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Original Article

Local sensitivity analysis of the AquaCrop model outputs for wheat under Semi-Arid water stress condition

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ABSTRACT

The FAO AquaCrop model has been extensively reported to simulate wheat growth and productivity in response to environmental conditions in many parts of the world. However, the calibration of the model could be tedious due to its large number of input parameters. The complexity in the model evaluation could be simplified by conducting a prior sensitivity analysis (SA), which information on it is hard to come-by in the North-eastern Nigeria. The SA of the model's output variables to its input parameters was conducted using the local sensitivity analysis (LSA) technique. An early maturing REYNA-28 wheat variety was used under water deficit conditions in the semi-arid North-eastern Nigeria. The analysis revealed that the simulation of grain yield was highly influenced by days-to-flowering (DtF), normalized water productivity (WP*), reference harvest index (HI_o), crop coefficient when the canopy is complete but prior to senescence (K_{cTrx}) and maximum effective rooting depth (Z_x) with sensitivity coefficients (SCs) of 1.23, 1.05, 0.83, 0.75 and 0.61, respectively. Biomass yield was highly sensitive to days-to-emergence (DtE), WP*, K_{cTrx}, number of plants per hectare (den), soil surface covered by individual seedlings at 90 % emergence (cc_s) and initial canopy cover (cc_o). The sensitivity of canopy cover was more to its related parameters such as DtE, maximum canopy cover (CC_x), days-to-maximum canopy cover ($DtCC_x$), canopy growth coefficient (CGC), cc_s, cc_o, den and days-to-start of senescence (DtSS). Stress parameters were found to be either insensitive or with negligible sensitivity except lower soil water depletion threshold for canopy expansion (P_{exlw}). The analysis also revealed that the model outputs were insensitive to half of the model's input parameters. These parameters could be fixed within their ranges in order to simplify the model and ease its calibration. The influential/sensitive parameters on the other hand require higher consideration during data collection, fine-tuning and calibration. This work can be validated using different SA techniques and wheat variety and under different environmental condition.

1. Introduction

Climate variability alongside population growth imposes pressure on global freshwater availability. Agricultural production is affected by drought globally and efforts are being made to evaluate its severity and imapcts on the productivity of agricultural produce. To assess this, the prediction of yield losses under drought conditions at both local and regional levels is being achieved using remote sensing data coupled with crop models (1).

Optimal irrigation scheduling that will enable sustainable utilization of limited water is a nonlinear problem that is affected by uncertainty due to competing and conflicting dynamic environmental conditions (2). Crop models are cheap tools that help in optimizing water resources used in agricultural production. They provide the possibility to

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assess various water management strategies both in rainfed and irrigated environments for efficient utilization of scarce water resources. The simplifications and assumptions involved in their equations and parameterizations lead to uncertainty and variation of output variables (3,4). Some sources of uncertainties in model inputs include errors in measurement, lack of adequate and current information and inadequate or partial understanding of the model's driving forces and mechanisms (5) which lead to the inaccurate setting of crop parameters' values. Furthermore, some natural spatio-temporal variability of input variables occurs in response to events such as climate change and geological actions among others (6).

The suitability of models for their applications is affected by their requirement for large number of input parameters. Parameters that are difficult to obtain are usually estimated during calibration (3,7). Manual one-at-time estimation and adjustment of all models input parameters is tedious and time-consuming. Sensitivity analysis (SA) reveals the degree of vulnerability of model's output to variations in the model's building elements, which are most likely influenced by uncertainties and/or variations in soil, crop, and climatic compositions (3). It could be categorized into Local Sensitivity Analysis (LSA) and Global Sensitivity Analysis (GSA). LSA or one-at-a-time estimates the sensitivity at one point in the parameter space, while GSA estimates sensitivity over the entire space (3). SA, therefore, identifies high-impact parameters that need to be measured or estimated with high precision. It also permits the appropriate fixing of low-impact or insensitive parameters during model parameterization and calibration.

The simpler crop models have limitations, especially in simulating crop productivity under water or nutrient-limiting conditions and in simulating physiological processes related to soil water conditions. On the other hand, the dynamic and complex crop models that effectively simulate crops' responses to variations in environmental conditions at different growth stages predict crop development and productivity more realistically (2). However, many complex crop models are site-specific, cumbersome and require extensive data set, which negates their application elsewhere (8). Distinctively, the AquaCrop model possesses specific characteristics of simplicity, precision, and resilience, thus having a universal applicability. Evidently, it is one of the most preferred crop model by soil and crop-related scientists, including but not limited to extension workers, water users, consultants, irrigation managers, and economists. Despite this preference, the practical running of the model is easier said than done for many scientists due to the complexities involved in its mathematical operations and large data requirement, thereby limiting its wide adoption (9). For effective implementation of such models, it is thus necessary to critically analyze the unbiguities involved at the various stages of the modeling processes (4). Simplifying the AquaCrop model by reducing its required data and calibration procedure would aid in increasing the number of its users in the semi-arid region of Nigeria.

Variations in the sensitivities and ranking of parameters as a function of environmental conditions make it impracticable to generate a universally valid list of significant data for the AquaCrop model (4,10). Also, Guo *et al.* (11) stated that some model parameters' behaviours vary with cultivars, field management and environmental conditions. The SA of the AquaCrop model using LSA technique is scarce in literature because of the criticism it received in dealing with complex models. Among the few researches are the work of Adabi *et al.* (7) who studied the sensitivity of the model input parameters on its output variables using the LSA technique in a semi-arid environment in Iran. They established wheat and maize output variables to be highly sensitive to canopy growth coefficient, days from sowing to maturity and start of senescence, and maximum canopy cover. They further stated that simpler LSA could lead to outcomes similar to analysis conducted using the complex and highly computational GSA techniques. Using similar LSA technique, Salemi *et al.* (12) and Geerts *et al.* (13) evaluated the sensitivity of a single AquaCrop output variable (grain yield) to fourteen (14) input parameters only. Thus, in most of the studies conducted using the LSA, limited number of input parameters and single variable as the model output were considered. This could be insufficient in making inference on the model's influential parameters. Hence, there is need to evaluate the effect of many input parameters on various output variables to extensively identify the most sensitive parameters for the model evaluation and application.

Despite the wide acceptance of wheat as a stable food in northern Nigeria, there is a dearth of information regarding the sensitivity of the AquaCrop model to its building components to inform decision-making for wheat production in the semi-arid environment of North-eastern Nigeria. To the best of the authors' knowledge, this is the first work on the sensitivity analysis of the AquaCrop model for wheat in the region. Consequently, this work studied the sensitivity of thirty eight (38) model's input parameters at the initial, mid and late season growth stages of wheat under water deficit condition to the three major model's output viz. grain yield, biomass yield and canopy cover. The outcome of this analysis distinguishes

AquaCrop model's sensitive/influential parameters from insensitive parameters. The former parameters require higher consideration during their determination, data collection and model evaluations while the values of insensitive parameters could be designated within their ranges. Thus, this would aid in simplifying and reducing the workloads in the model's evaluations and provide some crucial information for future researchers involving in modelling wheat production under similar environmental conditions.

2. Materials and Methods

2.1 Study Location and Crop Variety

The study was conducted based on the climate and soil characteristics of the Lake Chad Research Institute (LCRI) experimental site, located in Maiduguri, Borno state, North-eastern Nigeria. It lies between latitudes 11°45'N and 11°51'N, longitudes 13°2'E and 13°9'E, on 345 m above mean sea level with a mean annual rainfall of about 625 mm (14). Figure 1 shows the map of the study area (15). The crop selected was REYNA-28 wheat variety which has outstanding characteristics of medium maturity (90-95 days), heat tolerant, good yielding (5-5.5 t/h) and baking quality and well adapted to irrigated conditions of the entire Northern Nigeria.

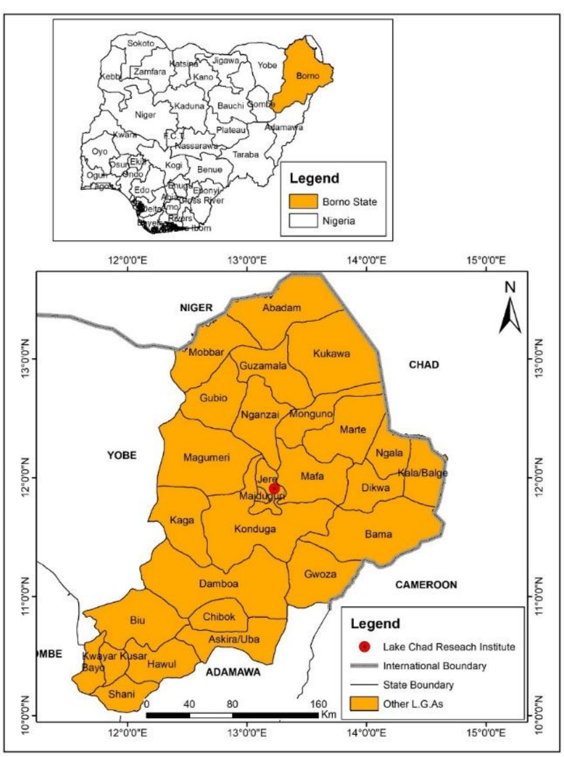

Fig 1. Map of Borno state indicating the study location

The texture of the soil at the experimental site is sandy loam to sandy clay loam which it becomes more clayey towards the east direction. Table 1 presents the soil information of the site (15).

Table 1. Physical properties of the soil at the experimental site

Properties/Layers	0-30cm	30-60cm	60-90cm	90-120cm	120-150cm
Textural Class	Sandy loam	Sandy clay loam	Sandy loam	Sandy clay loam	Sandy clay loam
SAT (g/g)	0.325	0.428	0.394	0.444	0.444
FC (g/g)	0.257	0.104	0.085	0.104	0.118
PWP (g/g)	0.027	0.055	0.051	0.066	0.077
Bulk density (g/cm^3)	1.63	1.46	1.70	1.56	1.52
Ksat (mm/day)	1200	269	1200	273	342

NB: SAT = gravimetric moisture content at saturation; FC = gravimetric moisture content at field capacity; PWP = gravimetric moisture content at permanent wilting point; Ksat = saturated hydraulic conductivity.

The meteorological data used in running the model (as climate input) was a ten-year historical data (2005-2015) comprised the average monthly daily minimum and maximum air temperature, relative humidity, wind speed and sunshine duration. Wheat is grown in the location during the dry harmattan period from November to March. Table 2 gives the monthly average daily climatic data of the location (15).

Table 2. Monthly average daily climatic variables of the study area

Months	Min. Temp. (°C)	Max. Temp. (°C)	Relative Humidity (%)	Wind Speed (m/s)	Sunshine Duration (Hours)
January	13.4	32.7	32	1.2	7.8
February	17.8	35.2	25	1.3	8.6
March	20.8	37.8	20.7	1.6	9.7
April	24.7	40.3	28.3	1.6	9.9
May	26.1	39.3	41.8	1.6	9.1
June	24.6	36.6	55.6	1.6	8.3
July	23.1	32.2	71.2	1.5	7.6
August	22.0	30.8	80.2	1.3	6.9
September	22.4	32.7	71.9	1.5	8.4
October	22.4	35.2	55.9	1.4	8.3
November	16.8	36.0	36.0	0.9	7.7
December	13.3	33.0	34	0.9	7.7

2.2 The FAO AquaCrop Model

Estimating attainable yield under water deficit conditions is critical in arid, semi-arid and drought-prone environments. To address this need, the FAO has developed a yield-response to water model; AquaCrop, which simulates attainable yields of the major herbaceous crops. The FAO AquaCrop has evolved from the concept of yield response to water (16) to the concept of normalized water productivity and focuses its simulation on attainable crop biomass and yield in response to water availability.

The model components include the soil with its water balance; the crop with its development and productivity; the atmosphere with its thermal regime, rainfall, evaporative demand and CO_2 concentration and; the management such as irrigation, soil fertility, weed infestation, water conservation etc. which determine soil water balance, crop development and productivity. The model simulates the final yield of major herbaceous crops at a final stage of four developmental stages (Equations 1 to 6) (9) which include the simulations of canopy cover (CC), crop transpiration (T_r), aboveground biomass (B) and the final yield (Y). Temperature and water stresses directly influence one or more of the above processes. Soil fertility and salinity stresses are simulated by adjusting canopy development and by decreasing transpiration and normalized water productivity (WP*).

The model simulates CC using Equations (1) and (2) and canopy senescence using Equation (3). Equation (4) depicts the simulation of T_r.

$$\mathrm{CC} = \mathrm{cc_o} * e^{\mathrm{tCGC}} \text{ when } \mathrm{CC} \leq \mathrm{CC_x}/2 \quad (1)$$

$$\mathrm{CC} = \mathrm{CC_x} - 0.25\, \frac{(\mathrm{CC_x})^2}{\mathrm{cc_o}}\, e^{-\mathrm{tCGC}} \text{ when } \mathrm{CC} > \mathrm{CC_x}/2 \quad (2)$$

$$\mathrm{CC} = \mathrm{CC_x}\left[1 - 0.05\left(e^{\frac{3.33\mathrm{CDC}}{\mathrm{CC_x}+2.29}t} - 1\right)\right] \quad (3)$$

cc_o = initial canopy cover,
CGC = canopy growth coefficient,
CC_x = maximum canopy cover,
CDC = canopy decline coefficient.

$$\mathrm{T_r} = (\mathrm{Ks} * \mathrm{Ks_{Tr}} * \mathrm{Kc_{Tr}})\, \mathrm{ET_O} \quad (4)$$

Ks = water stress coefficient,
Ks_{Tr} = cold stress coefficient,
K_{cTr} = crop coefficient when the canopy is complete but prior to senescence.

The model simulates B as the product of WP*, and the cumulative ratio of the daily T_r over the ET_o for that day as shown in Equation (5). It simulates Y as the product of B and an adjusted reference harvest index (HI_o) (a cultivar-specific crop parameter), which is adjusted for stress effects with a factor (fHI) as shown in Equuation (6).

$$\mathrm{B} = \mathrm{WP}^* * \sum\left(\frac{\mathrm{T_r}}{\mathrm{ET_o}}\right) \quad (5)$$

$$\mathrm{Y} = f\mathrm{HI}\ \mathrm{HI_o}\ \mathrm{B} \quad (6)$$

2.3 The Sensitivity analysis of the Model

The sensitivity of three (3) major output variables of the AquaCrop model viz. grain yield (GY), biomass yield (BMY) and canopy cover (CC) to variations in its input parameters was analyzed at initial, mid, and late-season growth stages of wheat. This is in line with the time-dependence characteristics of the model's sensitivity to its input parameters (6,10). The sowing date selected was 26^{th} November and the harvest date was 23^{rd} February, 2020. Being frequent in many wheat growing environments, and to facilitate the evaluation of the model's sensitivity to water stress parameters as described by Lievens (17) and Upreti *et al.* (3), deficit irrigation scenario (weekly irrigation at 50 % gross depth throughout the growing season) was selected as the irrigation input. A local or one-at-a-time sensitivity analysis techniqe was employed and input parameters were altered by ±5 % of their default values since the change in variables is somewhat arbitrary. The relative change in output due to a change in a model's input parameter was measured by the sensitivity coefficient (SC) (12), as presented in Equation (7).

$$\mathrm{SC} = \left(\frac{\Delta \mathrm{O}}{\bar{\mathrm{O}}}\right) / \left(\frac{\Delta \mathrm{I}}{\bar{\mathrm{I}}}\right) \quad (7)$$

ΔO = Change in model's output due to change in model's input,
$\bar{O}$ = Output average,
ΔI = Change in model's input variable/parameter and
$\bar{I}$ = Average of input.

Classes of sensitivity were designated as high, moderate and low if the SC was higher than 1.5, between 1.5 and 0.2, and smaller than 0.2, respectively (12,17) and the sensitivity coefficient of zero gave null or insensitivity.

3. Results and Discussion

3.1 Sensitivity Analysis

The abbreviation, description and sensitivity coefficients output of the 38 model's input parameters for grain yield simulation are presented in Table 3. The sensitivity coefficients of the model's input parameters considering biomass yield and canopy cover outputs are presented in Table 4. The result showed that grain yield was most sensitive to WP* and days-to-flowering (DtF) with SCs of 1.05 and 1.23 respectively. This could be logical because the WP* is the proportional factor in determining biomass yield, which is the basis for grain yield simulation (Equation 5-6). Also, the quantity of yield is determined by the flowering time of crops (11).

Table 3. Sensitivity coefficients of AquaCrop input parameters for grain yield

Parameters	Description (units)	S.C (+5 %)	S.C (-5 %)
cc_o	Initial canopy cover (%)	0.06	0.05
ccs	Soil surface covered by individual seedling at 90% emergence (cm^2/plant)	0.06	0.05
den	Number of plants per hectare	0.06	0.05
CC_x	Maximum canopy cover (%)	0.28	0.33
CGC	Canopy growth coefficient (fraction/day)	0.61	0.55
CDC	Canopy decline coefficient (fraction/day)	0.06	0.05
Z_x	Maximum effective rooting depth (m)	0.61	0.60
Av. Zexp	Average root zone expansion (cm/day)	0.28	0.33
Z_n	Minimum effective rooting depth (m)	0.06	0.00
Z_{sh}	Shape factor describing root zone expansion	0.11	0.11
K_{cdcl}	Decline of K_c as a result of ageing (%/day)	0.00	0.00
K_{cTrx}	K_c when canopy is complete but prior to senescence	0.75	0.58
WP^*	Water productivity normalized for ET_o and CO_2 (g/cm^2)	1.05	0.94
WP^*-YF	Adjustment of WP^* during yield formation (% of WP^*)	0.42	0.36
HI_o	Reference harvest index (%)	0.83	0.83
P_{exup}	Soil water depletion threshold for canopy expansion-Upper	0.06	0.05
P_{exlw}	Soil water depletion threshold for canopy expansion-Lower	0.34	0.38
P_{exsh}	Shape factor for water stress coefficient for canopy expansion	0.11	0.05
P_{sto}	Soil water depletion threshold for stomatal control-Upper	0.11	0.11
P_{stosh}	Shape factor for water stress coefficient for stomatal control	0.06	0.05
P_{sen}	Soil water depletion threshold for canopy senescence-Upper	0.17	0.11
P_{sensh}	Shape factor for water stress coefficient for canopy senescence	0.00	0.00
P_{aer}	Anaerobic point at which deficient aeration occurs (vol %)	0.00	0.00
P_{pol}	Soil water depletion threshold for failure of pollination-Upper	0.00	0.00
PIHI/F	Possible increase of HI due to water stress before flowering (%)	0.11	0.08
Pos. HI	Coefficient describing positive impact on HI of restricted vegetative growth during yield formation	0.06	0.05
Neg. HI	Coefficient describing negative impact on HI of stomatal closure during yield formation	0.06	0.00
Max. Inc. HI	Allowable maximum increase of specified HI (%)	0.00	0.00
Pol. T_x	Maximum air temperature limiting pollination (^oC)	0.00	0.00
Pol. T_n	Minimum air temperature limiting pollination (^oC)	0.00	0.00
DtE	Days-to-emergence (days)	0.07	0.05
$DtCC_x$	Days-to-CC_x (days)	0.32	0.30
DtZ_x	Days-to-Z_x (days)	0.00	0.00
DtSS	Days-to-start of senescence (days)	0.08	0.20
DtM	Days-to-maturity (days)	0.00	0.73
DtF	Days-to-flowering (days)	1.23	0.34
DF	Duration of flowering (days)	0.00	0.13
LBHI	Length building up HI (days)	0.00	0.00

The grain yield was moderately sensitive to CC_x, CGC, Z_x, Av. Zexp, K_{cTrx}, WP*, WP*-YF, HI_o, P_{explw} and $DtCC_x$ at both ±5 % changes in their base values. Similarly, at both ±5 % changes, the grain yield exhibited low sensitivity to The model was sensitive to DtM, which significantly increased its SC from zero at +5 % change to moderate at - cc_o, ccs, den, CDC, P_{expup}, Z_{sh}, P_{expsh}, P_{sto}, P_{stosh}, P_{sen}, PIHI/F, Pos. HI, DtE and DtSS. The analysis indicated that the grain yield was insensitive to K_{cdcl}, P_{sensh}, P_{aer}, P_{pol}, Max. Inc. HI, Pol. Tx, Pol. Tn, DtZ_x and LBHI. 5 % change in its base value. The grain yield showed higher sensitivity to variations of DtF, WP*, HI_o, K_{cTrx},

CC_x, Z_x, WP*-YF, P_{explw}, CC_x, Av. Zexp, $DtCC_x$ and DtM. A similar set of influential parameters for grain yield of DtE. Similarly, Silvestro *et al.* (1) reported CDC, DtSS, LBHI, P_{sen} and P_{sto} among the input parameters to which grain yield was sensitive, contrary to this work's outcome. On the other hand, Vanuytrecht *et al.* (4) found DtF, HI_o and K_{cTrx} among the non-influential model input parameters, which were influential in this work. These wheat were reported by Upreti *et al.* (3) based on global sensitivity analysis methods, with the addition of CDC and deviations might be due to environmental conditions and differences in the approaches adopted for the analysis. Further, Salemi *et al.* (12) changed AquaCrop input parameters values with ±50 % using wheat crop and got SC values similar to those obtained in this work.

Table 4. Sensitivity coefficients of AquaCrop input parameters for biomass yield and canopy cover at various growth stages

PARAMETERS	BMY						CC					
	VEG		FLO		YF		VEG		FLO		YF	
	+5	-5	+5	-5	+5	-5	+5	-5	+5	-5	+5	-5
cc_o	0.79	0.78	0.04	0.14	0.03	0.00	0.80	0.79	0.08	0.05	0.08	0.00
ccs	0.90	0.78	0.04	0.13	0.03	0.00	0.95	0.79	0.08	0.05	0.08	0.00
den	0.90	0.78	0.04	0.14	0.03	0.00	0.80	0.79	0.08	0.05	0.08	0.00
CC_x	0.11	0.11	0.46	0.47	0.30	0.37	0.16	0.16	0.32	0.36	1.02	0.90
CGC	0.57	0.56	0.33	0.51	0.60	0.56	0.95	0.95	0.93	0.82	0.20	0.32
CDC	0.00	0.00	0.06	0.05	0.08	0.05	0.00	0.00	0.03	0.00	0.10	0.00
Z_x	0.00	0.00	0.24	0.43	0.44	0.43	0.00	0.00	0.24	0.23	0.05	0.34
Av. Zexp	0.00	0.00	0.24	0.32	0.25	0.24	0.00	0.00	0.19	0.21	0.00	0.22
Z_n	0.00	0.00	0.04	0.02	0.03	0.03	0.00	0.00	0.03	0.03	0.03	0.02
Z_{sh}	0.00	0.00	0.11	0.14	0.08	0.11	0.00	0.00	0.11	0.13	0.08	0.10
K_{cdcl}	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
K_{cTrx}	1.12	0.90	0.52	0.58	0.22	0.21	0.00	0.00	0.61	0.51	0.54	0.22
WP^*	1.12	0.90	1.07	0.93	1.05	0.94	0.00	0.00	0.00	0.00	0.00	0.00
WP^*-YF	0.00	0.00	0.02	0.02	0.41	0.40	0.00	0.00	0.00	0.00	0.00	0.00
HI_o	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
P_{exup}	0.00	0.00	0.01	0.01	0.03	0.03	0.00	0.00	0.03	0.05	0.03	0.02
P_{exlw}	0.00	0.00	0.07	0.08	0.30	0.35	0.00	0.00	0.46	0.52	0.15	0.17
P_{exsh}	0.00	0.00	0.03	0.02	0.06	0.05	0.00	0.00	0.08	0.08	0.03	0.02
P_{sto}	0.00	0.00	0.16	0.19	0.08	0.05	0.00	0.00	0.05	0.05	0.10	0.05
P_{stosh}	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.27	0.00	0.00	0.00
P_{sen}	0.00	0.00	0.00	0.00	0.17	0.11	0.00	0.00	0.14	0.13	0.00	0.20
P_{sensh}	0.00	0.00	0.00	0.00	0.00	0.03	0.00	0.00	0.00	0.03	0.00	0.00
P_{aer}	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
P_{pol}	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PIHI/F	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Pos. HI	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Neg. HI	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Max. Inc. HI	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Pol. T_x	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Pol. T_n	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
DtE	1.80	1.45	0.42	0.29	0.13	0.08	2.41	2.19	0.14	0.16	0.08	0.12
$DtCC_x$	0.58	0.65	0.45	0.38	0.26	0.21	1.00	0.91	0.36	0.48	0.28	0.22
DtZ_x	0.00	0.00	0.23	0.14	0.15	0.10	0.00	0.00	0.14	0.10	0.15	0.10
DtSS	0.00	0.00	0.00	0.00	0.11	0.25	0.00	0.00	0.00	0.00	0.46	0.69
DtM	0.00	0.00	0.00	0.00	0.00	0.65	0.00	0.00	0.00	0.00	0.00	0.00
DtF	0.00	0.00	0.07	0.10	0.55	0.25	0.00	0.00	0.22	0.29	0.15	0.39
DF	0.00	0.00	0.00	0.02	0.00	0.02	0.00	0.00	0.00	0.16	0.00	0.27
LBHI	0.00	0.00	0.00	0.00	0.00	0.14	0.00	0.00	0.00	0.00	0.00	0.00

Parameters as defined in Table 3.

The result showed that biomass yield and canopy cover were moderately sensitive to cc_o, ccs and den during the crop's initial stage. Their impacts declined from mid-season to late season when density is stable because they are crop characteristics at the seedling stage (10). Biomass yield and canopy cover were moderately sensitive to CC_x from mid-season, when the crop's canopy could reach maximum. From this period, CC_x is active in the model's simulations of canopy development and its senescence. Throughout the three growth stages, the sensitivity of the model to CGC was moderate.

Biomass yield and canopy cover were insensitive to Z_x earlier in the season because, at that time, the plant's root is yet to reach it maximum. The sensitivities of Z_x and Av.Z_{exp} increased from null to moderate at the mid and end seasons as observed by Xing *et al.* (10). During the initial and subsequent stages, BMY and CC exhibited zero and low sensitivities, respectively, to Z_n and Z_{sh}.

The SCs of Kc_{Trx} indicated that BMY was moderately sensitive to the parameter throughout the three growth stages. Canopy cover showed zero sensitivity to the parameter at the initial stage, but it later increased to moderate at both mid and late seasons. The parameter illustrated crop coefficient at maximum canopy (at which transpiration is maximum under non-limiting conditions).

Biomass yield indicated higher sensitivity to WP*, which is the major multiplier or deriving factor for biomass production from crop transpiration (Equation 5). The CC indicated zero sensitivity to the WP* because the parameter is not involved in its simulation (Equations 1-3). WP*-YF is the adjustment of WP* during the yield formation stage; thus, biomass yield was only sensitive to the parameter at the late season. The sensitivities of BMY and CC to HI and its related parameters were zero because the parameters are only involved at the final stage of partitioning grain yield from biomass yield (Equation 6).

Biomass yield and canopy cover were insensitive to the water stress parameters except P_{exlw}, P_{sto} and P_{sen} in mid and late seasons. The analysis also revealed that BMY and CC were highly sensitive to DtE at the initial stage, with SCs of 1.80 and 2.41, respectively. The high impact of the parameter could be because crop emergence establishes the bases of crop evolution which could influence all other growth and production phases. The effectiveness of the parameter dropped from the mid to the late season. The model's sensitivity to $DtCC_x$ was moderate throughout the three growth stages while the sensitivity to DtZ_x increased from zero to low in the mid and late seasons. Day to start of canopy decay which is attained lately in the season was only effective during the late season, as indicated by DtSS. The model's sensitivity to DtF and DF increased from zero at the early stage to moderate after the flowering period of the crop was reached (during the mid-season).

It could be deduced that BMY and CC were sensitive to cc_o, cc_s, den, CC_x, CGC, Z_x, Av.Z_{exp}, K_{cTrx}, WP*, WP*-YF, P_{explw}, DtE, $DtCC_x$, DtSS and DtF and exhibited the most sensitivity over DtE, WP*, K_{cTrx}, CGC and CC_x.

The analysis showed that water stress parameters did not have a high impact on the model under moderate water stress which is in line with Guo *et al.* (11) and Upreti *et al.* (3). The only influential water stress parameter in this analysis was P_{explw} which is the lower stress threshold below which leaf expansion halted. Change in this limit could have a significant effect on canopy development because of the severity of it impact (it does not only retard the rate of leaf expansion rather it terminates it). It could also be observed from Tables 3 and 4 that root development parameters such as Z_x and Av. Zexp had significant effects on the model's output, which can be supported by the report of a consensus on Z_x as a critical parameter in the AquaCrop model (17). Also, Jin *et al.* (6) and Xing *et al.* (10) reported that root development parameters that are difficult to obtain were sensitive, especially under water deficit conditions.

Overall, the influential model parameters from this analysis were cc_o, cc_s, den, CC_x, CGC, Z_x, Av.Z_{exp}, K_{cTrx}, WP*, WP*-YF, HI_o, P_{explw}, DtE, $DtCC_x$, DtSS, DtM and DtF which are mainly related to phenology, biomass accumulation, canopy growth and root development as it was reported in many works (1,3). Considering the three (3) selected output variables, half of the model's input parameters were ineffective. Many researchers reported similar outcomes (eg. 5,8,12,20), indicating the model's simplicity and robustness. The influential model parameters require proper consideration in their determination, estimation, fine-tuning and during the model calibration and localization. The ineffective parameters could be fixed within their range values in order to simplify the model evaluations and application.

4. Conclusion

The sensitivity analysis of the AquaCrop model was carried out to distinguish the model's influential parameters from non-influential parameters as a step in simplifying its evaluations. This would inform efficient decision-making and planning in wheat production using the model. The SA of the model using local sensitivity analysis technique was performed under the Semi-arid Northeastern Nigeria water deficit condition. Grain yield was found to be sensitive to DtF, WP*, HI_o, K_{cTrx}, CC_x, Z_x, WP*-YF, P_{explw}, CC_x, Av. Zexp, $DtCC_x$ and DtM. Some of the model's input parameters were found to have affected biomass yield and canopy cover at some growth stages and insensitive at other stages because the activities of certain parameters depend on time. These parameters included CC_x, Z_x and Av.Z_{exp} among others. The sensitivity coefficients (SCs) of most of the stresses parameters indicated their ineffectiveness in the model. It was also discovered that half of the model's input parameters were non-influential, indicating the model's simplicity. Overall, the influential model parameters from this analysis were cc_o, cc_s, den, CC_x, CGC, Z_x, Av.Z_{exp}, K_{cTrx}, WP*, WP*-YF, HI_o, P_{explw}, DtE, $DtCC_x$, DtSS, DtM and DtF. These parameters require proper consideration in their determination, estimation, fine-tuning and during the model calibration and localization. The ineffective parameters can be fixed within their range values in order to simplify the model evaluations and application. Validation of this outcome can be conducted using different SA approach, different wheat cultivars and under different environmental conditions.

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Conflict of Interest

The authors declare that they have no conflict of interest

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