Sensitivity analysis of the AquaCrop model for wheat crop in Campos Gerais region, Paraná[1]

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ABSTRACT

The use of crop modeling can be useful to understand the interactions between the soil-plant-atmosphere system. The objective of this study was to evaluate sensitivity analysis of the AquaCrop model parameters for wheat crop in the Campos Gerais Region. The varietie tested was TBIO Sinuelo in Castro, Ponta Grossa and Itaberá cities. The analyzed parameters refer to crop phenology, transpiration, biomass production, yield formation, stresses and soil management. The sensitivity analysis was realized varying individually each input parameter in the AquaCrop for the calculation of the Relative Sensitivity Index (*SI*). The most sensitive parameters of the AquaCrop were: reference harvest index (HI_o); water productivity normalized for evapotranspiration and CO_2 concentration (WP^*); crop coefficient when canopy expansion is complete ($Kc_{TR,x}$); fertility levels; and maximum canopy cover (CC_x). The higher sensitivity of HI_o and WP^* is because they are directly related to two main equations of AquaCrop, linked to the estimates of dry above-ground biomass and yield formation, respectively. The AquaCrop counts WP^* reflecting directly on dry above-ground biomass production and on final grain yield. The canopy decline coefficient (*CDC*) presented considerable sensitivity only in Castro due to the longer duration of the phenological cycle. Fertility levels and saturated hydraulic conductivity (K_{sat}) in Castro was the least sensitive parameters in the analysis.

Keywords: mathematical modeling; parameters; *Triticum aestivum*.

INTRODUCTION

The crop productivity evaluation with models simulations can help in the prediction of harvest and the understanding of the interactions resulting from the soil-plant-atmosphere continuum. The models consider the combination of the several factors that influence crop productivity (Gomes *et al.*, 2014) and help in decision making and crop planning, predicting the crop potential productivity in different scenarios (Basso *et al.*, 2013; Morell *et al.*, 2016). Crop models are highly recommended for research in places with high agricultural production, such as the Campos Gerais, in Paraná and São Paulo States, which stand out for presenting grain yields above the national agricultural average (Shimandeiro *et al.*, 2008).

The literature is rich in examples of mathematical models used to handle agricultural crops. Among them, the AquaCrop has been widely used (Raes *et al.*, 2009; Steduto *et al.*, 2012; Piekarski *et al.*, 2017). The main advantage of the AquaCrop is due to the small number of required input parameters, being data easily obtainable.

The AquaCrop is viable in the yield simulation of

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different crops, under different soil and climatic conditions (Heng *et al.*, 2009; Todorovic *et al.*, 2009; Bitri & Grazhdani, 2015; Mirsafi *et al.*, 2016; Bouazzama *et al.*, 2017; Pareek *et al.*, 2017). However, its application in Brazil is still scarce, especially for wheat, an important cereal cultivated in 2 million hectares, being the southern region of the country the traditionally producer (Conab, 2017). In Paraná State, wheat is the most important winter crop, reaching 934.527 hectares of planted area in the 2017 harvest, with a production of 2.3 million tons and an average yield of nearly 2.5 ton ha^{-1}. The Campos Gerais Region confirmed wide potential productivity in the 2017 harvest, once again yielding above the national average (IBGE, 2017).

The model's accuracy depends largely on the parameters involved. It is important to identify the parameters that most influence the results, as well as what each parameter causes in the model, aiming to reduce the uncertainties in the final result (Salemi *et al.*, 2011). However, the model parameters values are subject to variation and errors, being necessary for the investigation of the changes. For this, sensitivity analysis is performed, changing the value of a parameter in an individual way and verifying the influence of the variables in the results (Bouazzama *et al.*, 2017).

The main functions present in AquaCrop are described in Raes *et al.* (2012) and Raes *et al.* (2018b). The authors recommend that the variables susceptible to penalization of crop potential productive should be submitted to the sensitivity analysis.

Simulations in models allow identifying confidence intervals for the parameters (Taconeli & Barreto, 2003). The most sensitive parameters of a model are mostly submitted to the calibration process (Cibin *et al.*, 2010; Xing *et al.*, 2017). After identifying the most sensitive parameters and performing their calibration, it is possible to obtain the maximum potential of the model, making it able to identify better planting dates and consequently resulting in higher yields.

A key goal of agriculture is to achieve the maximum crop yield while minimizing inputs and losses from cropping systems. In this regard, the use of models that predict crop yields becomes a fundamental tool in decision-making. Considering the application of the AquaCrop model and the importance of the wheat crop for Brazilian agribusiness, the objective of this study was to perform the sensitivity analysis to identify the most sensitive parameters of the model for the wheat crop in the Campos Gerais Region.

MATERIAL AND METHODS

The present study was carried out considering the wheat crop. It was submitted to the sensitivity analysis the TBIO Sinuelo variety, with medium to late characterization cycle, in three cities of Campos Gerais Region, cultivated in 2014 crop year: Castro and Ponta Grossa, in Paraná State; and, Itaberá, São Paulo State. All the experimental plots used have flat to gently undulating relief. The management practices in the areas were no-tillage with residual vegetation covered from the previous harvest. The edaphoclimatic characterization of the analyzed areas is shown in Table 1.

The simulations were carried out with AquaCrop, Version 6.0, developed by researchers linked to the Food and Agriculture Organization of the United Nations (FAO, 2018). Sensitivity analysis was performed for the conservative and non-conservative parameters present in AquaCrop to verify the responses of input parameters changes. Input data inserted into AquaCrop refers to climate, crop, soil, and soil management.

Table 1: Edaphoclimatic characterization of Fundação ABC Experimental Stations, located in Castro, Itaberá and Ponta Grossa cities

Localitie	**Soil**	**Climate** [(1)]	**Latitude**	**Longitude**	**Altitude**
			--------- (degrees) ---------		(m)
Castro-PR	CAMBISSOLO HÁPLICO Distrófico típico	Cfa	24.85° S	49.93° W	1001
Itaberá-SP	PLANOSSOLO HÁPLICO Distrófico típico	Cfa	24.06° S	49.15° W	740
Ponta Grossa-PR	LATOSSOLO VERMELHO Distrófico típico	Cfb	25.30° S	49.95° W	908

(1) Adapted from Alvares *et al.* (2013).

The climate data was provided from the agrometeorological stations installed in the analyzed locations. Daily data inserted was referring to precipitation (*P*; mm day^{-1}); maximum (*Tx*; °C), minimum (*Tn*; °C) and average (°C) daily air temperature; incident solar radiation (*Rs*; MJ m^{-2} day^{-1}); relative humidity (*RH*; %); and wind speed (u_2; m s^{-1}). AquaCrop provides internally the values of atmospheric CO_2 concentrations (ppm) measured at the Mauna Loa, an observatory in Hawaii (Raes *et al.*, 2009), as well as automatically calculates the atmospheric evaporative daily demand expressed by reference evapotranspiration (*ETo*; mm day^{-1}), using the Penman-Monteith method (Allen *et al.*, 1998).

The wheat crop data were obtained from the Fundação ABC database protocols (Table 2).

Table 2: Wheat crop data, TBIO Sinuelo varietie, obtained from experiments at Fundação ABC, for Castro, Itaberá and Ponta Grossa cities, inserted in the AquaCrop program

Crop data	Local cultivation of wheat TBIO Sinuelo varietie		
	Castro	Ponta Grossa	Itaberá
Planting date	Jul 11, 2014	Jun 16, 2014	Jun 03, 2014
Harvest date	Nov 26, 2014	Oct 27, 2014	Oct 15, 2014
Duration of phenological cycle (days)	138	133	134
Emergence (1)	7	7	7
Maximum canopy (1)	86	88	79
Flowering (1)	87	89	83
Duration of flowering(1)	9	13	17
Senescence (1)	96	102	100
Maturity (1)	134	130	124
Plant density per hectare	3411800	2338200	2337100

(1) Day After Planting.

Three soil layers were considered in 0.00-0.10 m, 0.10-0.25 m and 0.25-0.40 m depths. The soil data inserted in the program was obtained in a previous study in the same areas, carried out by Piekarski *et al.* (2017) (Table 3).

With the parameters inserted, the AquaCrop derives and counts the evaporation of superficial soil layer, internal drainage, deep percolation, surface runoff, and capillary rise. To perform the analysis of the water balance in AquaCrop the initial soil water content was considered equal to the available water in the root zone.

The values attributed to the AquaCrop parameters related to the wheat crop were based on the literature (Raes *et al.*, 2017) and protocol data from Fundação ABC. Salinity stress was not considered. Calibration for soil fertility stress was adjusted to the program options, being: *i*) Biomass production near optimal; *ii*) Maximum canopy cover close to the reference (no stresses); and, *iii*) Canopy decline in the season was considered small.

Table 3: Soil physical-water atributes from the Experimental Stations of Fundação ABC, inserted in the AquaCrop for the sensitivity analysis of the parameters

Localitie	Layer (m)	Texture	Soil water content (m^3 m^{-3})			K_{sat} (4)
			θ_{PWP} (1)	θ_{FC} (2)	θ_{Sat} (3)	(mm day^{-1})
Castro	0.00 – 0.10	Clay	0.36	0.50	0.63	418.32
Castro	0.10 – 0.25	Clay	0.33	0.47	0.60	368.23
Castro	0.25 – 0.40	Clay	0.32	0.45	0.62	325.74
Itaberá	0.00 – 0.10	Clay	0.28	0.40	0.55	516.46
Itaberá	0.10 – 0.25	Clay	0.24	0.37	0.54	462.25
Itaberá	0.25 – 0.40	Clay	0.22	0.37	0.54	420.37
Ponta Grossa	0.00 – 0.10	Clay	0.20	0.39	0.51	743.27
Ponta Grossa	0.10 – 0.25	Clay	0.20	0.35	0.50	732.57
Ponta Grossa	0.25 – 0.40	Clay	0.25	0.36	0.54	636.30

(1)Volumetric water content at permanent wilting point; (2)Volumetric water content at field capacity; (3)Volumetric water content at saturation; (4)Saturated hydraulic conductivity.

The sensitivity analysis of the conservative and non-conservative AquaCrop parameters was performed by individually varying each input parameter, remaining the others fixed. As analysis criteria, it was adopting the Relative Sensitivity Index (*SI*), proposed by Silva *et al.* (2009):

$$SI = \frac{I_{12} \cdot \left(R_1 - R_2\right)}{R_{12} \cdot \left(I_1 - I_2\right)}$$

Where: *SI* is the model sensitivity index for the input parameters (dimensionless); R_1 is the result obtained with the model for the lowest input value; R_2 is the result obtained with the model for the highest input value; R_{12} is the average of the results obtained with the lowest and highest input value; I_1 is the lower value of input parameter; I_2 is the highest value of input parameter; I_{12} is the average value of input parameters.

The *SI* result indicates that as higher is the index obtained (in module) more sensitive the model is to the parameter. Values close to zero indicate that the model has no sensitivity (Silva *et al.*, 2009).

RESULTS AND DISCUSSION

The sensitivity index of the AquaCrop parameters and respective rankings are shown in Table 4. In all locations evaluated, the highest sensitivity was found for the reference harvest index (HI_o). The parameters also strongly sensitive were: normalized water productivity for *ETo* and CO_2 (*WP**); crop coefficient when the canopy is complete but before senescence ($Kc_{TR,x}$); maximum canopy cover (CC_x); and, fertility levels. The canopy decline coefficient (*CDC*) presented the highest sensitivity in Castro (Figure 1). The simulations were carried out for periods of no water deficit in the locations, to account the sensitivity under ideal conditions of crop development.

Crop phenology

The curve that represents the initial phase of canopy cover (*CC*) is equal to the canopy cover at 90% crop emergence (Figure 2: *CCo*). Posteriorly, in the second path, the curve has an exponential trend, and as the crop grows, the canopy cover becomes larger (Figure 2: Equation 1). Upon reaching maximum development the *CC* becomes equal to the maximum canopy cover (Figure 2: CC_x). In this phase, the radiation capture and photoassimilates production in the photosynthesis process tends to decrease due to the crop mutual shading, and the *CC* follows exponential decay function in the third stretch (Figure 2: Equation 2).

As the crop approaches maturity the *CC* declines, as a result of leaf senescence. The canopy decline coefficient (*CDC*) corresponds to the rate of canopy decay due to senescence. The *CDC* values are directly proportional to the rate of canopy decline (Figure 3: Equation 3).

The CC_x is determined in AquaCrop based on the planting density, being dependent on the environment and the management adopted (Steduto *et al.*, 2009; Raes *et al.*, 2011; Steduto *et al.*, 2012; Dalla Marta *et al.*, 2016; Raes *et al.*, 2018c). The sensitivity of this parameter is related to be part of two main equations that determine the crop canopy cover (Figure 2: Equation 2; and Figure 3: Equation 3). The CC_x was more sensitive in Castro (*SI* = 0.76; Ranking 4), followed by Ponta Grossa (*SI* = 0.72; Ranking 5) and Itaberá (*SI* = 0.58, Ranking 5) (Figure 1a). Razzaghi *et al.* (2017) when simulating the potato yield under different water stress conditions (irrigated, deficit irrigated, and not irrigated) in Denmark observed that the CC_x is one of the most sensitive parameters to changes in AquaCrop.

The canopy decline coefficient (*CDC*) presented considerable sensitivity for the wheat crop only in Castro (*IS* = 0.74; Ranking 5; Table 4 and Figure 1b). The sensitivity of this parameter is related to being part of the equation responsible for the canopy decline by senescence (Figure 3: Equation 3). This parameter was also sensitive to wheat crop in studies involving other locations, as observed by Xing *et al.* (2017) when evaluating the sensitivity of the AquaCrop parameters for winter wheat with the *Extended Fourier Amplitude Sensitivity Test* (EFAST) in Beijing, China, under different water treatments, found that *CDC* was one of the most sensitive parameters under irrigated (normal and over irrigation) and no irrigated planting condition (rainfall only). Vanuytrecht *et al.* (2014), evaluating the EFAST method, also observed sensitivity for *CDC* parameter for maize and winter wheat in Belgium (north-western Europe), and for rice in Vietnam (south-east Asia). However, Silvestro *et al.* (2017), using MORRIS and EFAST methods to perform the sensitivity analysis in three sites, two in China and one in Italy, representing contrasting environments in terms of extreme temperatures and water availability, found that *CDC* showed low influence on final productivity when compared to other parameters. The sensitivity of *CDC* in Castro is due to the longer duration of the variety phenological cycle (Table 2). The time interval between senescence and maturity was longer (38 days) when compared to other localities. Thus, the program counted for longer the influence of this parameter in the final wheat crop yield.

Table 4: Parameters evaluated in the sensitivity analysis of AquaCrop, respective sensitivity indexes (SI), score in which each parameter becomes more or less sensitive (Ranking) for TBIO Sinuelo varietie, in the localities of Castro-PR, Ponta Grossa-PR and Itaberá-SP

Parameter	Castro		Itaberá		Ponta Grossa	
	SI	**Ranking**	***SI***	**Ranking**	***SI***	**Ranking**
------------ Crop Phenology ------------						
CC_o: Soil surface covered by an individual seedling at 90% emergence (%) (2)	0.07	11	0.10	11	0.07	10
CC_x: Maximum canopy cover (%) (3)	0.76	4	0.58	5	0.72	5
CDC: Canopy decline coefficient (% day^{-1}) (1)	0.74	5	0.35	7	0.52	7
Z_{min}: Minimum effective rooting depth (m) (3)	0.00	20	0.01	17	0.00	23
$Z_{máx}$: Maximum effective rooting depth (m) (3)	0.19	9	0.10	12	0.00	16
Shape factor describing root zone expansion (1)	0.00	23	0.00	19	0.00	23
------------ Crop transpiration ------------						
$Kc_{TR,x}$: Crop coefficient when canopy is complete but prior to senescence (1)	0.88	3	0.91	4	1.00	2
Decline of crop coefficient as a result of ageing, nitrogen deficiency, etc. (% day^{-1}) (1)	0.08	10	0.19	9	0.18	8
Ke: Effect of canopy cover on reducing soil evaporation in late season stage (%) (1)	0.00	19	0.00	23	0.00	22
------------ Biomass production and yield formation ------------						
*WP**: Water productivity normalized for *ETo* e CO_2 (g m^{-2}) (1)	0.98	2	0.98	2	0.98	3
Water productivity normalized for *ETo* e CO_2 during yield formation (%) (1)	0.00	18	0.00	21	0.00	20
HI_o: Reference harvest index (%) (4)	1.00	1	1.00	1	1.00	1
Maximum possible increase of *HI* (%) (1)	0.00	23	0.00	23	0.01	14
------------ Stresses ------------						
$p_{exp.lower}$: Soil water depletion threshold for canopy expansion - Upper threshold (1)	0.01	16	0.01	18	0.01	15
$p_{exp.upper}$: Soil water depletion threshold for canopy expansion - Lower threshold (1)	0.00	22	0.00	22	0.00	18
Shape factor for water stress coefficient for canopy expansion (1)	0.00	21	0.00	20	0.00	21
p_{sto}: Soil water depletion threshold for stomatal control - Upper threshold (1)	0.03	12	0.01	14	0.04	11
Shape factor for water stress coefficient for stomatal control (1)	0.03	14	0.02	13	0.00	19
p_{sen}: Soil water depletion threshold for canopy senescence - Upper threshold (1)	0.01	17	0.11	10	0.02	13
Shape factor for Water stress coefficient for canopy senescence (1)	0.00	23	0.00	23	0.00	23
p_{pol}: Soil water depletion threshold for failure of pollination - Upper threshold (1)	0.00	23	0.00	23	0.00	23
Volume at anaerobiotic point (with reference to saturation) (%) (4), (3)	0.03	13	0.01	15	0.02	12
Minimum air temperature below which pollination starts to fail (cold stress) (°C) (1)	0.00	23	0.19	8	0.16	9
Maximum air temperature above which pollination starts to fail (heat stress) (°C) (1)	0.21	8	0.00	23	0.00	23
Minimum growing degrees required for full biomass production (°C day^{-1}) (1)	0.43	7	0.39	6	0.55	6
------------ Field management ------------						
Soil Fertility (3)	0.56	6	0.96	3	0.97	4
Mulches (3)	0.02	15	0.01	16	0.00	17

(1)Conservative generally applicable; (2)Conservative for a given specie but can or may be cultivar specific; (3)Dependent on environment and/or management; (4)Cultivar specific.

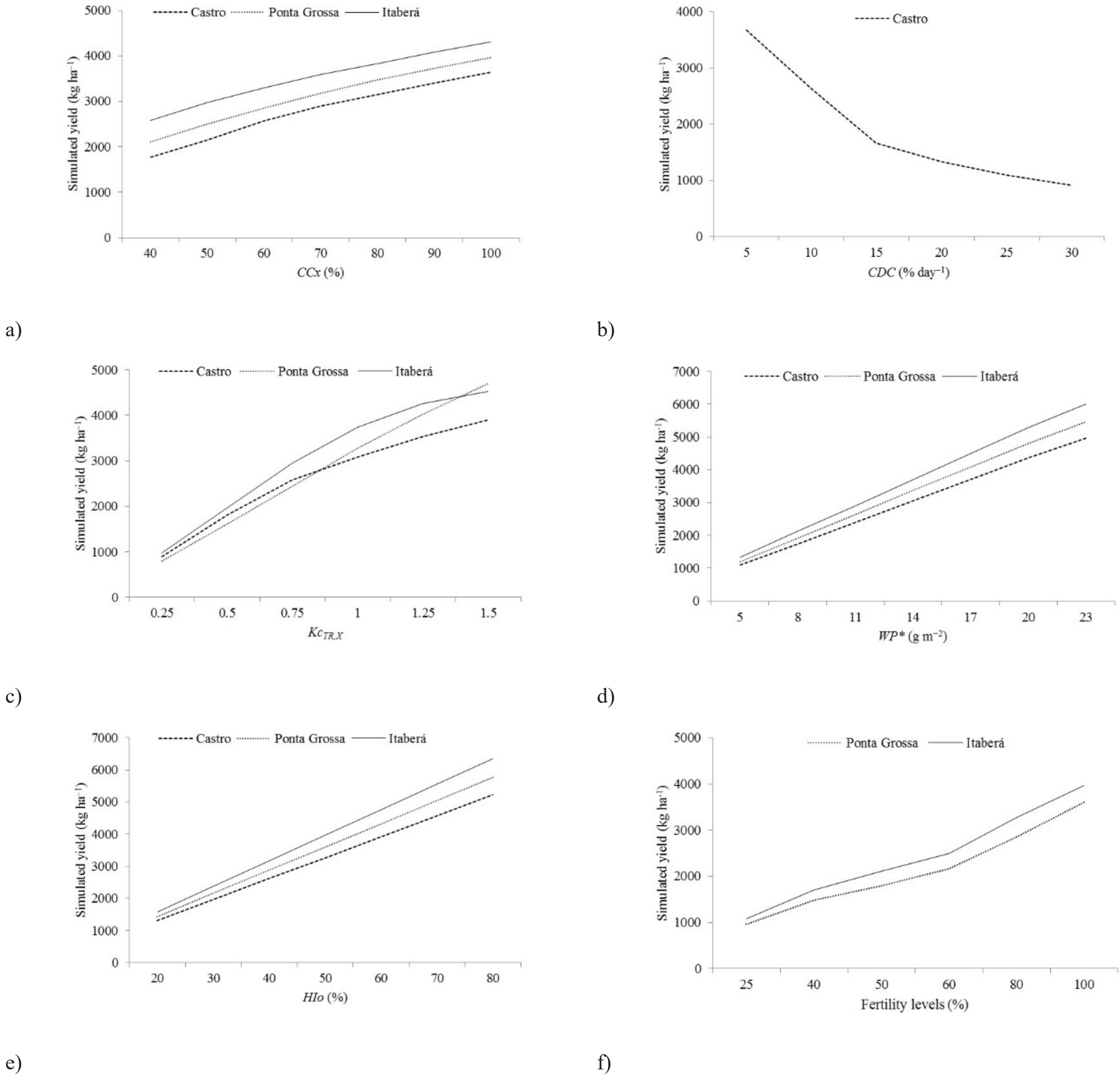

Figure 1: Variation of simulated productivity for wheat crop in AquaCrop, for the localities of Castro, Ponta Grossa and Itaberá, by adjusting the most sensitive parameters of the model, being: a) maximum canopy cover (CC_x; %); b) canopy decline coefficient (*CDC*; % day^{-1}); c) crop coefficient when the canopy is complete ($Kc_{TR,x}$; dimensionless); d) normalized water productivity (*WP**; g m^{-2}); e) reference harvest index (HI_o; %); and, f) soil fertility levels (%).

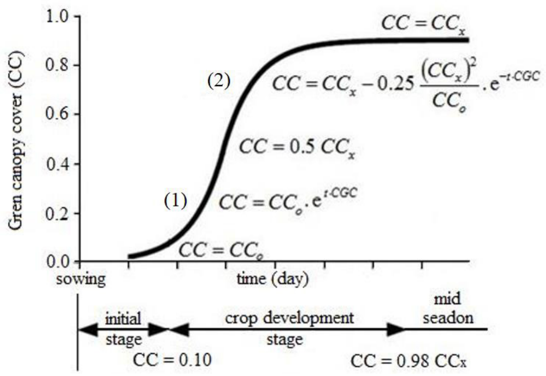

Figure 2: Schematic representation of canopy development during the exponential growth (Equation 1) and the exponential decay (Equation 2) stages (Raes *et al.*, 2018c).

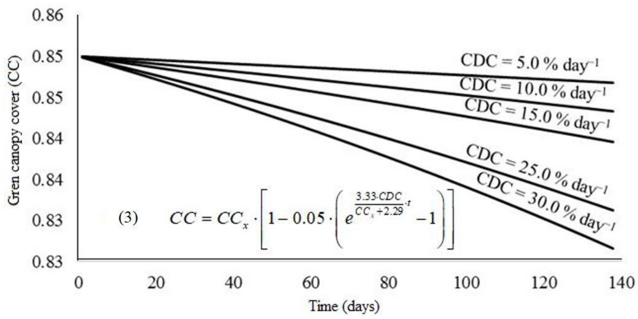

Figure 3: Decline of green canopy cover during senescence for *CDC* values.

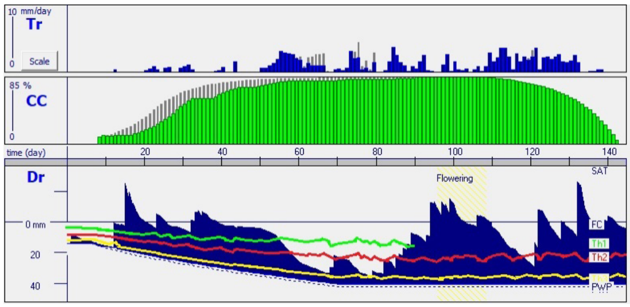

Figure 4: Depletion of root zone soil water (*Dr*), green canopy cover (*CC*) and transpiration (*Tr*) during the crop cycle, for Castro-PR, with the three water stress thresholds affecting: *i*) the canopy expansion (below the green line, bottom graph); *ii*) stomatal closure (below the red line) affecting *Tr*; and *iii*) triggering canopy senescence (below the yellow line).

The other phenology parameters presented a negligible influence (Table 4). Significantly changes in the input values did not result in expressive differences on the program output data, mainly in the "Shape factor describing root zone expansion" and the "Minimum effective rooting depth" (Z_{min}).

Crop transpiration

The proportionality factor of crop transpiration in AquaCrop is known as $Kc_{TR,x}$, being the coefficient that indicates when canopy expansion is complete (CC = 1) and without stresses condition. The $Kc_{TR,x}$ is a parameter considered conservative and approximately equivalent to the basal crop coefficient at mid-season, in cases of canopy complete expansion (Dalla Marta *et al.*, 2016; Raes *et al.*, 2018b; Raes *et al.*, 2018c). The parameter $Kc_{TR,x}$ presented high sensitivity (Table 4, Figure 1c), being: *SI* = 1.00 in Ponta Grossa (Ranking 2), *SI* = 0.91 in Itaberá (Ranking = 4); and, *SI* = 0.88 in Castro (Ranking 3).

The crop transpiration (*Tr*) depends on the fraction of land area covered by the canopy (*CC*) when there is insufficient stress to limit stomatal opening. When the canopy fully covers the ground (*CC* is close and approaching 1.0), the program multiplies the value of $Kc_{TR,x}$ by the effective canopy cover adjusted for micro-advective effects and reference evapotranspiration (*ETo*), resulting in crop transpiration values (*Tr*) (Raes *et al.*, 2009; Steduto *et al.*, 2012). Raes *et al.* (2018c) remark that the $Kc_{TR,x}$ is proportional to the *CC* and for this reason is continuously adjusted throughout the crop cycle. When water stress occurs in the soil, besides the canopy development being affected, the program can also consider that there was stomatal closure (Equation 4 and Figure 4). The whole mechanism occurs through the water stress coefficient for stomatal closure (Ks_{sto}), interfering in crop transpiration.

$$Tr = Ks \cdot Kc_{Tr,x} \cdot CC^* \cdot ETo \qquad (4)$$

Xing *et al.* (2017) observed sensitivity for winter wheat in China. In the analysis, the $Kc_{TR,x}$ was among the most sensitive parameters in AquaCrop, both in estimative of dry above-ground biomass production and final grain yield. Razzaghi *et al.* (2017) also obtained high sensitivity for $Kc_{TR,x}$ with the potato crop. Salemi *et al.* (2011) observed moderate sensitivity for winter wheat in Iran, and Vanuytrecht *et al.* (2014) changing the values of $Kc_{TR,x}$, verified low impact on the final grain yield. Silvestro *et al.* (2017) verified highest influence of $Kc_{TR,x}$ in Yangling, China, where temperature and evapotranspiration values were higher in all evaluated seasons of the year. As the crop transpiration (*Tr*) is influenced by the climate region during the cropping-cycle (precipitation, temperature, incident solar radiation, evapotranspiration, relative humidity, and wind speed), it can be considered that the sensitivity of $Kc_{TR,x}$ parameter depends on the environment under analysis, explaining the sensitivity variation in several places.

The sensitivity of $Kc_{TR,x}$ parameter is due to the direct connection with crop transpiration (*Tr*), being part of one of the two main equations which are in the core of the AquaCrop growth engine (Figure 5; Equation 5), determining the dry above-ground biomass.

The effect of canopy cover on reducing soil evaporation in the late season stage (*Ke*) did not present a considerable sensitivity in the analysis.

Biomass production and yield formation

The normalized biomass water productivity (*WP**) presented high sensitivity, with *SI* = 0.98 for all localities, resulting in Ranking 2 in Castro and Itaberá (Table 4; Figure 1d), and Ranking 3 in Ponta Grossa (Table 4).

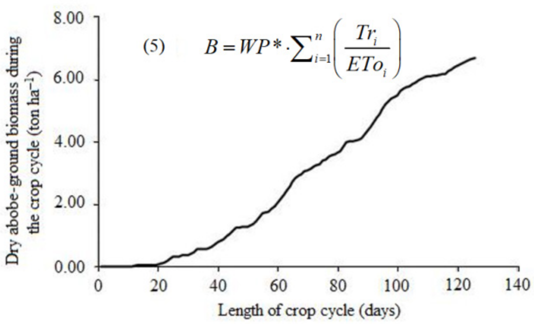

Figure 5: Dry above-ground biomass production (ton ha^{-1}) during the wheat crop cycle, in Castro-PR.

*WP** is based on the evaporative demand of the atmospheric (*ETo*) and the atmospheric CO_2 concentration. The program counts *WP** (Equation 6) reflecting directly on dry above-ground biomass production (Equation 5) and, consequently, on final grain yield (Equation 7).

$$WP^* = \left[\frac{B}{\sum_{i=1}^{n} \left(\frac{Tr_i}{ETo_i} \right)} \right]_{[CO_2]} \quad (6)$$

$$Y = f_{HI} \cdot HI_o \cdot B \quad (7)$$

Where: *WP** – Water productivity normalized for *ETo* and CO_2 (g m^{-2}); *B* – dry above-ground biomass (kg ha^{-1}); Tr_i – crop transpiration at each *i*-day (mm); ETo_i – reference evapotranspiration at each *i*-day (mm); *Y* – crop productivity (kg ha^{-1}); HI_o – reference harvest index (%); f_{HI} – adjustment factor that adjusts the crop index from the reference value, being positive ($f_{HI} > 1$) or negative ($f_{HI} < 1$) (dimensionless), adjusted only under temperature or water stress conditions (Steduto *et al.*, 2009; Steduto *et al.*, 2012; Raes *et al.*, 2018a; Raes *et al.*, 2018c).

As the $Kc_{TR,x}$, the sensitivity of *WP** occurs due to the participation in the equation that determines the dry above-ground biomass (Equation 5) being one of the main equations of AquaCrop. Xing *et al.* (2017) and Razzaghi *et al.* (2017) also observed sensitivity for *WP**. Vanuytrecht *et al.* (2014) noted a sensitivity of *WP** only in rice crop, and Silvestro *et al.* (2017) for wheat, mainly in Yangling (China) and Viterbo (Italy). The sensitivity of *WP** obtained by Salemi *et al.* (2011) was considered moderate. Bouazzama *et al.* (2017) at the National Institute of Research in Morocco found that *WP** was highly sensitive in simulating the wheat final yield and, with the maximum effective rooting depth, were the most sensitive parameters to simulate AquaCrop biomass production.

The reference harvest index (HI_o) was the most sensitive parameter in AquaCrop, with *SI* = 1.00 for all localities (Table 4; Figure 1e). Considering the small and higher values adopted for the parameters during simulations, differences observed were above 30000 kg. The HI_o presented high sensitivity for being part of the second main equation of AquaCrop. Together with the equation that determines the dry above-ground biomass (Equation 5), the HI_o determines the grain yield formation (Equation 7).

Sensitivity analysis performed by Xing *et al.* (2017), considering simulations with water input only by rainfall, indicated the HI_o in the third sensitivity position to estimate final grain yield. Silvestro *et al.* (2017) observed higher sensitivity of HI_o in Viterbo, Italy. The HI_o was also sensitive in the simulations performed by Bouazzama *et al.* (2017) and Razzaghi *et al.* (2017).

Steduto *et al.* (2012) describe that HI_o is considered a conservative parameter for most high-yielding varieties. However, some varieties may require adjustments to obtain better results by the program (Silvestro *et al.*, 2017). AquaCrop is a crop water productivity model very sensitive to water stress. The effects of water scarcity directly interfere on reference harvest index (HI_o). One negative impact of drought on simulated productivity occurs in pollination and embryo formation. In the case of severe and long water stress, there is a reduction in HI_o, and consequently yield drop (Steduto *et al.*, 2012).

Stresses

The AquaCrop responses for water loss are indicated by stress depletion in the root zone, expressed as a *p* factor of available soil water. The stress coefficient (K_s) ranges from 0 (p_{lower} – full stress) to 1 (p_{upper} – no stress). The low Ranking values obtained for *p* factor in the analysis indicated that no calibration adjustments were necessary. Farahani *et al.* (2009) analyzing the sensitivity of some parameters in the AquaCrop, for the cotton crop, obtained low sensitivity for Ks_{sto}. Ks_{sto} has minor importance in the calibration since AquaCrop automatically adjusts its values, based on daily crop evapotranspiration in the localities evaluated.

The effects of air temperature stress in AquaCrop are accounted in growing degree-day. Raes *et al.* (2017) consider that 5 °C is the minimum air temperature below which pollination starts to fail (cold stress) and 35 °C is the maximum air temperature above which pollination starts to fail (heat stress). During the flowering period, temperatures below 5 °C or above 35 °C were not observed in the localities evaluated in Campos Gerais.

Soil fertility levels were shown to be sensitive for all localities (Table 4; Figure 1f), mainly Ponta Grossa (*SI* = 0.97; Ranking 4) and Itaberá (*SI* = 0.96; Ranking 3), resulting in differences of 2644 kg ha^{-1} and 2889 kg ha^{-1}, respectively. The AquaCrop is a program directed by soil water balance and, in this way, the lowest sensitivity obtained for Castro (*SI* = 0.56; Ranking 6) is assigned to the lower average value of saturated hydraulic conductivity (K_{sat}; Table 3). The lowest K_{sat} value is directly related to the lower water flow along with the profile, providing for a long time period the water content in the root zone. As fertility stress is also related to the water content in the soil profile (Steduto *et al.*, 2012), by the availability of solutes, there was a lower sensitivity of the parameter when compared to the other locations. Ponta Grossa presented the highest mean saturated hydraulic conductivity (Table 3) and, consequently, higher sensitivity (*SI* = 0.97; Table 4).

The soil covered by mulches presented low sensitivity in AquaCrop (Table 4), as it does not interfere directly with the final crop yield. Its function is related only to reducing evaporation losses from the soil surface (*E*).

The parameters referring to soil physical-water attributes, which emphasize the volumetric water content at field capacity, permanent wilting point, saturation, and saturated hydraulic conductivity, depends on the environment in which the crop is located or the management adopted. These parameters were not submitted to the sensitivity analysis once they were inserted in the program based on values observed in laboratory analysis.

The interrelation that influences the wheat crop in the different studied regions may be associated with the edaphoclimatic characterization of the regions, mainly soil and climate. Although all soils have different classes (Table 1), the textural classification is predominantly clayey and the physical-water atributes of the soils are relatively similar in all locations (Table 3). In addition, the simulations performed at the three sites were performed for the same variety (TBIO Sinuelo) and in periods without water deficit.

CONCLUSIONS

In the analyzes performed it was observed that the most sensitive parameters of the AquaCrop model for wheat crop in the Campos Gerais Region were the reference harvest index (HI_o), crop coefficient when the canopy is complete ($Kc_{TR,x}$), water productivity normalized for *ETo* e CO_2 (*WP**), soil fertility levels and maximum canopy cover (CC_x).

The reference harvest index (HI_o) was the parameter that presented the highest sensitivity for wheat crop in the AquaCrop, in all locations evaluated.

The lower sensitivity related to the fertility levels observed in Castro was due to the lower average of saturated hydraulic conductivity (K_{sat}).

The sensitivity analysis carried out considered water conditions appropriate to the crop development, which may have reflected in the low indexes observed for the parameters related to water stress.

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The authors declare that have no conflicts of interest.

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