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Research Paper

Sensitivity analysis of AquaCrop model for simulating canopy cover, biomass and yield of pearl millet (*Pennisetum Glaucum* L.) in semi-arid region of Nigeria

NURENI I. LAWAL[1], MUHAMMAD M. HARUNA[2*], JIBRIN M. DIBAL[2], ABDU, D.[2], ADAMU Y. ARKU[2] and YUSUF A. UMAR[2]

[1]Faculty of Agriculture, Borno State University, Maiduguri, Borno State, Nigeria

[2]Department of Agricultural and Environmental Resources Engineering, Faculty of Engineering, University of Maiduguri, Maiduguri, Borno State, Nigeria

Corresponding Author email: mhmansur92@unimaid.edu.ng

ABSTRACT

The need for a localized crop model that will aid in evaluating various strategies for efficient water management, especially in the semi-arid Lake Chad region does not need to be overemphasized. Therefore, as a step to simplify the calibration of the AquaCrop model, this study assessed the sensitivity of the model's output variables to pearl millet crop input parameters under water stress conditions of Maiduguri, Northeastern Nigeria. The analysis was carried out using the Local Sensitivity Analysis (LSA) technique under a 50 % deficit irrigation scenario. The result revealed that the effects of the input parameters on canopy cover (CC) and biomass yield (BMY) simulations were time-dependent. Overall, a significant number of the model's inputs were found to be non-influential; these parameters could be set within their predetermined range in order to simplify the model. Whereas, the influential parameters should be given higher consideration during calibration, data collection, and future model development. The results of this study could also be validated using more advanced methods like the Global Sensitivity Analysis (GSA) technique, on different crop varieties that have longer phenological stages and under severe water and fertility stresses.

Keywords: AquaCrop model, Lake-Chad Nigeria, Pearl millet, Sensitivity analysis, Water stress.

Sustainable food production to feed the expanding population requires producing more with less water, which is achievable through efficient irrigation management. Pearl millet stands out for its resilience, thriving in hot, dry climates, and tolerating saline, acidic, and low fertility soils of the semi-arid environment (Seghatoleslami *et al.,* 2008). Many farmers in the semi-arid areas have demonstrated interest in pearl millet production for its economic, nutritional, and health benefits, besides its low input requirements during cultivation (Hassan *et al.,* 2021). Yet, the dearth of irrigation management data for this crop challenges the ability of agricultural extension officers and stakeholders to provide targeted support to subsistence farmers in the region.

The AquaCrop model has demonstrated its potential for exploring water management strategies across multiple crops (Sankar *et al.,* 2023), assessing climate uncertainty, and informing climate change adaptation and mitigation efforts (Balvanshi and Tiwari, 2019). However, the model's complexity and numerous input parameters pose significant calibration challenges, leading to tedious evaluation processes that can introduce uncertainty and compromise its reliability. To address this challenge, applying sensitivity analysis (SA) to the AquaCrop model is essential for identifying influential parameters, streamlining calibration, enhancing accuracy, and reducing data processing demands (Vanuytrecht *et al.,* 2014). Recent studies by de Souza *et al.,* (2022) and Haruna *et al.,* (2023) being a simple and important technology to develop studies aiming to improve the yields of the most agricultural crops, like the maize in Brazil. The objective of this study was to analyze the sensitivity of the main AquaCrop model input parameters, as well as their responses in maize yield estimation, in State of Paraná, Southern Brazil. The analyses were performed with the genotype 30R50YH, 2014/15 planted on April 11, 2014. The parameters analyzed refer to crop, soil and soil management. The parameters were modified individually, maintaining the others fixed. With the results, the

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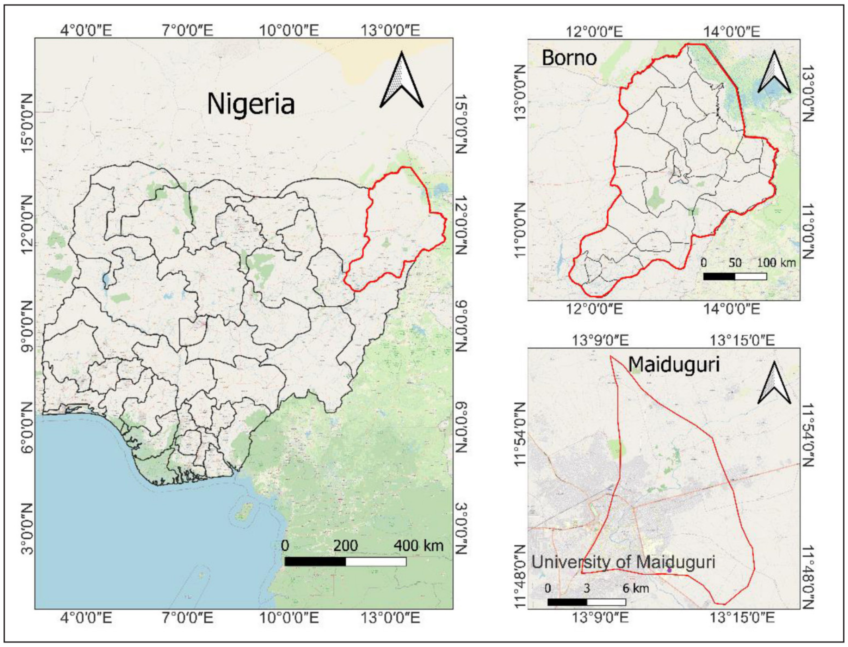

Fig. 1: Map of the study area in Nigeria-Maiduguri, Borno state

sensitivity index (SI show that Local Sensitivity Analysis (LSA) can yield similar outcomes to those obtained from Global Sensitivity Analysis (GSA). The LSA is less computational and could be a pragmatic alternative to obtain reliable information regarding the model's behavior towards uncertainty in its input parameters.

Numerous studies such as Vanuytrecht *et al.,* (2014) have applied sensitivity analysis to the AquaCrop model across various crops including wheat and maize under diverse environmental conditions. These studies show that the sensitivity of the model is influenced by environmental conditions, crop type, target output, parameter ranges, and the methods and techniques employed. Previous studies predominantly focus on grain yield, often overlooking canopy cover—an essential basis for biomass and grain yields, especially across different phenological stages (Lu *et al.,* 2021)a global sensitivity analysis on crop yield and transpiration was performed for 49 parameters in the FAO-AquaCrop model (version 6.0. A more detailed SA across the crop lifecycle could improve model accuracy and simplify its application. In Nigeria's northeast, SA research remains limited, with a single known study on wheat (Haruna *et al.,* 2023)thecalibration of the model could be tedious due to its large number of input parameters. Thecomplexity in the model evaluation could be simplified by conducting a prior sensitivityanalysis (SA which could not be adopted for another crop like pearl millet. Given these gaps, the present study investigates the sensitivity dynamics of AquaCrop model input parameters throughout the pearl millet growing season under the semi-arid conditions of Maiduguri, Northeastern Nigeria.

MATERIALS AND METHODS

Study area

This study was carried out based on the climate and soil conditions of the Faculty of Agriculture Research Farm, University of Maiduguri, Borno state, Nigeria (Fig. 1), geographically located between latitudes 11° 46\` 18\`\` to 11° 53\` 12\`\` N and longitudes 13° 03\` 23\`\` to 13° 14\` 19\`\` E at an altitude of 355 m above mean sea level. The area experiences a semi-arid climate with tropical grassland vegetation (Haruna *et al.,* 2023)thecalibration of the model could be tedious due to its large number of input parameters. Thecomplexity in the model evaluation could be simplified by conducting a prior sensitivityanalysis (SA and two distinct seasons: a wet season (June to September) and a dry season (October to April).

Table 1 presents the monthly averages of thirty years (1992-2023) ground-based measured meteorological variables of the study area, obtained from the Nigerian Meteorological Agency (Nimet). The region is marked by high temperatures for most of the year, with average maximum, minimum, and mean values of 35.6°C, 20.7°C, and 28.2°C, respectively. Relative humidity is moderate, averaging 41.8 %. Annual rainfall is also moderate (mean: 793.4 mm), but with highly inter-annual variability over the last three decades, ranging from 500 to 1400 mm.

The soil of the experimental site was sampled randomly by the use of an auger at an incremental depth of 15 cm down to 60 cm depth. The result of the physical and chemical properties of the samples analyzed at the Department of Soil Science laboratory, University of Maiduguri are shown as presented in Table 2.

The decreasing trend of field capacity and permanent wilting point with soil depth reflects typical variations in soil properties—upper layers, richer in organic matter and finer particles, retain more water, while deeper layers are coarser and less organic, reducing water-holding capacity**.** The mean value of available water was 300 mm m^{-1} and the saturated hydraulic conductivity (K_{sat}) was 13.96 mm hr^{-1}, indicating moderate permeability. Organic matter (OM) content averaged 0.47 %, considered low as per Tekalign (1991), potentially affecting pearl millet yield. Electrical conductivity (EC) obtained was low within the USDA acceptable range (< 2.0 dS m^{-1} at 25 °C), thus making the soil suitable for millet

Table 1: Average monthly climate data of the experimental area

Months	Max. temp. (°C)	Min. temp. (°C)	Rel. hum. (%)	Wind speed (m s^{-1})	Sunshine (h day^{-1})	Rainfall (mm)
Jan.	32.0	13.0	25.0	2.9	8.0	0.0
Feb.	34.7	16.4	19.7	3.0	8.8	0.0
Mar.	39.3	20.4	16.4	3.1	8.1	0.1
Apr.	41.5	25.1	25.5	2.9	7.7	4.7
May	40.5	26.5	40.7	3.0	8.5	31.4
Jun.	36.7	25.3	54.9	3.2	8.0	83.2
Jul.	33.2	23.8	68.7	3.2	6.8	236.7
Aug.	31.3	22.9	75.8	2.8	6.6	256.6
Sept.	33.3	23.2	70.3	2.4	7.3	160.4
Oct.	36.4	21.8	48.9	2.2	8.4	20.6
Nov.	36.0	16.7	28.5	2.7	9.3	0.0
Dec.	32.8	13.4	27.1	2.8	8.6	0.0

Table 2: Properties of soil at the experimental site

Soil property	Soil depth (cm)		
	0 – 30	30 – 60	Average
Textural class	Sandy clay loam	Sandy clay loam	
Bulk density (gcm^{-3})	1.11	1.12	1.12
Saturation (%)	25.07	18.13	21.60
Field capacity (%)	8.27	7.67	7.97
Permanent wilting point (%)	5.57	4.63	5.05
Available water (mm m^{-1})	300	300	300
Saturated hydraulic conductivity (mm hr^{-1})	14.36	13.56	13.96
Organic matter (%)	0.47		
Salinity (dS m^{-1})	0.22		

cultivation.

Crop variety

The study utilized an early maturing pearl millet variety (LCICMV4 – PEO594), developed and distributed by the Lake Chad Research Institute (LCRI), Maiduguri. This variety, commonly called "JIRANI", is widely adopted by farmers due to its outstanding characteristics, including early maturity (70 - 90 days), high iron (Fe) and zinc (Zn) content, resilience to water stress, and a yield potential of 2.5-3.0 t ha^{-1}.

By default, the AquaCrop model does not contain millet crop file data base. However, the model permits creation of new crop file. A millet crop file was created due to the significance of the crop to the semi-arid region and was the sole crop under study. Some crop parameters mainly conservative were adopted from previous literatures such as Bello and Walker (2016)mainly drier tropics. Although it is easy to cultivate under semi-arid and arid regions, it still responds very favourably to slight improvements in growing conditions such as supplementary irrigation. Because this crop is mostly cultivated under water-limited conditions, there is a need to develop strategies to promote efficient water use, and this can be achieved through field experiments and or crop modelling. The AquaCrop model requires a minimum number of crop parameters, with the aim of balancing simplicity, accuracy, robustness and user-friendliness. In this study, we calibrate and validate the AquaCrop model for an underutilised crop, pearl millet under irrigation and rainfed conditions. Experiments were carried out in lysimeters with two varieties of pearl millet (GCI 17, improved variety; Monyaloti, local variety; and Guo *et al.,* (2018). Table 3 presents the symbols, descriptions, units and base values of the AquaCrop pearl millet input parameters considered in this analysis.

Sensitivity analysis of the model

A LSA (one-at-a-time) was conducted to assess how variation in input parameters affect key AquaCrop outputs— canopy cover (CC), biomass yield (BMY), and grain yield (GY)—for pearl millet at three growth stages: vegetative, flowering, and yield formation represented by 20, 50 and 70 days after planting (DAP) respectively. Each parameter was varied by ± 25 % of its base value (Table 3) while others were kept fixed. The impact was quantified using the Sensitivity Index (SI), as given below (Rosa *et al.,* 2023) 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.

$$SI \quad \frac{I12\ (R1\text{-}R2)}{R12(I1\text{-}I2)}$$

Where: R_1 and R_2 are outputs at low and high input values respectively; I_1 and I_2 are low and high input values respectively; and I_{12} and R_{12} are means of input and corresponding output value, respectively.

Sensitivity was classified as high sensitivity (SI > 1.5), moderate sensitivity (0.3 < SI < 1.5), low sensitivity (0 < SI < 0.3), and non-sensitive (SI = 0) (Hsiao and Xu, 2000)growth is readily inhibited and growth of roots is favoured over that of leaves. The mechanisms underlying this differential response are examined in terms of Lockhart's equations and water transport. For roots, when water potential (Ψ.

RESULTS AND DISCUSSION

The parameters' sensitivities indicate that the effect of the

Table 3: Input parameters considered during the analysis of the model

Symbol	Description	Unit	Base Value
T_{base}	Minimum threshold temperature for crop growth	^oC	7
T_{upper}	Maximum threshold temperature for crop growth	^oC	31
P_{den}	Plant density	ha^{-1}	50000
DtE	Time from planting to seedling emergence	days	4
$DtCC_x$	Time to attain full canopy cover	days	45
DtSS	Time from planting to inception of senescence	days	65
DtM	Days to crop maturity	days	80
DtZ_x	Time to maximum rooting depth	days	40
DtF	Time from planting to flowering	days	50
DF	Duration of the flowering period	days	10
LBHI	Duration of harvest index building up	days	30
Z_{rx}	Maximum effective rooting depth	m	1.2
Z_{rn}	Minimum effective rooting depth	m	0.3
$AV.Z_{exp}$	Average rate of root expansion	cm day^{-1}	2.5
Z_{sh}	Factor for root zone expansion profile		1.3
cc_s	Soil cover per seedling at 90% emergence	cm^2 $plant^{-1}$	3
cc_o	Initial percentage of canopy cover	%	0.15
CC_x	Maximum percentage of canopy cover	%	50
CGC	Rate of canopy growth	% day^{-1}	21.6
CDC	Rate of canopy decline	% day^{-1}	20.5
K_{cTrx}	Crop coefficient at full canopy stage		0.98
K_{cdcl}	Decline of K_c as a result of ageing	% day^{-1}	0.3
WP*	Normalized water productivity (adjusted for ETo and CO_2)	g m^{-2}	22.6
WP-YF	Adjustment of WP* during yield formation	% of WP*	75
HI_o	Reference harvest index	%	47
Max.Inc.HI	Maximum allowable increase in HI	%	25
PIHI/F	Potential increase of HI under water stress before flowering	%	16
Pos. HI	Coefficient for positive effect of limited vegetative growth during yield formation on HI		1
Neg. HI	Coefficient for negative effect of stomatal closure during yield formation on HI		3
P_{exlw}	Lower threshold for soil water depletion factor for canopy expansion		0.6
P_{exup}	Upper threshold for soil water depletion factor for canopy expansion		0.25
P_{exsh}	Shape factor for canopy expansion water stress response		2.5
P_{sto}	Upper threshold for soil water depletion fraction for stomatal control		0.55
P_{stosh}	Shape factor for stomatal closure under stress		3
P_{sen}	Soil water depletion factor for canopy senescence		0.65
P_{sensh}	Shape factor for water stress coefficient for canopy senescence		3.5
P_{aer}	Volumetric saturation threshold for Anaerobiotic point	%	10
$Pol.T_x$	Maximum temperature restricting pollination	^oC	40
$Pol.T_n$	Minimum temperature restricting pollination	^oC	10
K_{sTr}	Minimum thermal threshold for full biomass production	^oC day	12
S_{xtop}	Maximum root water uptake in top soil layer	m^3 m^{-3} soil day^{-1}	0.048
S_{xbot}	Maximum root water uptake in bottom soil layer	m^3 m^{-3} soil day^{-1}	0.012

input parameters on the simulation of GY, CC and BMY varied with output variable and the crop growth stage as shown in Table 4. The Table presents the sensitivity indices of GY at harvest, and CC and BMY at vegetative (VEG.) flowering (FLO.) and yield formation (YF) growth stages of the crop.

Grain yield (GY)

The results indicate that the GY was most sensitive to time from planting to inception of canopy senescence (DtSS) and minimum air temperature restricting pollination ($Pol.T_n$), with sensitivity indices (SI) of 2.49 and 2.34, respectively. This emphasizes the parameters' critical roles in influencing reproductive success and overall productivity. The timing of the inception of canopy senescence, which varies among varieties significantly impacts grain yield (Sattar *et al.,* 2023). Early or delayed onset of senescence affects crop reproductive period and photosynthesis, leading to an increase or decrease in GY. Similarly, suboptimal temperatures during pollination can result in reduced fertilization, ultimately decreasing GY (Sattar *et al.,* 2023).

The GY exhibited notable sensitivity to days to crop maturity (DtM), crop coefficient at full canopy stage (K_{cTrx}),

Table 4: Sensitivity indices (SI) of AquaCrop input parameters

Parameters	Grain yield	Canopy cover			Biomass yield		
		Vegetative	Flowering	Yield formation	Vegetative	Flowering	Yield formation
T_{base}	0	1.88	0.11	1.21	1.53	0.26	0.08
T_{upper}	0	1.96	0	0.87	1.68	0.64	0.29
P_{den}	0.01	0.6	0.02	0.02	0.73	0.03	0.02
DtE	0.01	0.62	0.03	0.03	0.72	0.02	0.01
$DtCC_x$	0.07	3.13	0.05	0.05	2.65	0.57	0.36
DtSS	2.49	0	0.44	4.12	0	0.04	0.59
DtM	1.14	0	0	0.21	0	0	0.14
DtZ_x	0.03	0.27	0.01	0	0.17	0.04	0.02
DtF	0.11	0	0	0	0	0	0
DF	0.04	0	0	0	0	0	0.05
LBHI	0.24	0.83	0.03	0.06	0.36	0.02	0.03
Z_{rx}	0.39	0.48	0.08	0.03	0.32	0.35	0.25
Z_{rn}	0.02	0.09	0	0	0.07	0.01	0.01
$AV.Z_{exp}$	0.37	0.28	0.01	0.01	0.19	0.05	0.02
Z_{sh}	0.39	0.33	0.01	0.01	0.22	0.02	0.02
cc_s	0.05	0.64	0.03	0.02	0.74	0.02	0.01
cc_o	0	0.71	0.02	0.02	0.76	0.04	0.02
CC_x	0.12	0.39	0.91	1	0.3	0.32	0.36
CGC	0.12	2.87	0.1	0.03	2.36	0.69	0.41
CDC	0.48	0	0.03	0.14	0	0	0.02
K_{cTrx}	0.53	0.05	0.3	0.42	0.99	0.28	0.09
K_{cdcl}	0	0	0	0	0	0	0
WP*	0.99	0	0	0	0.93	0.91	0.91
WP-YF	0.27	0	0	0	0	0.01	0.24
HI_o	0.98	0	0	0	0	0	0
Max.Inc.HI	0.09	0	0	0	0	0	0
PIHI/F	0.16	0	0	0	0	0	0
Pos. HI	0	0	0	0	0	0	0
Neg. HI	0	0	0	0	0	0	0
P_{exlw}	0.13	0.73	0.03	0.03	0.5	0.11	0.08
P_{exup}	0.01	0.28	0	0	0.17	0.03	0.02
P_{exsh}	0.07	0.16	0.01	0	0.11	0.02	0.01
P_{sto}	0.08	0	0.09	0.12	0	0.10	0.13
P_{stosh}	0.01	0	0.06	0.11	0	0.07	0.04
P_{sen}	0	0	0.06	0.11	0	0.08	0.04
P_{sensh}	0	0	0.03	0.03	0	0	0.23
P_{aer}	0	0.83	0	0	0.83	0	0
$Pol.T_x$	0	0	0	0	0	0	0
$Pol.T_n$	2.08	0	0	0	0	0	0
K_{sTr}	0	0	0	0	0	0	0
S_{xtop}	0.02	0	0	0	0	0	0
S_{xbot}	0.01	0	0	0	0	0	0

Where color represent degree of sensitivity

High (SI > 1.5), Moderate (0.3 < SI < 1.5) Low (0 < SI < 0.3) Zero (SI = 0) normalized water productivity (WP^*) and reference harvest index (Hl_o), along with their related parameters such as WP*-YF, LBHI, and PIHI/F. These parameters directly contribute to the conversion of crop evapotranspiration into biomass yield and the partitioning of BMY into GY as defined by the main AquaCrop Equations. The rate of canopy decline (CDC), moderately influenced the GY with an SI value of 0.48. Crop canopy where light is intercepted for photosynthesis is crucial for growth, development, and ultimately yield production.

Interestingly, parameters often assumed to be influential—such as CGC, CC_x, and $DtCC_x$—demonstrated low sensitivity in this analysis, contradicting several studies that found them to be highly influential on GY across various crops (Haruna *et al.,* 2023; Lu *et al.,* 2021)thecalibration of the model could be tedious due to its large number of input parameters. Thecomplexity in the model evaluation could be simplified by conducting a prior sensitivityanalysis (SA. Lu *et al.,* (2021)a global sensitivity analysis on crop yield and transpiration was performed for 49 parameters in the FAO-AquaCrop model (version 6.0 argued that canopy development parameters have large impacts on the model irrespective of the output considered. Parameters related to the simulation of root expansion such as Z_{rx}, Av.Z_{exp}, and Z_{sh} significantly impacted the GY; consistent with findings from several researchers (Haruna *et al.,* 2023)thecalibration of the model could be tedious due to its large number of input parameters. Thecomplexity in the model evaluation could be simplified by conducting a prior sensitivityanalysis (SA. Moderate to high water stress conditions increase the influence of root development parameters as crops with deeper roots (such as pearl millet) tend to make better use of the limited available water (Lu *et al.,* 2021)a global sensitivity analysis on crop yield and transpiration was performed for 49 parameters in the FAO-AquaCrop model (version 6.0.

Most water stress parameters, particularly those associated with stomatal control and senescence thresholds, showed negligible impact on GY under the imposed conditions. The only influential water stress parameter was P_{explw}—lower threshold for leaf expansion under water stress—due to its role in early canopy development.

Canopy cover and biomass yield

The results showed that canopy cover was highly sensitive to $DtCC_x$, CGC, $T_{base,}$ and T_{upper} during the vegetative stage. The sensitivity of phenological parameters such as DtE, $DtCC_{x,}$ and DtZ_x along with P_{den} decreased progressively from the vegetative through the flowering and yield formation. Conversely, the sensitivity of DtSS and DtM, which occur later in the crop cycle, increased from zero to low for DtM, and up to high for DtSS during the yield formation stage. Root development parameters—excluding Z_{rn} which was insensitive—exhibited significant drops in their sensitivities at the flowering and yield formation stages, consistent with the cessation of root expansion once maximum rooting depth is reached.

Maximum canopy cover (CC_x) was sensitive across all three growth stages, while early canopy cover parameters (cc_o and cc_s), alongside the CGC, affected CC simulation only during the vegetative stage. Canopy decay parameter (CDC) became slightly more relevant later in the cycle, while K_{cTrx} maintained moderate sensitivity during periods of high transpiration demand. The sensitive stress parameters over canopy cover included P_{exlw}, P_{exup} and P_{aer}, with moderate sensitivity during the period of canopy growth as observed by Lu *et al.,* (2021)a global sensitivity analysis on crop yield and transpiration was performed for 49 parameters in the FAO-AquaCrop model (version 6.0. This underscores that parameters are impactful only during the phases where their associated processes are active.

The sensitivity of biomass yield to T_{base} and T_{upper} varied, with high SI values at vegetative, moderate at flowering and low at yield formation. Similarly, a noticeable drop in the BMY sensitivity to P_{den}, DtE, and LBHI was also observed at the late stages. Canopy parameters (CGC, CC_x and $DtCC_x$) were sensitive across all three growth stages with declining effects towards maturity. Similar to canopy cover, the sensitivity of BMY to root development parameters, $cc_{o,}$ and cc_s was significant at the vegetative stage but decreased as biomass accumulation slowed. Conversely, DtSS was only influential at the yield formation stage, when canopy senescence occurs. CDC was observed to be non-influential because it is related to the simulation of canopy decay when the active growth or biomass accumulation phase of the crop seizes later in the growing cycle.

Similar to CC, BMY showed moderate sensitivity to K_{cTrx} during the active plant growth phase. WP* which indicates the efficiency of biomass accumulation from crop transpiration was influential throughout the crop cycle. WP-YF, a coefficient for the adjustment of WP* during yield formation was sensitive only at the yield formation. Reference harvest index (HI_o) and its related parameters were largely inactive in the simulation of CC and BMY, as these relate to yield portioning—a process that occurs beyond CC and BMY simulation phases. The stress parameters did not influence the simulation of BMY except P_{exlw} and P_{aer} during early growth, possibly affecting canopy expansion and biomass accumulation.

Overall, it can be deduced that the sensitivity of the model to its input parameters is time-dependent, and roughly, half of the input parameters were classified as non-influential across all outputs and growth stages.

CONCLUSION

The analysis of the sensitivity of the AquaCrop crop model conducted to identify influential and non-influential input parameters for the production of pearl millet revealed that approximately half of the model parameters—mostly stress parameters—did not impact the simulations of canopy cover, biomass yield, and grain yield. The model output variables were mainly influenced by parameters that are directly involved in their determination, as defined by the governing equations. Phenologically, canopy and root development parameters exhibited noticeable impacts during simulations. Therefore, to ensure accurate simulations and reliable results, it is crucial to carefully consider and determine these parameters. This involves proper estimation, fine-tuning, calibration, and localization. On the other hand, non-influential parameters could be fixed within their predetermined range values to simplify the model evaluations and facilitate its practical application. Future research should consider validating these findings using more advanced methods like the Global Sensitivity Analysis (GSA) across diverse crop types and environmental conditions.

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Authors contributions: **N. I. Lawal**: Conceptualization, writing original draft; **M. M. Haruna**: Methodology and analysis; **J. M. Dibal**: Editing and supervision; **Abdu, D.**: Editing and supervision; **A. Y. Arku:** writing review and editing; **Y. A. Umar**: simulation and analysis.

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