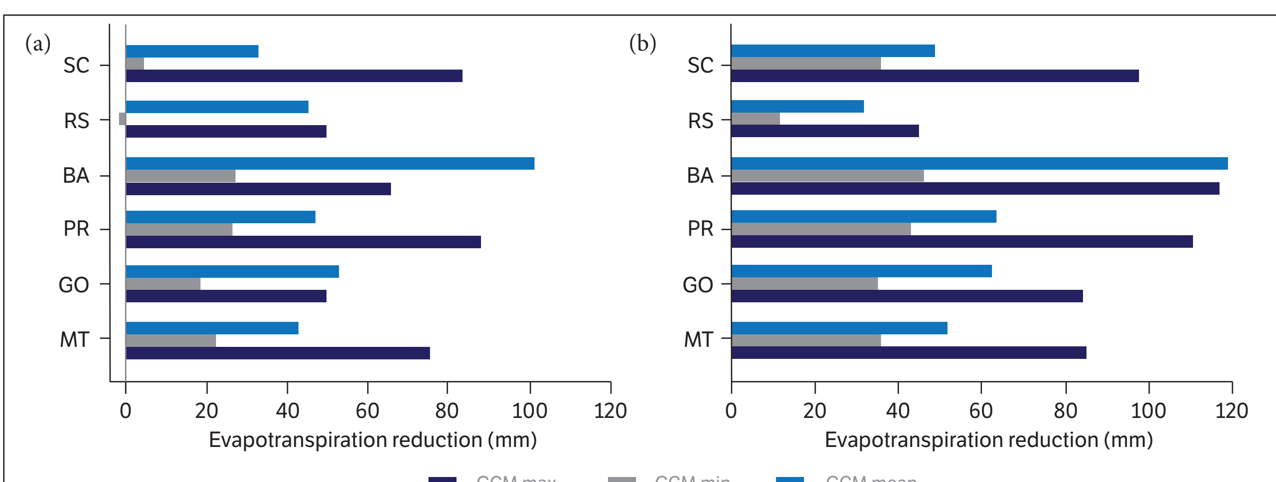

Figure 3. Projected evapotranspiration reduction (mm) in relation to the baseline for RCP 4.5 (a) and RCP 8.5 (b) for summer rainfed maize in Brazil

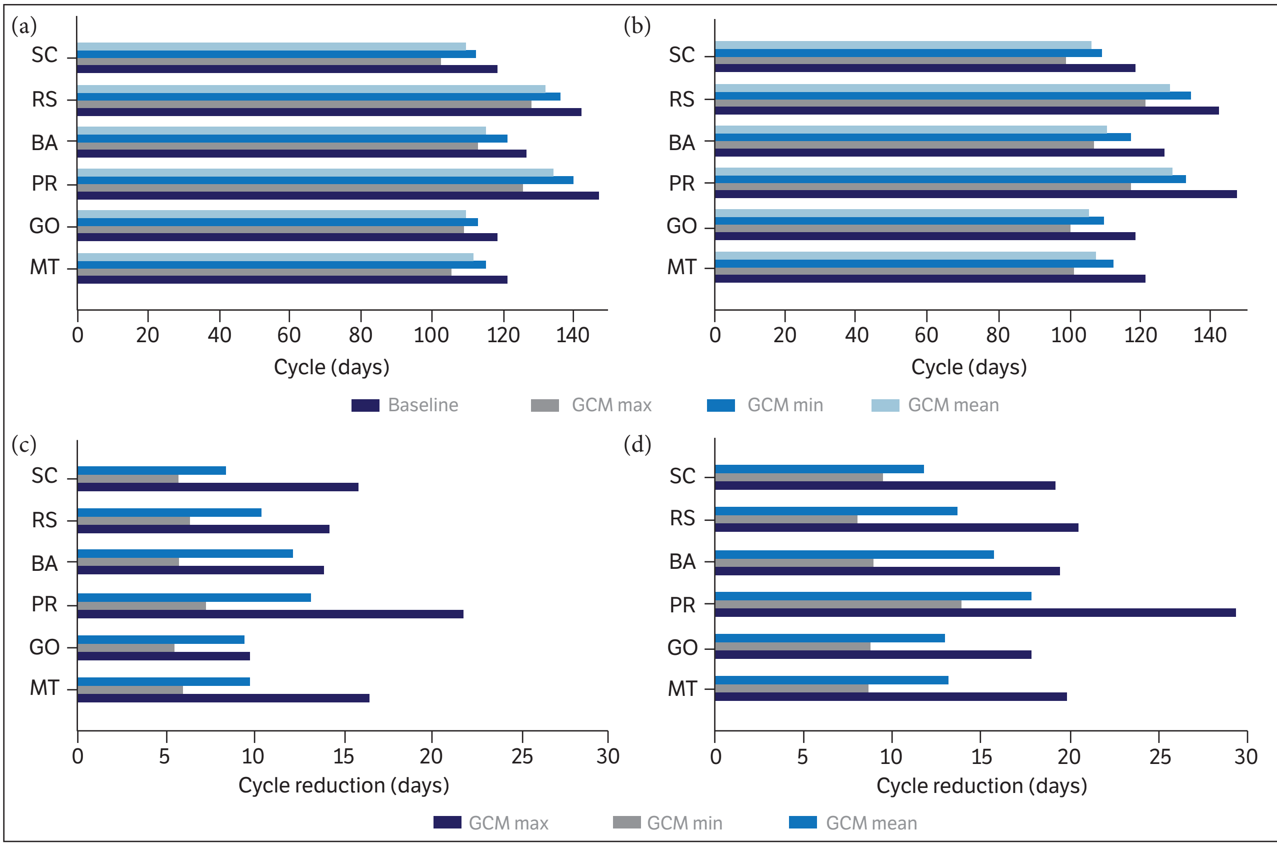

Figure 4. Crop cycle length simulated for different Brazilian states for summer crops under RCP 4.5 (a) and RCP 8.5 (b) and cycle reduction (days) under RCP 4.5 (c) and RCP 8.5 (d).

The increased atmospheric CO_2 lead to a small yield reduction mainly for the rainfed simulations both for summer (Fig. 1) and autumn (Fig. 2) seasons. Leakey (2009), Olesen and Bindi (2002) and Li et al. (2011) reported that photosynthesis of C_4 plants is almost saturated under the current atmospheric CO_2 and the positive effect of increased CO_2 comes mostly from changes in stomatal regulation related to CO_2 increase, as reported for other C_4 crops (Marin and Nassif 2013). Thus, the effect of CO_2 on the yield of C_4 plants and on the water use efficiency (WUE) in the future climate is mainly due to a reduction in stomatal conductance. Inherently, water use reduction is also associated to increase of soil water availability (Leakey 2009; Olesen and Bindi 2002) and this affects mainly rainfed crops, as observed in our simulations (Figs. 1 and 2).

Our results showed that despite irrigation or CO_2 increase, there is a decrease of maize yield in Brazil and the negative effect of temperature was augmented in regions where water deficits occur (Figs. 1 and 2). The reduction in grain yield was attributed to air temperature and rainfall (Table 3). Air temperature has a stronger effect when we compare the 4.5 and 8.5 scenarios (Figs. 1 and 2), due to the phenological development rate in maize hybrids, accelerating their metabolic processes and basal respiration rate, as previously reported by Hatfield (2016), Minuzzi and Lopes (2016) and Bergamaschi (2017b). Damages caused by excessive heat and physiological disturbances in plants could also reduce yield, as previously reported by Wahid et al. (2007). However, our simulations did not take this factor into account. Water deficits lead to an increase in leaf temperature and a reduction in relative humidity of the leaf boundary layer in a way that plants exposed to a water deficit show enhanced crop evaporative demand, leading to rapid and intense stress (Bergamaschi 2017a). Even for irrigated crops, adequate use of genotypes regarding to the crop cycle are necessary to keep the current yield levels in the future climate.

Finally, the main cause for yield reduction observed in our simulations were attributed to temperature increase in crop cycle (Fig. 4). This finding agrees with previous experiments that reported the inverse relationship between average air temperature and maize crop cycle, and also demonstrated that relationship to explain maize yield →

(Crawford et al. 2012; Islam et al. 2012; Araya et al. 2017; Leng 2017). Therefore, these reductions negatively affected the phenological development and the accumulation and partition of synthesised biomass, besides reducing the time available for translocation of the photoassimilates (Li et al. 2011; Bassu et al. 2014). Therefore, considering continuous increases in air temperature, maize production is likely to be compromised. Thus, the cycle duration of maize plants needs to be particularly considered, as well as the choice of the genotype (Hatfield 2016).

CONCLUSION

Simulated future scenarios indicate an overall downward trend in maize yield and an increase in climate risk in Brazilian maize, assuming the current farming systems would remain.

The increase of air temperature and the consequent crop length reduction are argued as the leading causes of maize yield decline in the future, due to climate change.

Management strategies are actions that could minimise the projected yield reduction, particularly those related to the use of genotypes with extended length cycles.

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AUTHOR'S CONTRIBUTION

Conceptualization, Souza T. T., Antolin L. A. S., Bianchini V. J. M., Pereira R. A. A., Silva, E. H. F. M. and Marin F. R.; Methodology, Souza T. T., Antolin L. A. S., Bianchini V. J. M., Pereira R. A. A., Silva, E. H. F. M. and Marin F. R.; Investigation, Souza T. T., Antolin L. A. S., Bianchini V. J. M., Pereira R. A. A., and Marin F. R.; Writing – Original Draft, Souza T. T., Antolin L. A. S., Bianchini V. J. M., Pereira R. A. A., and Marin F. R.; Writing – Review and Editing, Souza T. T. and Marin F. R.; Funding Acquisition, Souza T. T. and Marin F. R.; Resources, Souza T. T., Antolin L. A. S., Bianchini V. J. M., Pereira R. A. A., Silva, E. H. F. M. and Marin F. R.; Supervision, Marin F. R.

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