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AGRONOMY

Analysis of Sensitivity of Soybean Yield to the Increasing Temperature under Humid Tropical Climate of Nigeria

Omotayo B. Adeboye[1*], Olaniran J. Matthew[2], Amaka P. Adeboye[1], Bart Schultz[3] and Kenneth O. Adekalu[1]

[1]Department of Agricultural and Environmental Engineering, Obafemi Awolowo University, Ile-Ife, Nigeria
[2]Institute of Ecology and Environmental Studies, Obafemi Awolowo University, Ile-Ife, Nigeria
[3]Department of Land and Water Development, IHE Delft, Lelystad, The Netherlands

*Corresponding author: adeboyeob@oauife.edu.ng (**ORCID ID:** 0000-0002-2428-4226)

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ABSTRACT

This study simulates the leaf area index (*LAI*), above-ground dry matter (*ADM*) and seed yield of soybean grown in an alfisol soil and humid tropical climate of Nigeria, West Africa. It used the calibration datasets for 2011 and 2012 to validate the field experiment conducted at the Teaching and Research Farms, Obafemi Awolowo University, Ile-Ife, Nigeria from September 2015 to December 2015. The model was evaluated using root-mean-square-error (*RMSE*), mean bias, (*MB*) and percentage bias (*PMB*). Model sensitivity tests were also carried out to assess the potential impacts of higher temperatures on soybean growth and development. There were good agreements between model simulations of the crop parameters and the field measurements. The models effectively replicated the observations of *LAI* (*MB* = 0.339 kg ha^{-1}; *PMB* = 26%; *RMSE* = 0.611 kg ha^{-1}) and grain yields (*MB* = 3.28 kg ha^{-1}; *PMB* = 0.17%; *RMSE* = 3.28 kg ha^{-1}). Sensitivity tests revealed that additional warming up to 6°C could reduce *VPD* (~ 2.0%) and *LAI* (~ 23.5%). However, soybean *ADM* and grain yield improved with increase in temperatures near the optimal threshold value during the growing period. Further increase in temperatures by ≥ 4°C reduced the *ADM* by ~ 23.8% and the grain yield by ~ 1%. The findings suggested that future warmer climate could have significant negative impacts on the growth and development of soybeans in the study area.

HIGHLIGHTS

- There were fairly good agreements between model simulations and field measurements of leaf area index, biomass and seed yield of soybeans
- The simulations replicated the essential hydro-meteorological features of humid tropical region of Nigeria adequately.
- Grain yield and aerial biomass of soybean improved with increase in temperatures by 1 to 4°C in the seasons.
- Temperatures above the optimal threshold value, 30°C reduced the aerial biomass and grain yield.
- In the future, warmer climate could reduce productivity of soybeans in the humid southwest Nigeria.

Keywords: Soybean, growth and development, sensitivity, increasing temperature, Nigeria

Soybean (*Glycine max* (L.) *Merr*.), yields three times more than the protein per hectare of other cultivated cereal crops such as rice, wheat or maize (Masuda and Goldsmith 2009). It is one of the most efficient producers of protein (Khojely *et al.* 2018). Soybean is a major industrial crop for production of animal feed, cooking oil, powdered milk, biodiesel, candle, seasonings (Dugje *et al.* 2009; Ishaq and Ehirim 2014). Nigeria is one of the

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leading producers of soybean in sub-Saharan Africa, SSA (Khojely *et al.* 2018). The crop, usually grown using low agricultural input, and it performs well in the southern and northern Guinea Savannah of Nigeria where annual rainfall is more than 700 mm (Dugje *et al.* 2009). It is a staple source of income for smallholder farmers and improves soil fertility. The demands for soybean for the production of human and animal foods, paint, pharmaceutical, and confectioneries industries in Nigeria has increased substantially (Omotayo *et al.* 2007). In the recent times, the yields of soybeans have reduced in SSA. This can be attributed to cultivation of poor varieties and application of limited quantity of fertilizers and rhizobial inoculants in soils with no history of soybean production (Khojely *et al.* 2018). Opportunities for improving production of soybean across SSA could be harnessed through improved and accurate prediction of the crop phenology such as leaf area index (*LAI*), biomass, yields, and cultivar specific coefficients in different environmental conditions.

Growth and yield responses of soybean to planting dates depend on the environmental conditions such as changes in climate, variety and crop management practices (Ishaq & Ehirim 2014; Khojely *et al.* 2018). By mid-century, the southwest Nigeria is projected to experience higher air temperatures and more frequent, intense and extreme rainfall (Olajire *et al.* 2020). In addition, field crops in the region have been shown to be vulnerable to climate change, particularly increased temperatures (Adejuwon 2006). Previous studies suggested that optimum temperature required for different genotypes of soybean development range between 25 and 30^{o}C (Onat *et al.* 2017). Thus, elevated temperatures may benefit crops below their optimal temperature threshold but reduce the growth of the crops near or past their thresholds (Kandil *et al.* 2013). Furthermore, literature suggests that soybean varieties could differ in their sensitivity to high temperatures while high temperature could negatively affect the seed yield of soybean varieties (Onat *et al.* 2017). For examples, increased mean temperatures above the optimal threshold can shorten the growth cycle and grain filling period as well as reduce number of flowers, seeds per pod and yields of grain crops (Asseng *et al.* 2015; Onat *et al.* 2017). The timing of extreme warming or heat events has important repercussions on plant physiology (Elias *et al.* 2018). During reproduction, for example, heat stress may reduce the effectiveness of pollinators, reduce grain set, and could cause sterility (Lobell *et al.* 2007). Predictions from mechanistic and empirical models showed that additional warming above optimal temperature thresholds during the entire growing period could severely reduce soybean grain yield (Sionit *et al.* 1987). Occurrence of yield reduction is attributed to the fact that plants close their stomata at temperatures above the temperature optimum which in turns decreases crop photosynthesis (Elias *et al.* 2018).

Thus, potential impact of increased day (maximum) and night (minimum) time temperature, still remain a big challenge to global sustainability of the soybean cropping system in the future (Zheng *et al.* 2009). However, few research information is available on the responses of soybeans to increasing temperature under humid tropical climate of West Africa. Therefore, the objective of this study is to simulate the yield components (leave area index, dry biomass and grain yields) of soybeanin in alfisol under sub-humid tropical conditions of Nigeria; using a model with a reduced complexity and lesser cultivar-specific parameters. This was with a view to assessing the sensitivity of the soybean crop growth and development to hypothetically increasing temperatures in the study area. The present study provides baseline information useful for economic assessment of impacts of future climate change on soybean yield and production in Nigeria, West Africa.

MATERIALS AND METHODS

Study area

The Teaching and Research Farms of Obafemi Awolowo University (OAU), Ile-Ife, is located in southwest Nigeria (latitude 7.5033^{o}N and longitude 4.5033^{o}E). The study area is characterised by wet season from April - October and dry season from November – March (Matthew 2020). The mean minimum and maximum temperatures are 20 and 28^{o}C respectively. Annual cycles of rainfall demonstrate bimodal distribution with peaks in June and September while the total annual rainfall is about 1200 mm. The basement soil at the experimental field is alfisol; sandy loam, slightly acidic and with low fertility (Komolafe 2019). The soils are extremely susceptible to erosion and compaction with low water retention capacities and thus susceptible to drought. Organic carbon of the soils declined rapidly when the lands is cultivated and the rate depended on climate and soil factors (Lal 1986).

Field experiments

Crop data from the field experiments on soybeans in 2011, 2012 and 2015 at the Teaching and Research Farms of OAU, Ile-Ife, were used in this study. The 2011 and 2012 datasets as reported in Adeboye *et al.* (2017) were used for model calibration while those of 2015 (Table 1) were used for validation and sensitivity analyses. Detail experimental procedures and measurements have been well documented (Adeboye *et al.* 2017; Adeboye *et al.* 2019). In addition, daily ground measurements of minimum and maximum temperatures, relative humidity, solar radiation and precipitation during the entire growing periods were obtained from the metrological station near the farm. At an average interval of 10 days from 18 Days after planting (*DAP*) the *LAI*, above and below photosynthetically active radiation (*PAR*) were measured using AccuPAR LP80 (Meter Group, USA) near solar noon. Ten samples of the below and above *PARs* were taken from triplicate by placing the line sensor perpendicular to the rows above and below the plant canopy. The daily *LAI* was determined by interpolation. Above ground biomass (*DAB*) was measured at intervals of 1 week from 32 DAP. Plants were harvested and oven dried at 70°C (Memmert, Sweden) for 48 h. The oven-dried mass was multiplied by the plant population, and the biomass (t ha^{-1}) was estimated. Eleven consecutive measurements of the *DAB* were made in the seasons.

Model's calibration and simulations

A time series graph of the *LAI* versus DAP was developed from which the *LAI* of the crop at any period was determined using Eqn. (1) (Setiyono *et al.* 2008):

$$LAI_i = L_{net_i} PD_i \times 10^{-4} \quad \dots(1)$$

where,

LAI = leaf area index (m^2 m^{-2}),

L_{net} = net leaf area (cm^2 plant^{-1}),

PD = population density (plants m^{-2}) on the i^{th} day.

Reduction in PD between emergence and the physiological maturity stage was modelled as a function of initial PD and the decrease in population density due to post-emergence attrition using Eqn. (2):

$$PD_i = PD_0 + \frac{\left(PD_0\left(\frac{PD_{red}}{100}\right) - PD_0\right)\left(DOY_i - DOY_0\right)}{DOY_0 - DOY_{Harv}} \quad \dots(2)$$

$$PD_{red} = \frac{1 - 0.00412PD_0}{0.067 - 0.0003PD_0} \quad \dots(3)$$

where,

DOY_i = day of the year,

PD_0 = population density (m^{-2}),

DOY_0 = day of year at the emergence,

DOY_{Harv} = day of year at the physiological maturity.

Daily temperature response function describing acceleration of leaf area expansion and senescence due to increasing temperature (T) was determined using Eqn. (4):

$$f(T_g) = \begin{cases} \dfrac{2(T - T_{Base})^{\alpha}.(T_{Opt} - T_{Base})^{\alpha} - (T - T_{Base})^{2\alpha}}{(T_{Opt} - T_{Base})^{2\alpha}} & T_{Base} \le T \le T_{Upper} \\ 0 & T < T_{Base} \ or\ T > T_{Upper} \end{cases} \quad \dots(4)$$

where,

$$\alpha = \frac{In2}{In\left[(T_{Upper} - T_{Base})/(T_{Opt} - T_{Base})\right]} \quad \dots(5)$$

$$f(T_s) = \begin{cases} \dfrac{T-4}{30-4} & T > 4 \\ 0 & T \le 4 \end{cases} \quad \dots(6)$$

The effect of water availability on leaf expansion was taken into account by using a modified simple water balance model to determine the ratio of actual transpiration to the potential transpiration. The soil–water balance model used a tipping bucket (cascade) type approach. Water deficit response function for leaf expansion $f\left(\frac{TR_a}{TR_p}\right)$ was determined using Eqn. (7):

$$f\left(\frac{TR_a}{TR_p}\right) = \left[\frac{2}{1 + e^{-20(ln[-(1/14)(((2/(TR_a/TR_p))-1)]-0.05)}}\right] - 1 \quad \ldots(7)$$

Expanding and senescing leaf areas (L_g and L_s) were determined using the current daily rates of change and the previous values of these variables using Eqn. (8):

$$L_{g_i} = L_{g_{i-1}} + \Delta L_{gx_i}\left(\frac{dX_g}{di}\right)$$
$$L_{s_i} = L_{s_{i-1}} + \Delta L_{sx_i}\left(\frac{dX_s}{di}\right) \quad \ldots(8)$$

where,

L_{g_i}, $L_{g_{i-1}}$, L_{s_i}, $L_{s_{i-1}}$ = Current and previous days of expanding and senescing leaf area (cm^2 plant^{-1}), respectively;

ΔL_{gx_i} = Current day change in expanding leaf area for a given change in cumulative;

ΔL_{sx_i} = Change in senescing leaf area for a given change in cumulative;

X_g and X_s are cumulative $f(T_g)$ and $f(T_s)$ after emergence;

dXg/di and dXs/di = Changes in cumulative $f(T)$ during expansion and senescence per given change in calendar days, respectively. Thus, the net leaf area (L_{net}) was estimated as the difference between expanding and senescing leaf area:

$$L_{net_i} = L_{g_i} - L_{s_i} \quad \ldots(9)$$

In the first iteration, 2 cm^2 plant^{-1} was used for L_{g0} based on field measurements (expanded leaf area at emergence) and 6 cm^2 plant^{-1} was assumed for L_{s0} (initial leaf area senescence). For all other iterations the values of L_{g0} and L_{s0}in the simulation was determined from the logistic Eqn. (10) at $X_g = X_s = 0$.

$$L_g = \frac{a_g}{1-b_g exp(-c_g X_g)}; \quad L_s = \frac{a_s}{1-b_s exp(-c_s X_s)} \quad \ldots(10)$$

where,

a = L-asymptote,

b = shape factor,

c = rate constant

g and s subscripts = represent expansion and senescence variables, respectively

The rate of leaf expansion, ΔL_{gxi} and rate of change in senesced leaf, ΔL_{sxi} were simulated using the first derivative of logistic functions in Eqn. (11) (Milthorpe & Moorby 1979):

$$\Delta L_{gx_i} = \frac{a_g b_g c_g exp(-c_g X_g)}{[1 + b_g exp(-c_g X_g)]^2} f(T_g) f\left(\frac{TR_a}{TR_p}\right) \ldots(11)$$

$$\Delta L_{sx_i} = \frac{a_s b_s c_s exp(-c_s X_s)}{[1+b_s exp(-c_s X_s)]^2} f(T_s) \quad \ldots(12)$$

$$b_g = \left(\frac{a_g}{L_{g_0}}\right) - 1; \quad b_s = \left(\frac{a_s}{L_{s_0}}\right) - 1 \quad \ldots(13)$$

$$c_g = \frac{4[\Delta L_{gx}]_{max}}{a_g}; \quad c_s = \frac{4[\Delta L_{sx}]_{max}}{a_s} \quad \ldots(14)$$

where,

$[\Delta L_{gx}]_{max}$ and $[\Delta L_{sx}]_{max}$ = maximum rate of change in expansion and senescing leaf areas for a given change in X_g and X_s (cm^2 plant^{-1} unit X g^{-1} or X s^{-1}) respectively. Finally, dry matter accumulation and partitioning as well as grain yield were simulated using the framework of (Supit & der E. Goot 2003) as fully documented in (Setiyono *et al.* 2010).

The 'cultivar-specific' model input parameters such as plant population density and leaf expansion rates were first estimated as proposed in (Setiyono *et al.* 2008) using the calibration datasets from field experiments conducted in 2011 and 2012. During the calibration, the input parameters (α_g, Lg$_0$, ΔL_{gxmax}, α_s, Ls$_0$, $\Delta L_{sx\,max}$) were optimized to allow the model to accurately simulate of phenology, LAI, ADM, and final seed yield. This was achieved by conducting a non-linear regression analysis with the maximum rate of expansion and senescence ($\Delta L_{gx\,max}$ and ΔL_{sxmax}) as independent variables while the shape factors for expansion and senescence (bg and bs) and rate constants for expansion and senescence (c_g and c_s) were considered as dependent variables. Then, the maximum expanding and senescing leaf area (a_g and a_s) were obtained as the intercepts of L at $x = 0$ (Lg_0 and Ls_0).

Statistical analyses

The means, range, variances, minimum and maximum values and standard deviations of the daily hydo-meteorological parameters were estimated using the MATLAB® 2019b. In addition, derived hydo-meteorological parameters such as the vapour pressure deficit (*VPD*) in kPa and vapour density deficit (VDD) in °C were estimated Eqns. (15) and (16) respectively (Allen *et al.* 1998):

$$VPD = 0.6108 \exp\left[\frac{17.27 - T_{mn}}{T_{mn} + 237.3}\right] (1\text{-RH}/100) \quad \ldots(15)$$

$$VDD = (T_{max} - T_{min})[(0.00109T_{mn} + 0.011) T_{mn} + 0.35] \quad \ldots(16)$$

Where RH is the relative humidity, T_{min}, T_{max}, and T_{min} are minimum, maximum and mean temperatures respectively.

Then, weekly averages of all the parameters were determined. This enabled effective discussion of the impacts of variations in hydo-meteorological parameters on the soybean growth and development during the growing periods. The model simulations for 2015 growing season were validated by comparing the simulated and observed crop parameters using the root mean square error (*RMSE*), mean bias (*MB*) and percentage mean bias (*MPE*) in Eqns. (17) to (18) respectively:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(H_{sim\,i} - H_{obs\,i})^2}{n}} \quad \ldots(17)$$

where H_{sim}andH_{obs} are simulated and observed global radiation respectively while n the total sample size and i = 1, 2, 3, … n.

$$MB = \sqrt{\frac{\sum_{i=1}^{n}(H_{sim\,i} - H_{obs\,i})}{n}} \quad \ldots(18)$$

The percent mean error (*PME*) describes the mean relative difference of the simulated series to the observed discharge series in percentages over the periods of observation. It is the measure of the deviation of data being evaluated, expressed in Eqn. (19):

$$PMB = 100 \times \sqrt{\frac{\sum_{i=1}^{n}(H_{sim\,i} - H_{obs\,i})}{n(H_{obs\,i})}} \quad \ldots(19)$$

A low *RMSE* is desirable while *NSE* and *r* should approach unity as closely as possible. A positive value of *MB* or *PMB* indicates overestimation, while a negative value indicates underestimation.

Furthermore, sensitivity tests were carried out by hypothetically increasing the observed daytime (maximum) and night (minimum) air temperatures during the entire growing period by 1, 2, 3, 4, 5 and 6°C respectively. This was with a view to assessing the effects of increased canopy temperatures on soybean yield components in the study area.

RESULTS AND DISCUSSION

Variations in hydro-meteorological parameters during the field experiment

Summary descriptive statistics of daily datasets of the observed hydro-metrological parameters during the growing season of soybean (September 1 to December 12, 2015) at the experimental site are presented in Table 2. Seasonal rainfall was about 40% of the annual rainfall in the area. Air temperatures were moderate during the season. It ranged from 15.1°C to 27.4°C while humidity was low. Average solar radiation was 26 MJ m^{-2} and 3.8 MJ m^{-2}. On the planting date, T_{min} was about 22°C, T_{max} was 29°C and T_{min} was 25°C while VPD was 0.78 mbar (Fig. 1). There was an apparent steady increase in T_{min} by 1°C, T_{max} by 4°C, T_{mn} by 3.6°C and *VPD* by 0.14 mbar from the day of sowing until 6 weeks after planting (WAP). Thereafter, there were rapid increase and decrease in air temperatures and *VPD* and the peaks of *VPD* coincided with the trough of air temperatures and *vice-versa*. A marked peak in air temperatures and trough of *VPD* occurred during the *6 WAP*, 9 – 10 WAP and 13 *WAP* respectively. The late stage of the development of the crop that is from 8 WAP was warmer and less humid than the first 6 WAP). Seasonal rainfall was 557 mm (Table 2) and range of values of T_{max}, T_{min}, T_{min} and humidity (Fig. 1).

Variations in the weekly mean total rainfall and estimated rainfall, surface runoff, change in surface soil water and drainage from planting to harvest are in Fig. 2. It rained more than once in every week with 10 to 100 mm week^{-1} within the first 6 WAP (Fig. 2). There was a short break in rainfall between the 6th and 7th week while a long break occurred after 10 WAP until maturity. Furthermore, changes in soil water increased until the end of the 5 WAP

Table 1: Location of experimental field, year, cultivar, phenology, row spacing, population density, and crop parameters used for calibration and validation of simulations of soybean'sleave area index (LAI), grain yield and above-ground dry matter (ADM)

Location	Teaching and Research Farm, Obafemi Awolowo University Campus, Ile-Ife, Nigeria (7.5033°N – 7.5788°N; 4.5033°E – 4.5788°E)													
Year	2015													
Cultivar	TGX 1448 2E													
Purpose:	Model validation													
Parameters	Stages													
	Planting	**S0**	**S1**	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8**	**S9**	**S10**	**Sm**	**Maximum**
DOY	244	253	276	283	290	297	304	311	318	325	332	339	346	
LAI ($m^2 m^{-2}$)	—	0.0	0.74	1.51	2.15	2.19	4.25	5.61	5.01	2.93	2.15	1.70	1.58	5.61
PD (plants m^{-2})		22.22	—	—	—	—	—	—	—	—	—	—	—	—
ADM (kg ha^{-1})		—	60.0	80.0	190.0	360.0	560.0	780.0	900.0	1150	1240	1230	1190	1240
Row Spacing (m)	0.6 × 0.3	—	—	—	—	—	—	—	—	—	—	—	—	—
Yield (kg ha^{-1})		—	—	—	—	—	—	—	—	—	—	—	1920	1920

DOY = Julian day (244 Julian day ≡ Sep-01)S0, S1, S2… Sm = Emergence stage to Maturity, PD = population density.

Table 2: Statistics indices of the observed daily hydro-meteorological parameters during the field experiment (September 1 to December 12, 2020) at the Teaching and Research Farm, Obafemi Awolowo University campus, Ile-Ife, Nigeria

Statistical Index	**Hydro-meteorological Parameters**					
	PRECIP (mm)	**RAD (MJ m-2)**	**RHUM (%)**	**TMIN (°C)**	**TMAX (°C)**	**TMN (°C)**
Mean	557.1	16.9	80.5	22.0	31.9	27.0
Minimum	0.0	3.8	48.7	15.1	27.4	23.4
Maximum	48.8	22.5	93.7	25.8	36.2	30.2
Range	48.8	18.7	45.0	10.7	8.8	6.8
Standard Deviation	10.5	3.7	11.2	2.6	2.2	1.5
Variance	110.3	13.7	125.1	6.6	4.7	2.4

PRECIP = Precipitation; RAD = Solar radiation; RHUM = Relative humidity; TMIN = Minimum temperature TMAX = Maximum temperature; TMN = Mean temperature.

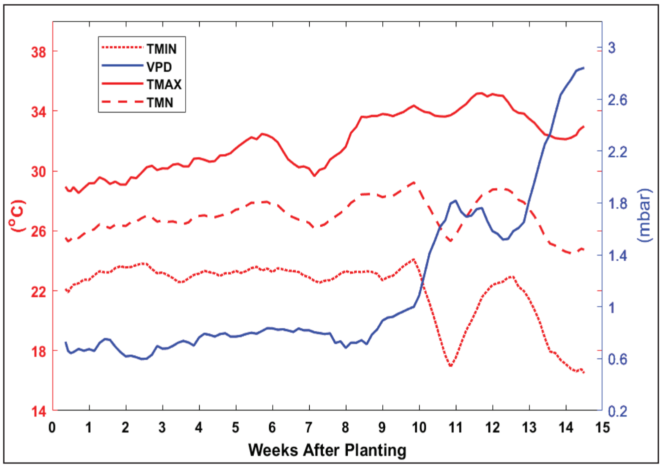

Fig. 1: Observed air temperatures (minimum, TMIN; maximum, TMAX; and mean, TMN) and vapour pressure deficit (VPD), during the growing season of soybean

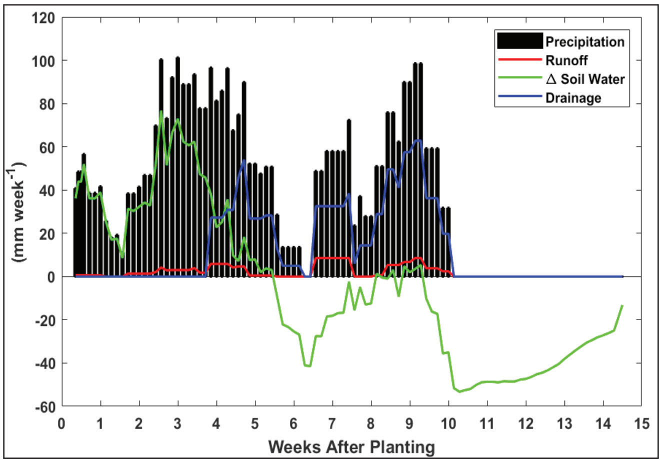

Fig. 2: Observed weekly precipitation, estimated surface runoff, change in surface soil water and drainage to the underground soil (mm $week^{-1}$) during the growing season

with the peaks of 70 -73 mm week^{-1} at 3 and 9 WAP. The excess water surplus thereafter saturated the surface soil layer and there were increased runoff and the seepage to the underground soil. The soil water was 40 mm week^{-1}) at 6 *WAP* and after 10 *WAP* until the maturity. Fig. 3 describes weekly variations in solar radiation (RAD in MJ m^{-2} week^{-1}), potential evapotranspiration (PET in mm week^{-1}), surface evaporation (PE in mm week^{-1}) and crop transpiration (PT in mm week^{-1}) at the experimental site. Potential crop transpiration (PT) increased from zero at 2 *WAP* during crop emergence date to about 3.0 mm at 6 *WAP, which is* its first major peak. During the same period, solar radiation and potential evapotranspiration (PET) increased to the first major peaks of 20 MJ m^{-2} and 8.3 mm respectively. However, the trio later decreased to attain their minimum at 8WAP and increased thereafter. Potential surface evaporation initially increased but later decreased after crop emergence to a minimum of 0.8 mm during 8 to 10 *WAP*.

Simulated soybean LAI, grain yields and other crop parameters

Fig. 4 illustrates the observed and simulated *LAI* as well as simulated population density (PD), root depth (RD), fraction of radiation intercepted (FRI) and the *DAB* of soybean from planting to maturity. The observed and simulated daily *LAI* compared well. *LAI* increased from about 0.9 m^2 m^{-2} at emergence to 5.6 m^2 m^{-2} at 10 *WAP* (Fig. 4a). Thereafter, it reduced progressively to about 0.8 m^2 m^{-2} at harvest due to senescence triggered by dryness of air and soil as well as warming. As expected, *FRI* showed similar trend with the *LAI*. The maximum simulated *FRI* was about 90% at 10 WAP (Fig. 4d). The daily variations in the simulated *FRI* closely followed those of the observations. However, the simulations are slightly higher. The maximum *PD* of about 22 plants m^{-2} was obtained

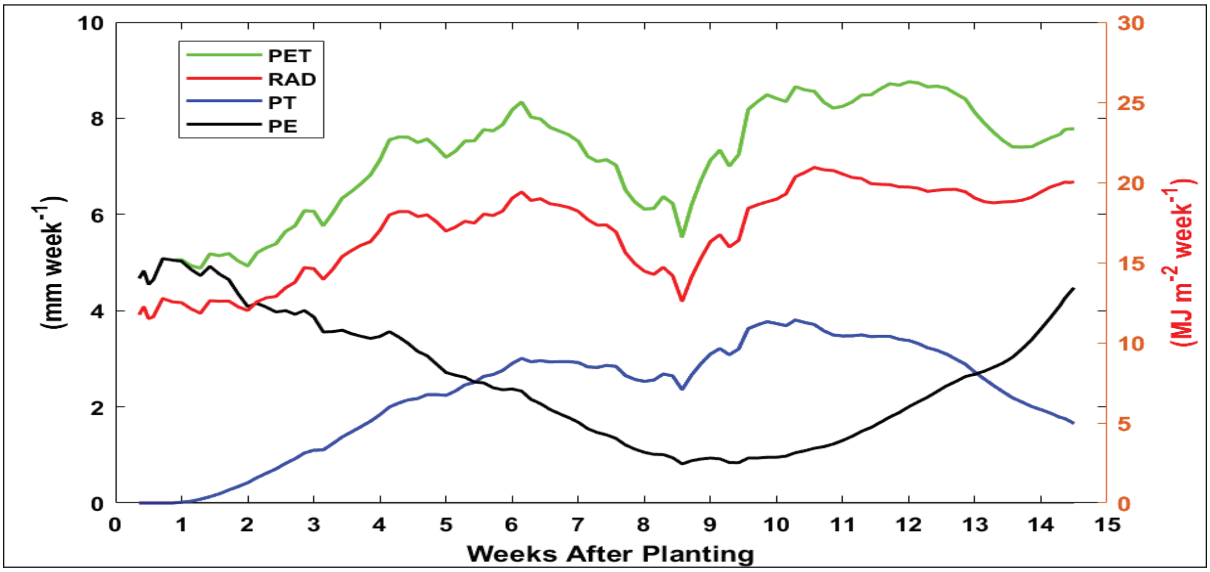

Fig. 3: Observed weekly solar radiation (RAD), simulated potential evapotranspiration (PET), surface evaporation (PE) and crop transpiration (PT) during the growing season

Table 3: Performance evaluation of the simulated soybean leave area index, fraction of radiation intercepted, grain yield and above ground dry matter

Crop Parameter	Performance Index		
	MB	**PMB (%)**	**RMSE**
LAI (m^2 m^{-2})	0.3394	26.1487	0.6105
FRI (%)	7.9636	19.7926	9.3502
Yield (kg ha^{-1})	3.2801	0.1708	3.2801
ADM (kg ha^{-1})	-89.4591	-72.2236	105.9532

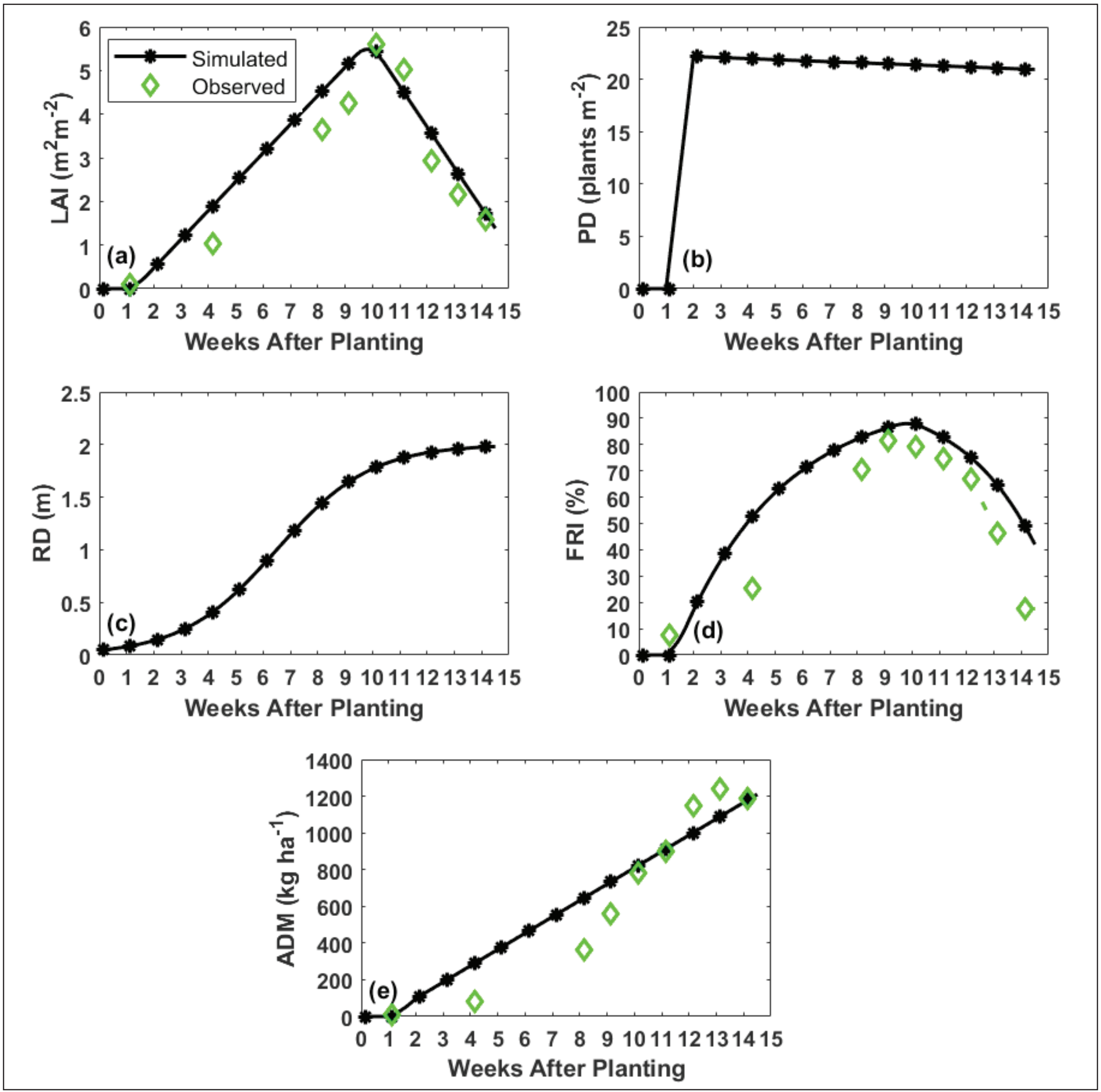

Fig. 4: Observed and simulated **(a)** leave area index, LAI; **(b)** population density, PD; **(c)** root depth, RD; **(d)** fraction of radiation intercepted, FRI; and **(e)** aboveground dry matter, ADM by soybean during the growing season

at emergence, which decreased almost linearly to 20 plants m^{-2} at harvest (Fig. 4b). The RD increased exponentially a couple of days before emergence to a maximum of about 2 m at maturity (Fig. 4c). The above ground matter increased almost linearly from about 10.0 kg ha^{-1} at emergence to 1200 kg ha^{-1} at maturity (Fig. 4e)

Model performance evaluation

Evaluation of the performance of the model was measured using root-mean-square error (*RMSE*), mean error (*MB*), and percentage mean error (*PMB*) as presented in Table 3. In general, there was fairly good comparison between the model simulations and the observations. The simulated *LAI*, *FRI* and final grain yield of soybean compared fairly well with the observations. The models slightly overestimated *LAI* (*MB* = 0.339 kg ha^{-1}; *PMB* = 26%; *RMSE* = 0.611 kg ha^{-1}) and yield (*MB* = 3.28 kg ha^{-1}; *PMB* = 0.17%; *RMSE* = 3.28 kg ha^{-1}). On the other hand, *FRI* was slightly underestimated (*MB* = 7.96 %; *PMB* = 19.79%; *RMSE* = 9.35%). However, performance evaluation of the above-ground dry matter was found to be unsatisfactory with *PME* = -72%.

Model sensitivity to increasing canopy temperature

Results of the sensitivity of the crop parameters (FRI, PET, PE, PT, VPD, VDD, LAI and ADM) to hypothetically increased air temperatures (by 1, 2, 3, 4, 5 and 6°C) during the entire growing period compared with the normal observations of 27.0°C mean value; see Table 2) are presented in Fig. 5. These sensitivity tests reveal the impacts of climate change on soybean growth and development. Results suggested maximum reductions in *FRI* (8%), *LAI* (1.4 $m^2 m^{-2}$) and ADM (400 kg ha^{-1}) when mean air temperatures increased by 1 to 6°C (Fig. 5b-d). No substantial changes in *VPD* when the air temperatures were increased (Fig. 5a). This is because the relative humidity was assumed constant in the simulations. However, as expected, *VDD*, *PET*, *PT* and *PE* increased significantly with steady increase in air temperatures from 1 to 6°C (Fig. 5e-h). A rise in air temperature by 6°C caused a 10°C

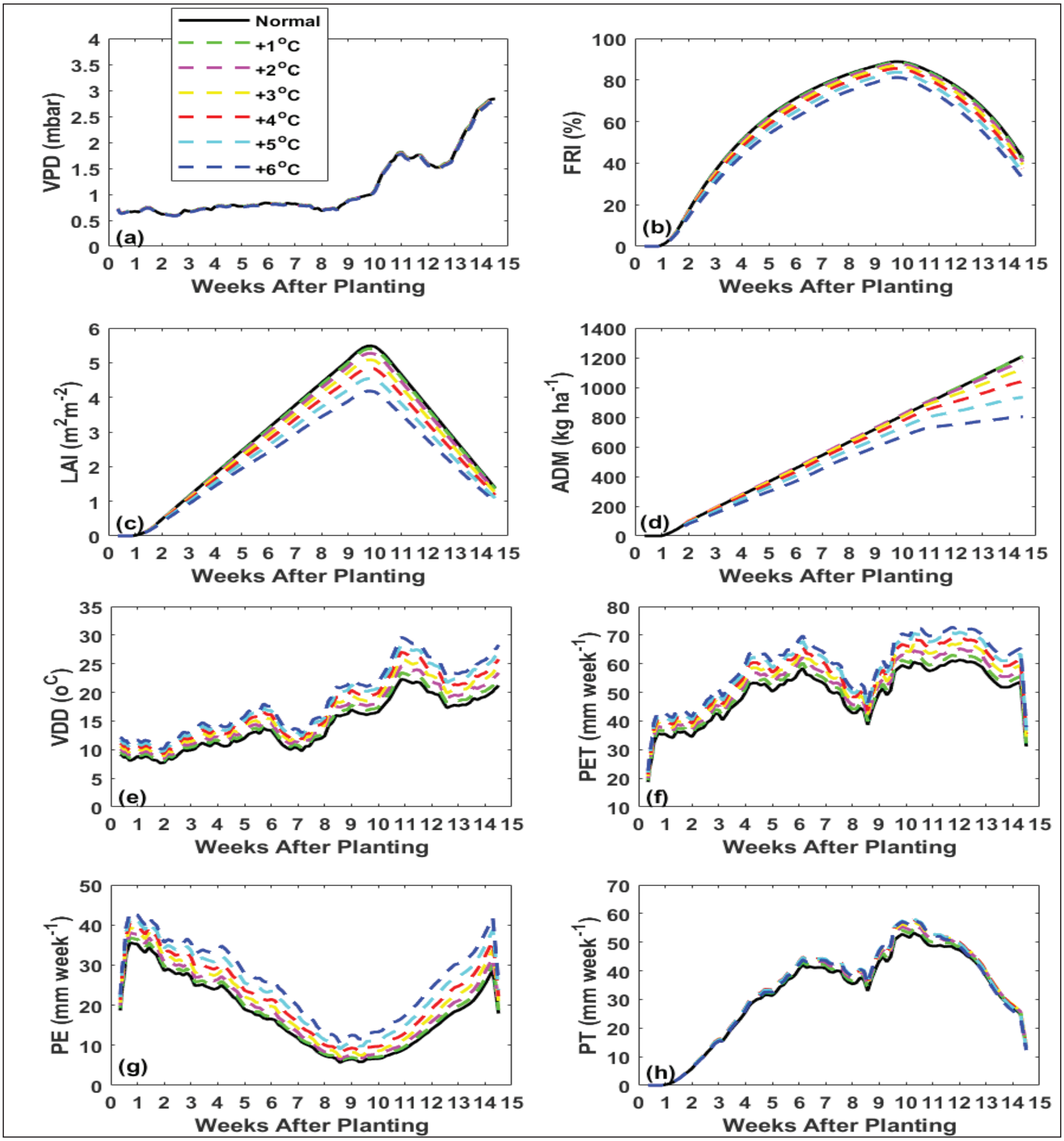

Fig. 5: Variations in **(a)** vapour pressure deficit, VPD; **(b)** fraction of radiation intercept, **(c)** leave area index **(d)** above ground dry matter, ADM; **(e)** Vapour density deficit (VDD); **(f)** potential evapotranspiration, PET; **(g)** potential evaporation, PE; and **(h)** potential transpiration, PT of soybean to increase in the mean air temperatures by 1, 2, 3, 4, 5 and 6°C

change in VDD, 18 mm for PET and 10 mm for PT and 5 mm for PE. The PE has the least change due to rise in air temperature. However, solar radiation remains unchanged and this tends to decrease canopy photosynthetic in the crop.

Potential changes in *VPD*, *LAI*, *ADM* and grain yield of soybean due to the increase in the mean air temperatures are presented in Fig. 6. There is reduction in VPD from 0.3 to 2.0% and LAI from 1 to 23.5% with increasing warming by 1 to 6°C (Figs. 6a & b). The ADM is projected to increase by 1% when temperature is increased by 1°C (Fig. 6c). Increments in air temperature from 2 to 6°C decreased the simulated *ADM* by 23.8%. There was progressive increase in the yield from 2 to 5% when air temperature was increased by 1 to 3°C (Fig. 6d). This indicated a tendency for reductions in the percentage rise in yield to about 1% when air temperature was increased to 6°C.

Environmental conditions varied during the soybean cropping periods. The mean observed meteorological parameters during the 2015 field experiment were 22.0°C (minimum temperature), 31.9°C (maximum temperature), 27.0°C (mean temperature), 80.5% (relative humidity), 557.1 mm (precipitation.) and 16.9 MJ m^{-2} (global solar radiation). These values were within the mean meteorological values previously reported in Matthew (2020) for the same region and time frame during 1996–2015 period. There was an apparent steady increase in weather parameters from the day of sowing until 6 WAP. The results also revealed that it rained at least twice in every week during this period. However, high daily variability in weather was observed thereafter till the harvest date. As expected, the peaks of *VPD* coincided with the trough of air temperatures and vice-versa [during the *6 WAP*, 9 – 10 WAP and 13 *WAP*]. Similarly, period between 8 WAP till harvest (14 WAP) was warmer and less humid than the earlier period. The soaring up of *VPD* at 10 *WAP* without a reversal until the harvest date was a signal of cessation of rainfall or the beginning of dry season with a potential weather condition for increased plant senescence due to rising dryness of air. Studies have shown that the cessation of rainfall usually

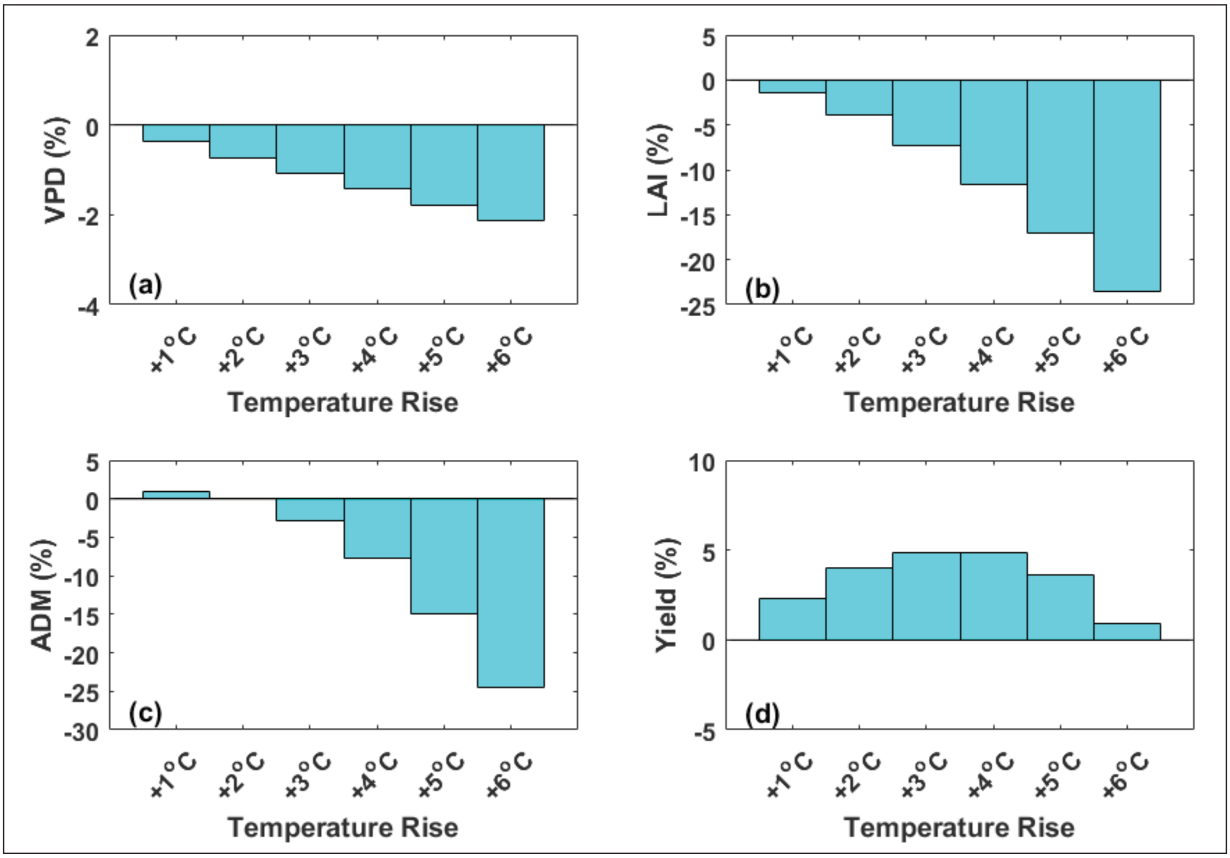

Fig. 6: Percentage changes in soybean **(a)** vapour pressure deficit, VPD; **(b)** leave area index, LAI; **(c)** above ground biomass, ADM; and **(d)** grain yield of soybean due to the impacts of increase in the mean air temperatures by 1, 2, 3, 4, 5 and 6°C

occurred in November (Matthew, 2020); the period that coincide with the noticeable increasing *VPD* in this study.

In brief, the results effectively capture the essential climatic features of the study area; typical of humid tropical region of southwest Nigeria. The observed increasing patterns of (daily and weekly) variations in solar radiation with increasing crop transpiration, *PET* and *VPD* suggested direct linear relationship between the variables (Yates and Strzepek, 1994; Allen *et al.* 1998). It has been proven that emergence of crop and increase in the leaf surface area will reduce evaporation from the ground surface but increase the PT (Boote & Jones 1988). Thus, potential surface evaporation initially increased but later decreased after crop emergence to a minimum of 0.8 mm during 8 to 10 *WAP*. Similarly, observed sharp drop in *PET*, *PE* and *PT* at 8 WAP could be linked to the effects of significant decrease in solar radiation as well as air temperatures and *VPD*. Increased VPD that is greater than 2.0 mbar in soybean has been reported to be associated with significant increase in PT and possibility of occurrence of abiotic stresses, which can reduce crop yield significantly (Gilbert *et al.* 2011; Machado Júnior *et al.* 2017).

Furthermore, the findings of this present study demonstrated good agreements between the model simulations and field measurements. The patterns of daily variations in the simulated *FRI* closely followed those of the observations. In agreements with our results (which produced an estimate of maximum FRI = 90% and *LAI* = 5.6 $m^2 m^{-2}$ at 10 WAP), previous studies reported soybean intercepts of about 95% of the total incoming *PAR* at the critical *LAI* on 74 DAP (Setiyono *et al.* 2008). In addition, the simulated root growth increases exponentially till harvest date which supports the fact that root growth of some soybean cultivar may continue until physiological maturity (Olajire *et al.* 2020). The simulated *DAB* also increased linearly from about 10.0 kg ha^{-1} at emergence to 1200 kg ha^{-1} at maturity. Performance evaluation indices suggested fairly good comparison between the model simulations and the observations. The simulated *LAI*, *FRI* and final grain yield of soybean compared fairly well with the field measurements while the biases were found to be within the tolerable limits except for the simulation of the above-ground dry matter. These noticeable discrepancies in the model simulations could be attributed to the influence of external factors such as diseases and pests, damage done to the crop during the growing period.

Sensitivity analyses suggested reductions in *FRI* (8%), *LAI* (1.4 $m^2 m^{-2}$) and *ADM* (400 kg ha^{-1}) but significant increase in VDD (10°C) PET (18 mm), PT (10 mm) and PE (5 mm) when the mean temperature was increased by 1 to 6°C. Reduction in *LAI* under warmer conditions could be explained by increased *PT.* Reduction in *LAI* and *ADM* under higher temperatures could also be attributed to decline in *FRI*. Furthermore, additional warming by 1 to 6°C resulted in 2.0% reduction in VPD, and 23.5% decline in LAI. However, 1% rise in ADM was obtained when temperature is increased by 1°C. Further warming was found to shrink the *ADM* by 23.8% which could be attributed to fall in *LAI* as speculated by (Gilbert *et al.* 2011). A rise from 2 to 5% in soybean grain yield was obtained when the day and night times temperature was increased by 1 to 3°C during the growing period. However, the yield was suggested to decline by 1% when temperature was further increased to 6°C. This pattern of results demonstrated that soybean yield could benefit from higher temperature near the optimal threshold value (about 30°C) as previously documented in the literature (Kandil *et al.* 2013; Setiyono *et al.* 2008). However, additional warming above optimal temperature thresholds during the entire growing period could severely reduce soybean grain yield (Asseng *et al.* 2015; Onat *et al.* 2017).

Finally, a clear positive response of soybean yields to daytime temperature within the optimum temperature range of 27 - 30°C have been reported in other regions of the world (Gibson & Mullen 1996; Zheng *et al.* 2009). However, while (Gibson & Mullen 1996) proposed that duration of seed growth could be insensitive to increases in daily maximum temperature above the optimum other authors suggested that excessively high daytime temperature (particularly during flowering and seed filling) could have a negative impact on grain yield of soybean (Tacarindua *et al.* 2013; Zheng *et al.* 2009). Although it has been reported that genotypes differ in their sensitivity, high temperature is found to inhibit pollen germination and pollen tube growth and accelerates ethylene production that increase flower abortion and plant senescence

(Elias *et al.* 2018; Onat *et al.* 2017). These suggest that the farmers in the study area should integrate vulnerability of total regional crop acreage and its composition with a view to effectively mitigate and adapt to future rise in temperatures. However, further research is required to determine the effects of higher temperatures on floral bud differentiation and pod setting as a limiting factor of soybean seed yield in the study area.

CONCLUSION

Our findings revealed high variability in daily weather conditions during the soybean cropping periods. The mean observed meteorological parameters during the 2015 field experiment were 22.0°C (minimum temperature), 31.9°C (maximum temperature), 27.0°C (mean temperature), 80.5% (relative humidity), 557.1 mm (precipitation.) and 16.9 MJ m^{-2} (global solar radiation). Our results effectively capture the essential hydro-meteorological features of humid tropical region of south-western Nigeria. It revealed fairly good agreements between the model simulations and field measurements and the percentage biases in LAI and grain yields were within the tolerable limits. Results of the sensitivity analyses suggested reductions in FRI (8%), LAI (1.4 m^2 m^{-2}) and ADM (400 kg ha^{-1}) but significant increase in VDD (10°C) PET (18 mm), PT (10 mm) and PE (5 mm) when the mean temperature was increased up to 6°C. Additional warming was suggested to reduce VPD by 2.0% and LAI by 23.5%. However, soybean above ground dry matter and grain yield improved with increase in temperatures near the optimal threshold value of about 30°C during the growing period. Further warming above 4°C was found to shrink the *ADM* by 23.8% and the yield by 1%. We conclude that projected future warmer climate could have significant negative impacts on soybean growth and development in the alfisol soil and sub-humid tropical climate of Nigeria, West Africa. Thus, in order to reduce temperature risk under future warmer climate, soybean growers could mitigate crop heat stress by increasing irrigation which provides evaporative cooling as proposed by Haim *et al*. (2008). Another adaptation option for elevated temperatures is early planting of the crop to adjust for temperature shifts.

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