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The impact of climate change on the productivity of cowpea (*Vigna unguiculata*) under three different socio-economic pathways

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Highlights

- *SIMPLACE crop model solution can reproduce cowpea yields for contrasting irrigation and fertilizer management.*
- *Compared to the baseline period, the model projected for the future period (2040 to 2070) slightly higher cowpea yields under three different socio-economic pathways.*
- *Cowpea biomass and yield remained high in future climate scenarios, despite slightly shorted growing cycle length, because of the rise in CO_2.*
- *The projected trends have been similar in the Sudan and in the Guinea Savanna of West Africa.*

Abstract

Crop models are useful tools for simulating the impact of climate change on crop growth, development and yield. This study assesses the impact of climate change on cowpea yield in soils with low levels of phosphorous content mainly in the Sudan Savanna and Forest Transition Zone of West Africa. A crop model solution within the general modelling framework SIMPLACE in combination with the output of four climate models for 3 contrasting shared socio-economic scenarios (SSP126, SSP370, and SSP585) was used to simulate the impact of climatic change on phenology, above ground biomass and yield parameters of cowpea. The simulations were carried out for Ouagadougou and Kumasi, representing the two major savanna biomes in West Africa (Sudan Savanna and Guinea Savanna). Previous field experimental data on the wide-spread cowpea genotype Asontem from a P-deficient soil at Kumasi (Ghana) were used to validate the SIMPLACE crop model solution. The model was able to simulate the impact of irrigation and fertilizer management on cowpea growth and yield assessment with adequate accuracy. Compared to historic simulations of the biomass and yield of cowpea, the model solution projected higher above ground biomass, and yield under the pre-dominant low input cropping systems for all the three SSPs as a result of the rise in CO_2 and in spite of slightly shorted growing cycle length in both locations.

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Introduction

Cowpea can thrive under drought conditions. Conditions that render other field crops unproductive (Ewansiha *et al*., 2006). However, tolerance to drought in cowpea has been attributed to morphological arrangements, increasing photosynthesis, quick shoot, and root growth (Hartmann *et al*., 2018; Adusei *et al*., 2021). It has also been reported that cowpea's resilience to drought is due to its reduction in chlorophyll content (Agbicodo *et al*., 2009). The crop is a relatively cheap source of high-quality protein because the grains contain 25% protein and several vitamins and minerals (Dovlo *et al*., 1976) and are important in the nutrition of the poor. It occupies a smaller proportion of the cropping area than cereals but contributes significantly to household food security, especially in West and Central Africa. In 2017, more than 7.4 million tons of dried cowpeas were produced worldwide, with Africa producing nearly 7.1 million. About 12.5 million hectares are harvested annually throughout the world and 98% of these are in Africa (Alexandre *et al*., 2016). The total area under cowpea cultivation in Ghana is about 163,700 ha with an annual production of 219,300 mt in 2010 (Egbadzor *et al*., 2013). This is an indication that the consumption of the crop is high in Ghana, which makes it one of the important crops under cultivation. However, high exposure to climatic changes is likely to challenge the crop's adaptive capacity to its tolerance to drought and other environmental stresses (Niang *et al*., 2014). Climate scientists have shown that the frequency of the occurrence of extreme temperatures has increased and simultaneously this will lead to the increase in heat stress on crops as well as in evapotranspiration and crop water demand, particularly in the Sahel and Savannah parts of Africa (Frimpong and Kerr, 2015; Seneviratne *et al*., 2012). Global climate change will have an impact on all sectors of the global economy in the coming decades and most of these impacts will be on the agricultural and water sector, which will result in food insufficiency in the developing world (Ringler, 2008; Nelson *et al*., 2009). Crop models are useful tools for simulating the impact of climate on crop yields (Ruane *et al*., 2013; Rosenzweig *et al*., 2013). Several crop growth and yield evaluation models have been developed for a large range of crops including cereals and legumes. Decision-support system for agrotechnology transfer (DSSAT) - maize (Tovihoudji *et al*. 2019); AquaCrop - Herbaceous crops (Raes *et al*., 2009; Steduto *et al*., 2009); agrometshell (AMS) - winter wheat (Yildiz *et al*., 2015); applicability of agricultural production systems simulator (APSIM) - wheat-maize continuous cropping (Wang *et al*., 2007); crop-environment resource synthesis (CROPGRO) - soybean (Dogan *et al*., 2007) and scientific impact assessment and modelling platform for advanced crop and ecosystem management (SIMPLACE) - maize (Srivastava *et al*., 2016) are some of the examples of models or modelling platforms developed to predict the growth, development, and yield of crops under changing environments. As a research tool, model development and application can be used to identify gaps in knowledge and these will enable more efficient and targeted research planning and execution. Models that are based on good morphological and physiological data are more credible in supporting the extrapolation of simulation results and alternative crop management options (Oteng-Darko *et al*., 2012). Growth and yield simulation models can simulate crops when they are grown in a manner that allows full expression of their yield potential (Setiyono *et al*., 2010). This will elicit the credibility of a model in simulating crop yields, from a wide range of different environments to access model performance under low and high yielding conditions. Detailed assessments of the impact of environmental changes on cowpea yield and production using crop models are scarce, especially in Central and West Africa which constitute major cowpea production regions (Alexandre *et al*., 2016). Few studies on cowpea modelling have concentrated on the growth and development of cowpea under varying soil and climatic conditions (Bastos *et al*., 2022) and under drought stress (Pejić *et al*., 2016). However, model evaluation and validation on the growth and yield of cowpea in response to P fertilizer application and its interaction with drought are lacking. Modelling the impact of climate change on P deficient soils on cowpea yield will enable a more robust assessment of climate change impact on cowpea and the identification of suitable adaptation measures. This study aimed to use a general modelling framework, SIMPLACE to assess the impact of climate change on cowpea yield in P deficient soils in the Sudan Savanna and the Forest transition zone of West Africa. For this purpose, a SIMPLACE model solution is calibrated and validated for the simulation of biomass and yield of the widespread cowpea variety Asontem underwater and phosphorus stress. The study will produce a more reliable assessment of climate change impacts on cowpea yields in West Africa, which is crucial for the identification of adaptation measures.

Materials and methods

Model description

'LINTUL5 is a process-based, bio-physical model that simulates plant growth, biomass and yield as a function of climate, soil properties, and crop management using experimentally derived algorithms' (Legesse *et al*., 2019). Among other sub-models, Lintul5 was embedded into a solution of the general modelling framework, SIMPLACE to simulate a continuous cowpea cropping system over the respective periods (Gaiser *et al*., 2013, www.simplace.net). In this study, the model solution Simplace<Lintul5, SLIM, SoilCNP, FAO56> was used including: i) Lintul5 routines for simulating biomass, phenology and plant nutrient uptake; ii) SLIM for simulating soil water and root growth dynamics, as well as the balance of mineral nitrogen and phosphorus; to this end, SLIM was extended by phosphorus adsorption and desorption sub-routines from the APEX model (Williams and Izaurralde, 2006); iii) SoilCN extended by P routines for organic P turnover was used to simulate the dynamics of organic C, N and P in the soil (Adam *et al*., 2012). SIMPLACE has been widely employed in various studies at the field, regional and continental scale (Srivastava *et al*., 2018; Gaiser *et al*., 2013; Eyshi-Rezaei *et al*., 2015). In the model solution, crop growth is limited by radiation, temperature, water, nitrogen, and phosphorus supply in the absence of biotic factors such as pests, diseases and weeds. Biomass production is influenced by intercepted radiations according to Lambert-Beer's law and light use efficiency (Srivastava *et al*., 2016). The potential crop growth rate was then estimated by multiplying intercepted light with the radiation use efficiency (RUE). Biomass produced is partitioned to various crop organs (leaves, stem, and roots) and storage organs in accordance with the partitioning coefficients which are defined as a function of the developmental stage of the crop. Thermal time above a defined base temperature was employed in simulating crop phenology. The physiological plant age in the model defined by development stages is characterized by the formation and appearance of plant organs. These developmental stages were expressed in a dimensionless variable, the development stage index, with the value of 0 for seedling emergence, 1 for flowering and 2 for maturity. Potential evapotranspiration was calculated using the Penman-Monteith method by FAO (Allen *et al*., 1998). SLIM is a conceptual soil water balance model, characterized by the subdivision of soil into a variable number of layers, thus substituting the two-soil layer approach in Lintul5. Besides radiation and temperature, water, and nutrients (N and P) stresses are restricting the daily accumulation of biomass, root growth, and yield. Stress indices were estimated daily for water and nutrient limitations and ranged from 0.0 to 1.0. On a given day, the maximum nutrient stressor (N or P) and the water stress index influence the estimation of the daily increase in crop biomass. When available water in the soil is lower than the crop water demand, water stress occurs. Similarly, phosphorus stress occurs when crop available phosphorus in the rooted soil profile at a given day was lower than crop phosphorus requirement.

Field experiments for model calibration and validation

Description of the study area

Two field experiments were conducted at the Crops Research Institute (CRI), Fumesua in the Ashanti Region, which is located in the middle belt of Ghana during the dry season of 2017/18 and 2018/19 growing cycle and this data were simulated using the climatic conditions in Ouagadougou and Kumasi cities of Burkina Faso and Ghana respectively (Figure 1). The region lies between longitudes 0.15 W and 2.25 W, latitudes 5.50 N and 7.46 N with a total land surface area of 24,389 km^2. The region expresses bimodal rainfall with a major raining season in March and May being the climax of the season. The dry season falls between November to February characterized by dry, hot, and dusty conditions. The region is positioned between 150 and 300 m above sea level with a mean annual temperature of 27°C (Srivastava *et al*., 2016). The mean daily temperature during the experimental period in the two years of this study was 30.4°C and 32.0°C with a relative humidity of 79.9% and 83.3%, respectively. Total rainfall during the growing cycle was 143 and 119 mm in 2017 and 2018, respectively.

Design and execution of field experiments

The widespread cowpea genotype Asontem was selected among ten different genotypes based on its adaptability and farmers' usage in the study area (southern part of Ghana) as well as its better response to phosphorous and water stress. The selection criterion was above ground biomass productivity. Both field experiments were conducted in a split-plot design with 3 factors (P fertilizer application levels, water regimes and cowpea genotypes) with three replicates. The main plot comprised of the cowpea genotypes and the subplot comprised of P fertilizer and water application. A total of four combinations of P fertilizer and water treatment were established. The seeds of the cowpea genotype were surfaced sterilized before planting, treatments (irrigation and stress) and agronomical management were carried out as it has fully described in Adusei *et al*. (2021).

Soil properties and analysis

Physical and chemical soil analyses were conducted on soil samples from four different soil depths before the beginning of the field experiments. The soil texture of both experimental sites was sandy loam in the topsoil and clay in the subsoil (>60 cm; Table 1). The water-holding capacity of the soil layers is expressed as the water content at field capacity (0.33 bar). Ammonium acetate, aluminium (titration method), and Bray 1 methods were used to extract exchangeable bases, exchangeable acids and available P, respectively (Table 2). The results of the physical analyses of the soils for experiments 1 and 2 are presented in Tables 1 and 2 (same as Adusei *et al*., 2021).

Model parameterizations

Most of the crop model parameters for the cowpea variety Asontem used in this study were default values of LINTUL5 as reported in Wolf (2012). Based on the literature review and the field measurements in the two years experiment, some parameter

Figure 1. Map of Africa showing two study sites *i.e.*, Ouagadougou and Kumasi in the target countries Burkina Faso and Ghana respectively.

values were manually adjusted during the calibration process in order to adapt the cowpea variety Asontem. Parameters that were adjusted in the model are shown in Tables 3 and 4.

Model calibration and validation

The climate change impact assessment focused on the widespread cowpea variety Asontem.

Model calibration: model calibration was done using 2017/18 field experimental data by manually adjusting the parameters influencing, phenology, biomass, yield and leaf area index (LAI) using treatment 60P and NWS (optimal condition). The calibration procedure followed a three-step approach. Step 1 involved phenology calibration by adjusting two parameters (Table 3). TSUM1 and TSUM2 were adjusted to correctly simulate the occurrence of anthesis and maturity dates. In Step 2, LAI was calibrated simultaneously by adjusting RGRLAI (maximum relative increase rate in

Table 1. Average physical characteristics of soil (0-90 cm depth) at Fumesua.

Soil layers (cm)	Sand (%)		Clay (%)		Silt (%)	
	2017	2018	2017	2018	2017	2018
0-15	73.8	72.4	14.6	16.9	11.9	10.5
15-30	75.8	73.9	14.0	14.7	10.0	11.2
30-60	60.3	59.5	29.8	30.9	09.8	09.4
60-90	40.9	41.6	49.2	47.7	09.7	10.5

Table 2. Average chemical characteristics of top and sub-soil (0-90 cm depth) at Fumesua.

Soil depth (cm)	PH		Avail. P (mg/kg)		Total N (%)		Exch. Bases (cmol/kg) K		Ca		Mg		Na		Exch. Acidity (cmol/kg) Al		H	
	2017	2018	2017	2018	2017	2018	2017	2018	2017	2018	2017	2018	2017	2018	2017	2018	2017	2018
0-15	6.37	6.01	6.04	8.04	0.15	0.11	0.18	0.09	12.05	11.96	5.36	5.21	0.11	0.20	0.20	0.23	0.24	0.30
15-30	6.46	6.14	5.70	4.92	0.06	0.04	0.07	0.03	10.84	10.54	5.04	4.93	0.04	0.05	0.25	0.29	0.08	0.09
30-60	5.79	5.93	7.41	7.15	0.04	0.05	0.08	0.08	12.87	12.99	5.91	5.98	0.11	0.16	0.23	0.28	0.09	0.09
60-90	5.32	5.21	5.04	6.05	0.05	0.06	0.12	0.14	12.08	12.86	5.08	5.16	0.08	0.09	0.42	0.52	0.09	0.09

Table 3. Crop parameters modification in LINTUL5 for genotype Asontem.

Crop parameters modified	Description	Unit	Changes made in crop file Initial value	Final value
Phenology				
TSUM1	Temperature sum from emergence to anthesis	°C day^{-1}	540	830
TSUM2	Temperature sum from anthesis to maturity	°C day^{-1}	500	460
RGRLAI	Maximum relative increase in LAI	ha ha^{-1} day^{-1}	0.0006	0.0004
LAI				
SLATB-0.0	Specific leaf area as function of developmental stage 0.0	m^2 g^{-1}	0.08	0.026
SLATB-2.0	Specific leaf area as function at developmental stage 2.0	m^2 g^{-1}	0.08	0.0325
Biomass and yield				
KDIFTB 0.0	Extinction coefficient for diffuse visible light as function of at developmental stage 0.0		0.63	0.92
KDIFTB 2.0	Extinction coefficient for diffuse visible light as function of at developmental stage 2.0		0.61	0.81
RUETB 0.0	Radiation use efficiency for biomass production as function at developmental stage 0.0	g/MJ	3.0	3.0
RUETB 1.5	Radiation use efficiency for biomass production as function at developmental stage 1.5	g/MJ	2.1	2.78
RUETB 2.0	Radiation use efficiency for biomass production as function at developmental stage 2.0	g/MJ	1.0	2.3
RDRRTB	Rel. death rate of root as a function of DVS	d^{-1}		
Soil parameters modified				
Soil phosphorus				
pH	pH value of soil per layer			
Soil Layer Depth 1 (0-15)	pH value of soil per layer depth 0-15	cm	7.3	6.4
Soil Layer Depth 2 (15-30)	pH value of soil per layer depth 15-30	cm	7.8	6.5
Soil Layer Depth 3 (30-60)	pH value of soil per layer depth 30-60	cm	6.9	5.7
Soil Layer Depth 4 (60-90)	pH value of soil per layer depth 60-90	cm	6.7	5.3

LAI, leave area index.

LAI) and SLATB (specific leaf area) and finally, (step 3) total biomass and grain yield were calibrated by altering the parameters KDIFTB (Extinction coefficient for diffuse visible light) and RUETB (radiation use effciency for biomass production). The nitrogen fixation (Nfix) parameter was set to 100 for both calibration and validation.

Model validation and evaluation: the model was validated using the 2018/19 dataset. The observed vegetative biomass (leaves + stems), phonological process, seed yield, and LAI data collected in all treatment levels were compared with simulated values. The performance of the model to simulate cowpea biomass, LAI and yield was based on a comparison between observed data and simulated values using the following two statistical indicators [Eq. 1: mean relative error (MR); and Eq. 2: mean residual error (ME)].

The MR as:

$$MR = \frac{1}{n}\sum_{i=1}^{n} \frac{(y_i - x_i)}{x_i} \quad (1)$$

The ME as:

$$ME = \frac{1}{n}\sum_{i=1}^{n} yi - xi \quad (2)$$

n represents the sample number; *x* is the observed and *y* is the simulated value. 0 value in ME means no systematic bias between simulated and measured values. 'The MR indicates the mean magnitude of the error in relation to the observed value. Small values indicate little difference between simulated and measured values' (Srivastava *et al*., 2016).

Database description for climate scenarios

Weather data is the driving force in crop simulation. To run simulations for projected climate change scenarios, weather data must match the requirements of crop models (Srivastava *et al*., 2018). Climate data were extracted for Kumasi and Ouagadougou for the time slices 1981-2000 and 2040-2070 representing the baseline and future climate, respectively. Projections of future climate were obtained using coupled model intercomparison project phase 6 (CMIP6) dataset available at 100 km spatial resolution, a project coordinated by the working group on coupled modelling (WGCM) as part of the World Climate Research Programme (WCRP), and three Shared Socioeconomic Pathways (SSPs), namely, ssp126, ssp370, and ssp585 for carbon emissions (IPCC, 2014). The future time scale weather series and the corresponding projected carbon dioxide (CO_2) concentration, according to SSPs (Table 4) were used in all crop model simulations. The four GCMs used in this study are as follows: i) GFDL-ESM4: Geophysical Fluid Science Laboratory-Earth System Modelling (https://www.gfdl.noaa.gov/earth-system-esm4/); ii) IPSL-CM6A: Institute Pierre-Simon Laplace (https://cmc.ipsl.fr/ipsl-climate-models/ipsl-cm6/); iii) MPI-ESM1: Max Planck Institute Earth System Model (https://cera-www.dkrz.de/WDCC/ui/cerasearch/cmip6?input=CMIP6.HighResMIP.MPI-M.MPI-ESM1-2-HR); and iv) UKESM1: U.K. Earth System Model (https://cera-www. dkrz.de/WDCC/ui/cerasearch/ cmip6?input=CMIP6.ScenarioMIP.MOHC.UKESM1-0-LL).

Results

Simulation of the impact of phosphorous and water stress on biomass and yield of cowpea

After model calibration for the cowpea genotype Asontem and its response to phosphorous and water stress, the model solution was able to reasonably mimic phenological development, crop growth and yield under different drought and phosphorous stress treatments in the field. The LAI was calibrated and validated under different phosphorous and water supply conditions during the 2017/18 and 2018/19 growing cycles respectively (Figure 2). After calibration, the simulated leaf area index under optimal phosphorous supply combined with or without water stress agreed well with the observed LAI in 2017/18 with a MR between –23.80 and –4.40% (Figure 2; Supplementary Tables S1 and S2) by the model. Under phosphorous stress, the model underestimated LAI when combined with optimum irrigation or water stress by 9.78 and 11.11% respectively. In the validation period (2019), the model slightly systematically overestimated the observed LAI values with a MR which ranged from 14.65 to 23.13% (Figure 2B, D, F and H; Supplementary Tables S1 and S2).

There was a good agreement between observed and simulated total above ground biomass in 2017/18. This agreement was also observed during the validation of the simulation of total above ground biomass in the 2018/19 growing cycle. Mean relative error range of 0.35 at 60P+NWS treatment to 15.85% at 0P+NWS treatment were recorded for validation and –3.14 to 9.54% for observation of total above ground biomass during 60P+NWS and 0P+WS treatments respectively (Figure 3; Supplementary Tables S1 and S2). After calibration, the model reproduced the grain yield with MR between –3.55 and 14.57% and the best agreement was noticed in the treatment with P and water stress (0P+WS) with 1.22% in 2018. However, in the validation period in 2019, the model overestimated the yield response in the treatments with water stress by 11.55 to 18.79%, whereas the simulated grain yield agreed well with the observed values in the treatments with no water stress (15.87 to 16.15%; Figure 4; Supplementary Tables S1 and S2).

Table 4. Projected carbon dioxide (CO_2) concentration (in ppm) used in the study for different climate scenarios.

Climate scenarios	CO_2 concentration (in ppm)
Baseline	380
ssp126	450
ssp370	550
ssp585	600

Table 5. Correction of radiation used efficiency as a function of atmospheric carbon dioxide (CO_2) concentration (in ppm) used in the crop model.

CO_2 concentration in ppm	Correction factor
40	0
360	1
600	1.35

Impact of climate change on phenology

The changes in the occurrence of anthesis and maturity due to climate change using three shared socio-economic pathways (ssp126, ssp370, ssp585) and the outputs from four climatic models were mostly similar in Ouagadougou and Kumasi (Tables 5 and 6). Under the investigated climate scenarios, the number of days to anthesis in Ouagadougou reduced on average by 1 day except for the climate model ukesm where the number of days to anthesis was

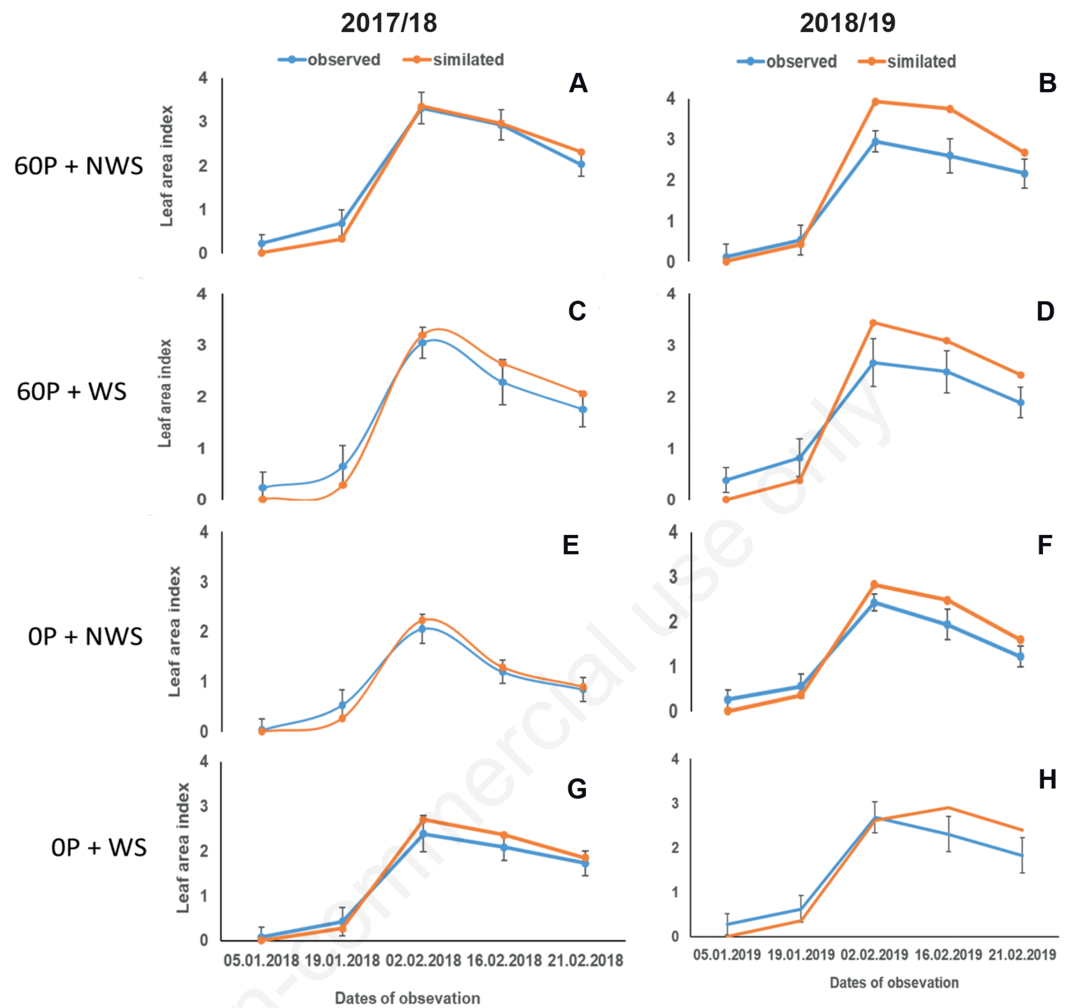

Figure 2. Model calibration and validation for leaf area index (LAI) of Asontem cowpea genotype under four different phosphorous fertilizer and water treatments [60P+NWS: 60P+No water stress (optimal condition), 60P+WS: 60P + water stress, 0P+NWS: 0P+No water stress and 0P+WS: 0P+No water stress]. Simulated (red line) *versus* observed (blue line) using 2017/18 field data for model calibration and 2018/19 field data for model validation.

Table 6. Simulated average number of days to anthesis and maturity in Kumasi and Ouagadougou for historic (1981-2010) and future time periods (2040 to 2070) under no irrigation and fertilizer conditions using the output of four different climate models (gfdl, ipsl, mpi-esm and ukesm) across three different shared socio-economic pathways (ssp126, ssp370 and ssp585).

Location climate model		Historic and future scenario							
		Days to anthesis				Days to maturity			
		hist	ssp126	ssp370	ssp585	hist	ssp126	ssp370	ssp585
Ouagadougou									
	gfdl	42	41	41	41	65	63	62	62
	ipsl	42	40	40	40	64	61	62	61
	mpi-esm	43	42	42	42	66	64	64	64
	ukesm	42	40	40	40	65	61	61	61
Kumasi									
	gfdl	42	41	41	41	65	63	62	61
	ipsl	42	40	40	40	64	61	61	61
	mpi-esm	42	40	40	39	65	62	62	60
	ukesm	42	40	40	39	64	60	61	60

reduced by 2 days when the three shared socio-economic pathways were compared to the historic period (hist). The trend of reduction as a result of the climatic change was also observed for the number of days to maturity. When using the output of the climate models mpi-esm and ukesm, the simulated number of days to maturity was reduced by 2 and 4 days respectively compared to the historic period, regardless of the SSP. However, when using the output of the climatic models gfdl, the reduction was by 2 days under ssp126 and by 3 days under ssp370 and ssp585 (Table 6).

In considering the impact of the climate change on the days to anthesis in Kumasi we noticed a reduction of 1 and 2 days when using the output of gfdl and ipsl respectively under all the three socio-economic pathways compared to the historic period. With the climate model mpi-esm the number of days to anthesis in the three socio-economic pathways ssp126, ssp370 and ssp585 reduced by 2, 2 and 3 days respectively. Under the climate model ukesm and the socio-economic ssp585, there was a reduction of days to anthesis by 3 days compared to the historic period (Table 6). Comparing the future to the historic period, climate change impacted mainly by reducing the number of days to maturity under all the three socio-economic pathways (Table 6).

Impact of climate change on above ground biomass and yield

The climate scenarios impacted positively the growth and yield of the Asontem cowpea genotype in both locations (Figure 5A and B; Table 7). The trend and pattern of above ground biomass over the socio-economic pathways in Ouagadougou showed an increase compared to the historic scenario (Figure 5A). The socio-economic pathway ssp585 had the highest accumulation of above ground biomass followed by ssp370 and then ssp126 with the following percentage differences of 9.47, 6.26 and 0.47% relative to the historic period (Figure 5A and Table 7). The impact of grain followed the same descending order from ssp585 to ssp370 and ssp126 (Figure 4B) in Ouagadougou. The percentage increase in grain yield over the three socio-economic pathways was, however, slightly lower compared to the above ground biomass (Figure 5A and B; Table 7).

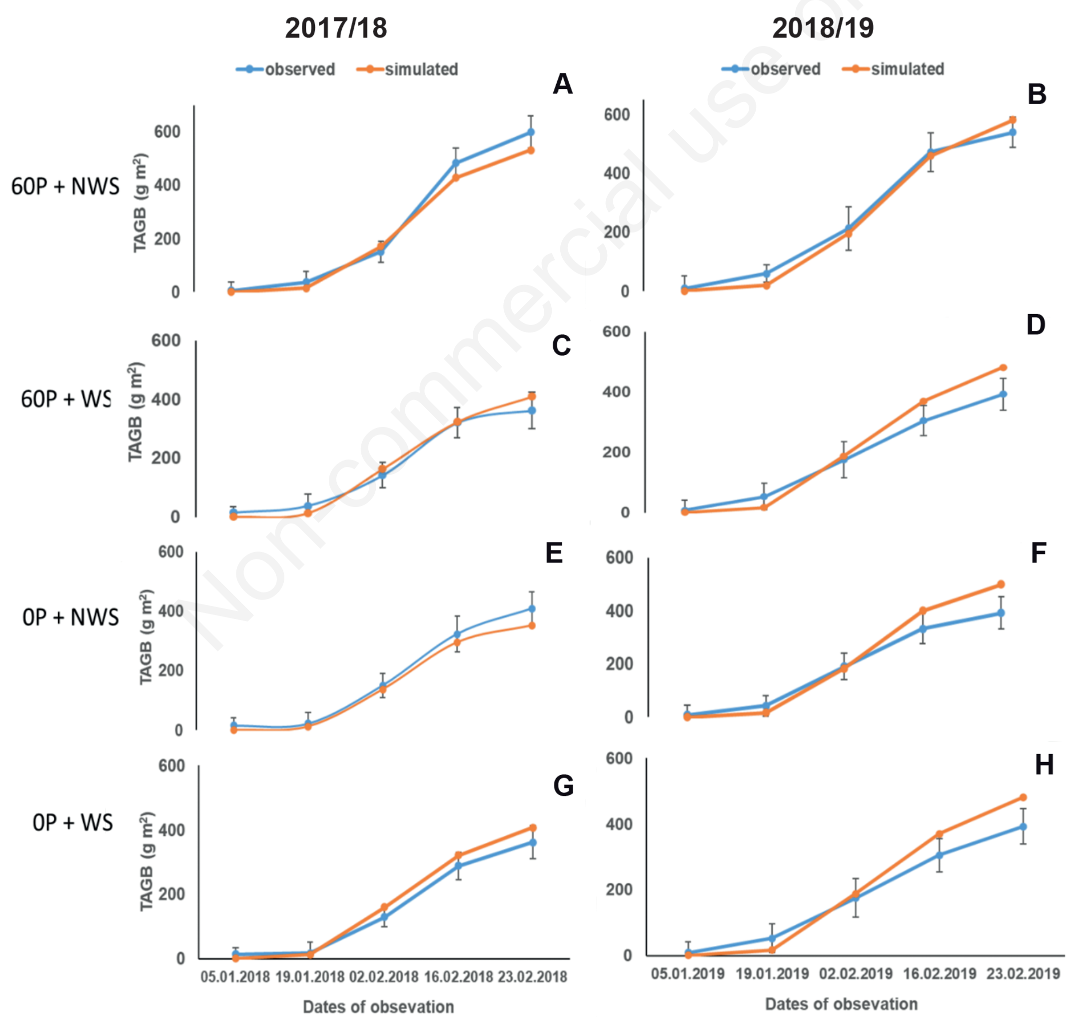

Figure 3. Model calibration and validation for total above ground biomass (TAGB) of Asontem cowpea genotype under four different phosphorous fertilizer and water treatments [60P+NWS: 60P+No water stress (optimal condition), 60P+WS: 60P+water stress, 0P+NWS: 0P+No water stress and 0P+WS: 0P+No water stress]. Simulated (red line) *versus* observed (blue line) using 2017/18 field data for model calibration and 2018/19 field data for model validation.

In Kumasi, the total above ground biomass increased in the socio-economic pathways ssp370 and ssp585 by up to 10.84% but was lesser (0.88%) in ssp126 compared to the historic period (Figure 5A and B; Table 7). The yield impacts in the climate scenarios were also positive in Kumasi (Figure 5A and B; Table 7). When estimating the percentage change, spp585 showed the highest yield increase of 10.47% followed by spp370 with 9.88% and ssp126 with 0.44% (Figure 5B and Table 7).

Changes in environmental factors when predicting future growth and yield performance

The impact of the socio-economic pathways on the precipitation and temperature during the growing season of the cowpea variety Asontem was assessed when simulating its growth and yield performance (Figure 6). The effect of the SSPs on precipitation in Ouagadougou during the growing cycle was quite low compared to the historic period (Figure 6A). Average air temperature

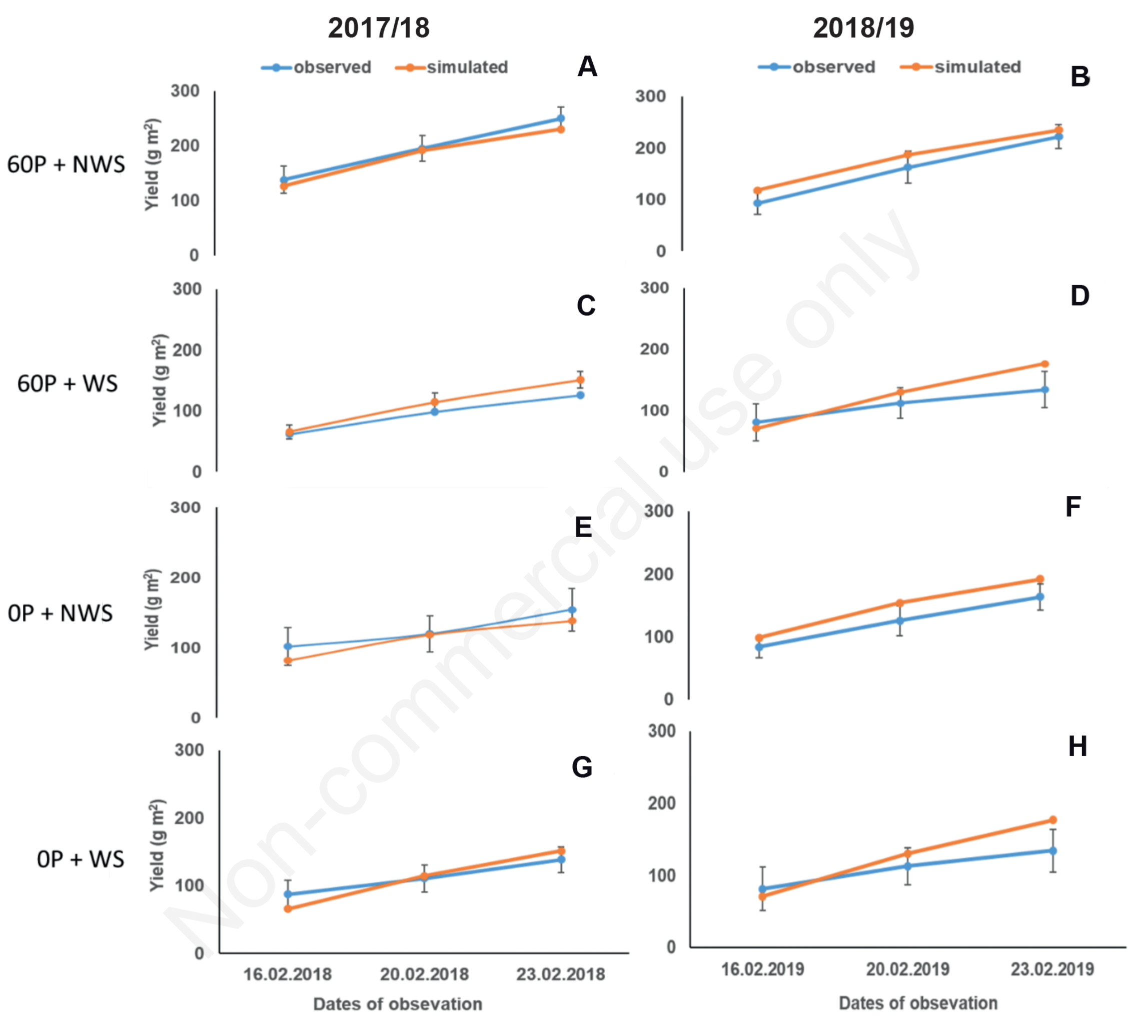

Figure 4. Model calibration and validation for seed yield of Asontem cowpea genotype under four different phosphrous fertilizers and water treatments (60P+NWS: 60P+No water stress (optimal condition), 60P+WS: 60P+water stress, 0P+NWS: 0P+No water stress and 0P+WS: 0P+No water stress). Simulated (red line) *versus* observed (blue line) using 2017/18 field data for model calibration and 2018/19 field data for model validation.

Table 7. Percent differences in total above ground biomass and yield of Asontem cowpea variety between historic and three different climate scenarios (ssp126, ssp370 and ssp585) averaged over four different climate models (gfdl, ipsl, mpi-esm and ukesm) at two different locations (Kumasi and Ouagadougou) under rainfed conditions without fertilizer application.

Climate scenario	TAGB		Yield	
	Ouagadougou	Kumasi	Ouagadougou	Kumasi
ssp126	0.47	0.88	0.58	0.44
ssp370	6.26	9.68	5.50	9.88
ssp585	9.47	10.84	8.86	10.47

TAGB, total above ground biomass.

during the growing period remained similar when socio-economic pathways, ssp126 and ssp370 were compared to the historic period (Figure 6B). Whiles, in ssp585, the temperature was higher by 4.71% when compared to the historic period (Figure 6B).

When analysing the future radiation conditions during the growing period to understand the growth and performance of cowpea under the socio-economic pathway in Ouagadougou, it appears that the historic runs radiation was slightly higher (1312.27 MJ m^{-2}) compared to the future socio-economic pathways. Among the socio-economic pathways, radiation input was highest in ssp126 followed by ssp370 and ssp585 with 1253.77, 1237.80 and 1223.78 MJ m^{-2} respectively (Figure 7).

The simulated phosphorus nutrition index (PNI) ranges between 0 and 1and low PNI is an indicator for P stress in cowpea. When simulating cowpea growth under the socio-economic pathway ssp585 in Ouagadougou, PNI was marginally lower compared to the historic period and the other socio-economic pathways. PNI ranged between 0.89 in the historic period and 0.85 in ssp585 (Figure 8A). The average water stress factor (transpiration reduction factor, TRANRF) in the historic period was 0.91, whereas an average of 0.90 was recorded for all the socio-economic pathways (Figure 7B). In Kumasi, the precipitation during the growing cycle of the cowpea variety was reduced in all socio-economic pathways relative to historic (Figure 6A). Average air temperature during the growing period remained similar when socio-economic pathways, ssp126 and ssp370 were compared to the historic period (Figure 6B). However, in ssp585, the temperature was higher by 5.42% when compared to the historic period (Figure 7B).

In comparing the simulated radiation under various socio-economic pathways in Kumasi, it was noticed that apart from socio-economic pathway ssp585 which had the least radiation of 998.41 MJ m^{-2}, the difference between historic and the rest of the socio-economic pathways was insignificant (Figure 7).

The simulated average PNI under the historic period and all the socio-economic pathways in Kumasi was similar with values close to 0.8 (Figure 8A). TRANRF in the historic period, ssp126 and ssp585 were also similar, with a value of 0.91. However, in ssp370, TRANRF was slightly reduced by a value of 0.03 when compared to the historic period and all other socio-economic pathways (Figure 8B).

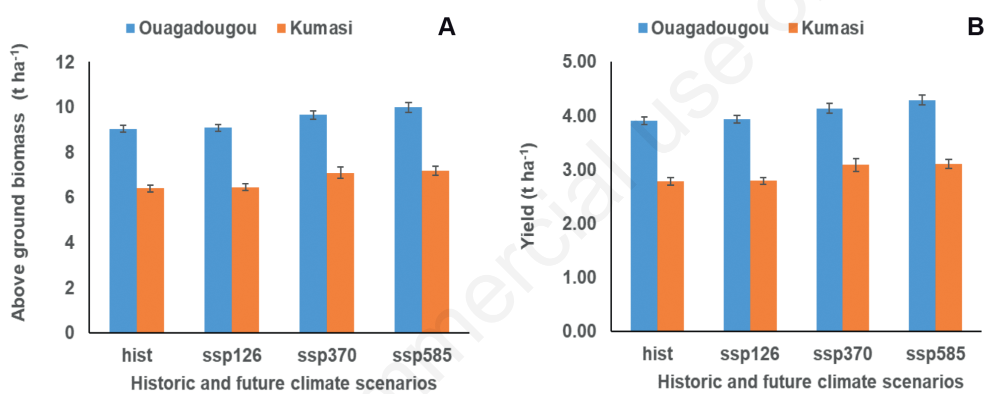

Figure 5. Simulated above ground biomass (A) and yield (B) over the growing cycle of Asontem cowpea variety in Ouagadougou and Kumasi predicted for the historic period (hist; 1981-2010; an average of 30 years) and future scenario period (2040-2070; an average of 30 years) under three shared socio-economic pathways (ssp126, ssp370 and ssp585) under no irrigation and fertilizer conditions using the output of four average different climate models (gfdl, ipsl, mpi-esm and ukesm).

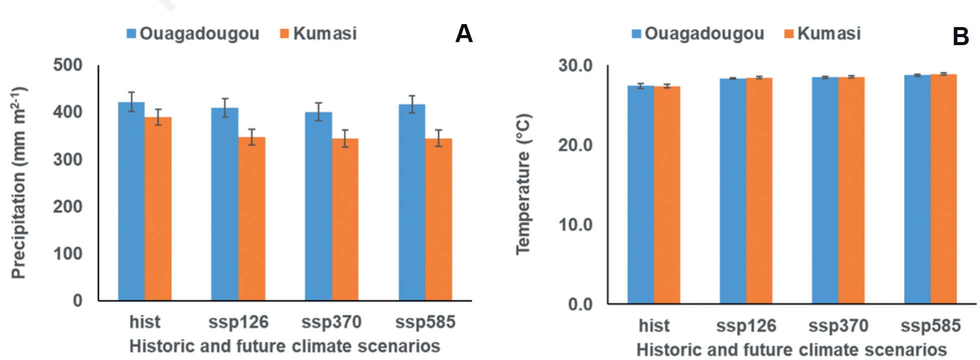

Figure 6. Simulated average precipitation (A) and average air temperature (B) over the growing cycle of Asontem cowpea variety predicted by four different climate models (gfdl, ipsl, mpi-esm and ukesm) for historic period (hist; 1981-2010; an average of 30 years) and future scenario period (2040-2070; an average of 30 years) under three shared socio-economic pathways (ssp126, ssp370 and ssp585) at Ouagadougou and Kumasi in West Africa.

Discussion

SIMPLACE crop model was employed to evaluate the growth and yield of the Asontem cowpea genotype commonly grown in Ouagadougou and Kumasi. This cowpea genotype was calibrated and validated and compared to observed values in the 2017/18 and 2018/19 growing cycles, respectively in response to phosphorous and water stress. This study shows the potential to use the model solution as a supporting tool in irrigation and fertilizer management for cowpea production in West Africa. The accuracy of crop growth simulation models hinged on the real-location correctness of simulating crop yields and other important variables (Choruma *et al*., 2019). The results of this study exhibited a realistic agreement between observed and simulated crop growth and yield parameters in two different locations corresponding to two contrasting agro-ecological zones. The radiation used efficiency as a function of atmospheric carbon dioxide (CO_2) concentration (in ppm) used in the crop model was corrected.

After calibration, the model predicted well LAI and total above ground biomass dynamics during the simulation, and this was indicated by the good agreement between observed and simulated values in response to phosphorous stress, water deficit, and their control conditions in the 2017/18 (Figures 2 and 3). The disagreement in 2018/19 during the model validation of leaf area, with observation in treatments 60P+WS and 0P+NWS (Figure 2 and Supplementary Table S1) is an indication that the genotype decreased growth and development in responding to water and phosphorous stress. The agreement and over-prediction of LAI when compared to the observation matched with Thorp *et al*. (2014) and Ortiz *et al*. (2009) reports on mixed underpredicted and overpredicted LAI using the CROPGRO-Cotton model. Total above ground biomass recorded in the observations compared to the simulations reduced in all treatments. Though, the genotype demonstrated the ability to develop biomass under water stress and available phosphorous (60P+WS) during simulation (Figure 3). This result indicated that the calibrated model is sensitive to the application of water and fertilizer. Water and nutrient stress have been reported to reduce biomass which in turn reduced photosynthesis and stomatal conductance (Chaves *et al*., 2009). However, Cowpea is known to have the ability to thrive under various

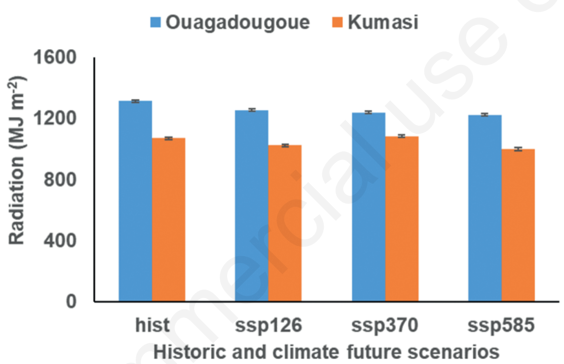

Figure 7. Simulated average radiation of Asontem cowpea variety during the growing period for the historic period (hist, 1981-2010, average of 30 years) and future scenario period (2040-2070, average of 30 years) under three shared socio-economic pathways (SSP126, SSP370 and SSP585) at two different locations in West Africa (Kumasi and Ouagadougou) under rainfed conditions without fertilizer application using the output of four different climate models (gfdl, ipsl, mpi-esm and ukesm).

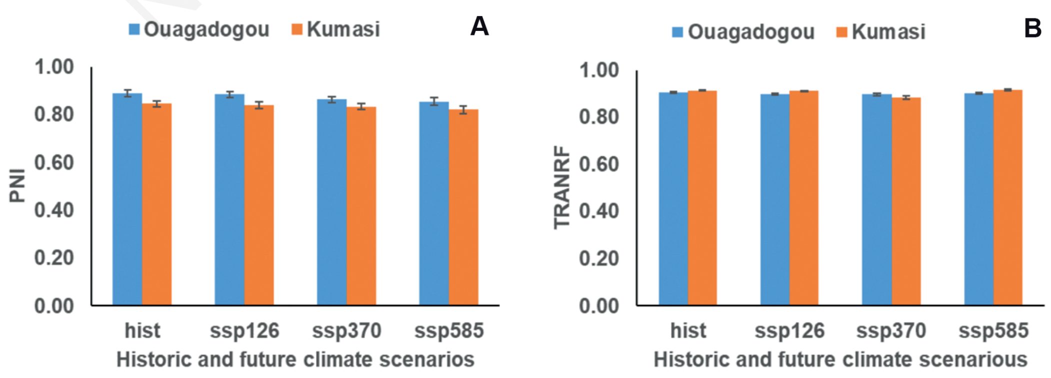

Figure 8. Simulated average phosphorous nutrition index (PNI; A) and water stress factor (TRANRF; B) of Asontem cowpea variety during the growing period for the historic period (hist, 1981-2010, average of 30 years) and future scenario period (2040-2070, average of 30 years) under three shared socio-economic pathways (SSP126, SSP370 and SSP585) at two different locations in West Africa (Kumasi and Ouagadougou) under rain-fed conditions without fertilizer application using the output of four different climate models (gfdl, ipsl, mpi-esm and ukesm).

drought and insufficient plant nutrition conditions (Ewansiha *et al*., 2006) and this is well reflected by the model for the genotype Asontem.

The best fit of the grain yields observed and simulated occurred during the 2017/18 growing cycle. The grain yields of the genotype fitted well with the model in response to phosphorous stress (0P+NWS) and 60 phosphorous and water stress (60P+WS). The observed and simulated yield also agreed well in the control treatment (60P+NWS) (Figure 4; Supplementary Tables S1 and S2). This finding is an indication that this model can actually, be used with adequate accuracy, to simulate the impact of irrigation and fertilizer management on cowpea yield. SIMPLACE was able to simulate seed yield accurately for two peanut varieties across seasons (Faye *et al*., 2018). Kanda *et al*. (2021) concluded that under optimum water conditions, cowpea grain yield can be accurately modelled using AquaCrop model. However, in 2019, the grain yields of the genotype were insignificantly overestimated in the following treatments: water stress (60P+WS) as well as phosphorus and water stress (OP+WS). This finding well agreed with Kanda *et al*. (2021) where they reported that AquaCrop model over-estimated cowpea yield under water deficit conditions. High over-estimations of sorghum yield especially during water deficit conditions have been reported by Habte *et al*. (2020) using AquaCrop and DSSAT models. The SIMPLACE insignificantly simulation of yield during water deficit could be attributed to the possible errors in the determination of canopy senescence (Espadafor *et al*., 2017).

The effect of climate change on phenology, above ground biomass, and grain yield of the genotype Asontem was simulated using the validated model solution (Figure 5; Tables 4 and 5). At first, changes in environmental factors such as precipitation, temperature, radiation, PNI, and TRANRF in Ouagadougou and Kumasi were analysed (Figures 6-8). The impact of the climate change, reduced phenology (number of days to anthesis and maturity) in both locations. This was due to a rise in average temperature over the growing season recorded in both locations when comparing socio-economic pathways with historic baseline climate (Figure 6A). Climate change has also been reported to impact wheat phenology in China (Liu *et al*., 2018). An increase in temperatures has been generally, reported to lead to the shortening of plant growth periods and consequently reduced yields. When this happened the total amount of absorbed radiation during the growing period decreased which led to a decline in the yield as shown in Kumasi (Mearns *et al*., 1997; van Oijen and Ewert, 1999). However, the reduction in growing period length in this study did not negatively affect above ground biomass and grain yield in both locations (Figure 6; Table 5). In the presence of optimum temperatures and adequate water supply, elevated CO_2 is reported to increase the rate of photosynthesis in plants. This positively influences the growth rate of above ground biomass contributing to higher yields (van der Kooi *et al*., 2016). However, grain yield increase was higher in Ouagadougou compared to Kumasi and this may be the result of differences in radiation and precipitation in all future scenarios in the two locations (Figures 6 and 7). Contrasting climate change impacts have been reported on wheat yields depending on varieties and locations (Xiao-Xu *et al*., 2022). In Ouagadougou cowpea yields in the historic period are generally higher than in Kumasi, due to higher incoming radiation and higher total precipitation during the growing period (Figures 5-7). This effect persisted under the different climate scenarios (Figure 5).

The future increase in temperature and decrease in radiation as a result of climate change reduced yield in wheat and increased evapotranspiration, which fastened the uptake of plant nutrients such as phosphorus and nitrogen in the soil (Xiao-Xu *et al*., 2022). However, high simulated PIN and TRANRF (implying low P and water stress) under future climate in Ouagadougou suggest that uptake of water and P was high despite higher cowpea yields (Figure 7A and B). There are several reports that show that cowpea is able to grow under moderate soil moisture and high-temperature conditions. This characteristic has been attributed to high-efficiency roots to take-up water and nutrients, maintaining high rates of photosynthesis under adverse environmental conditions (Singh *et al*., 2003).

Conclusions

The calibrated SIMPLACE model solution accurately estimated the growth and yield of the genotype in response to phosphorous and water stress in two years of field trials, under the impact of the future climate scenarios. The projected changes of above ground biomass and yield under the pre-dominant low-input cropping systems for all three SSPs was high. Compared to historic simulations of the biomass and yield of cowpea, the model solution projected higher above ground biomass, and yield under the predominant low input cropping systems for all the three SSPs as a result of the rise in CO_2 and in spite of slightly shorted growing cycle length in both locations.

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