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Using the CROPGRO Model to Predict Phenology of Cowpea under Rain-fed Conditions

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Authors' contributions

Author DL designed the study, performed the model simulations and statistical analysis, wrote the first draft of the manuscript. Authors MMK, AAA, SMO and YMK conducted the field and laboratory tests. All authors read and approved the final manuscript.

Original Research Article

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ABSTRACT

Field experiments were conducted in November of 2012 at the University of Juba demonstration farm on cowpea cultivar UCR 368 and local variety JUBA1. In this study, the DSSAT Cropping System Model, CROPGRO-Cowpea, was employed to simulate and predict cowpea yield in a 3-year production period under rain-fed conditions. The treatments selected were then subjected to sensitivity analysis under varied irrigation levels and seed planting dates. The model showed that the grain weight under default rain-fed conditions was on average at 111 kg/ha in all three years while this was between 250-300 kg/ha after varied planting date and over 1000 kg/ha after increased irrigation schedules in Years 2 and 3. For the three years, the model adequately simulated vegetative weight (RMSE=25.03, r^2=0.92, d=0.72) and grain weight (RMSE= 20.93, r^2=0.99, d=0.99) as well as Leaf Area Index (LAI) (RMSE=0.04, r^2=0.92, d=0.61) under the combined treatment effects of varied planting date and increased irrigation schedules. However, increased irrigation frequencies during pre- and post a thesis tended to increase Water Stress in Photosynthesis Days (WSPD) to between 0.7-0.8 but did not negatively influence the total grain weight and biomass. Phenology and yield were lowest under rain-fed conditions but increased with an integrated irrigation management option.

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The results in our study shows that the model could be used to improve our understanding of the long-term effects of management practices on cowpea yield under varied planting dates and water supply.

Keywords: Phenology; grain weight; water stress in photosynthesis days; model simulation and calibration.

1. INTRODUCTION

Cowpea [(*Vigna unguiculata*) Walp] yield in South Sudan is limited by several abiotic and biotic stress factors. Abiotic stress factors such as, late sowing date, variable rainfall, low soil fertility, pests and diseases and poor crop management practices while biotic stress factors such as crop variety based on specific genotypic traits may increase risks of crop failure and reduce plant physiological growth. The South Sudan has over 70% deficit in the annual legume production and has to therefore import much of this from the neighboring countries of Uganda, Kenya and Sudan. South Sudan´s average cowpea production in the Greenbelt agro-ecological region is between 300-450 kg.ha^{-1}. Much of this production is by subsistence farming with farmers using traditional methods. Ideally, with available water and good soils, cowpea could be grown any time throughout the year and would address the serious food insecurity situation in South Sudan. However, the lack of knowledge on the suitable sowing dates, amounts of irrigation water especially during off-seasons, amounts of insecticides to combat insect pests all increase the uncertainties pertaining to the attainment of maximum cowpea yield.

Cowpea is a cheap source of protein (20-26%) and starch (50-67%) [1]. In Central Equatoria State of South Sudan, the green fresh leaves, are consumed as "*ngete*". In South Sudan, several varieties under cultivation are unimproved with varied times to harvest maturity ranging between 70-120 days. These local varieties often remain stunted in growth with poor yields. Cowpea is known to have good adaptation to both abiotic and biotic stress e.g. high temperatures and resistance to drought stress [2,3] and has the ability to better tolerate a wide range of soil pH when compared to other grain legumes [4].

Determining the crop yield potential by classical methods requires long term and costly experimentation which, in most cases, may not be feasible in situations where resources are limiting. However, using soil and weather databases and knowledge of crop physiological process, potential yield can be determined by dynamic crop models [5,6]. The importance of knowing the crop potential yield and yield gap is twofold; first, it enables us to project the future crop yields and second, it facilitates the knowledge and understanding of the biophysical constraints to maximum yield [5].

Accurate estimation of model parameters for crop, soil and weather is an entry point in crop modeling for estimating crop potential yield and yield gaps in any location under any crop production setting. Genetic coefficients are input parameters in crop models that account for differences either in the duration of developmental phases or in the response of a specific plant process to management practices [7,8], tillage systems [9] different environments [10] and for crop risk analysis [11,12,13]. The coefficients summarize the way in which a specific crop cultivar divides up its life cycle, responds to different aspects of its environment e.g. day-length, temperature, moisture stress, disease organism) or appears/changes morphologically. An elusive, yet important step in crop modeling has been the estimation of cultivar coefficients in the current Decision Support System for Agro-technology Transfer (DSSAT) version 4.5 [14].

The objectives of the field study were (i) to evaluate the ability of the CROPGRO-cowpea crop growth model (Version 4.5) to simulate cowpea phenology under rain-fed conditions in a three year period (ii) to use the model to estimate temporal or time-dependent potential yields caused by varying planting dates as well as water supply.

2. MATERIAL AND METHODS

The study done from November 2011 to May 2012 was conducted at the Research Farm of the Department of Agricultural Sciences, College of Natural Resources and Environmental Studies (CNRES), University of Juba, South Sudan. The study area lies within the green belt agro-ecological zone of South Sudan and is located between latitude 4º50'28'' and longitude 31º35'24 with annual rainfall average of 650 mm mostly during the months of April to October. The climate of the area is tropical wet and dry climate with average temperatures ranging between 27Cº during the rainy seasons to about 35ºC during the dry season of November to March. The soils can be predominantly be classified as *Eutric Leptosol* with less associated *Eutric Gleysol* as shown in Table 1.

Table 1. Some of the physical and chemical properties of sandy loam soil (*Eutric Leptosol*) at the Nursery farm of the Dept. of Agricultural Sciences, University of Juba (CNRES, 2012)

Soil physical and chemical features	Description
Soil Mapping Unit*	*Eutric Leptosol*
USDA Texture Classification*	Sandy loam
Drainage Class (0-0.5%)*	Moderately well
Sand (average)	47.6%
Silt (average)	45.1%
Clay (average)	7.3%
pH (LaMotte STH Test Method)	7.2
Vol. Water Content (average)	18.4%
Bulk Density (gm/cm³)	1.34
Humus Content	2.95%

**Source: Harmonized World Soil Data Viewer Version 1.2*

The treatment consisted of UCR 368 cowpea variety planted in a completely randomized block design with four replications. The experimental units composed of 12 plots each 6 m² and spaced at 0.5 m apart with a plant-to-plant spacing of 0.2 m. Seedlings were thinned to two plants per stand at 14 days after planting. Malathion Mercaptothion 50% EC was sprayed at the rate of 0.5l/ha at vegetative, flowering and pod setting stages to protect the crop against insect pests that were damaging the buds. All plots were flooded with 10 mm water prior to planting to create moist soil conditions (Table 2).

2.1 Measurements

2.1.1 Data collection

The phenology of the cowpea plants were analyzed over the growth period. Fourteen days after emergence, 2-3 plants from each row within an area of 1 m² were carefully uprooted and the roots washed to remove any remaining soil clods that were still attached. These were later placed in polythene bags, tied and taken to the laboratory for growth analysis, dry matter content and grain yield. Plant sampling and data collection were done on a bi-weekly basis up to the end of the vegetation period.

Table 2. Relevant default data used to run the DSSAT 4.5 under Rain-fed conditions

Crop Type	Cowpea
Variety/cultivar	Kenyan UCR 368 and local variety JUBA1
Planting Date	19thNovember 2012
Emergence Date	23rdNovember 2012
Plants/m²	16
Planting depth	2 cm
Plant Spacing	30 cm
Row Spacing	40 cm
Rainfall	depending on rainfall regularity
Plot Area	6.5 m ²
Chemical Application	Malathion, Mercaptothion with active ingredient of 50% EC.This is a broad spectrum pesticide for control of sucking and chewing pests on vegetables, fruits and food crops. Average application of 0.5 l/ha
Application Dates	22nd December 2012 and 3rd January 2013
Application Method	Foliar spraying

The LAI estimation involved removing all green leaves from 2-3 randomly selected plants within a row after first measuring the leaf-covered ground surface. The LAI defined as one-half of the total leaf area per unit ground surface area was then computed for each plant and expressed in terms of all plants within the plot according to well established formulae [15,16] as:

Leaf Area Index, LAI= 0.5 L/P, where L is leaf area (cm²) and P, the ground area (cm²).

Dry matter content was done by the cutting into 4-5 cm long of the freshly collected from cowpea variety UCR 368 and local variety JUBA1 plant samples and then measured to the nearest gram as the initial wet weight. These samples were later placed in an oven at 100 °C for at least 2-3 hours until the samples began to dry and get brittle. Drying intervals were repeated until the samples did not show any change in the dry weight and the DM calculated as:

[Initial wet weight (g) - Final dry weight (g)]/Initial Wet Weight (g) x100%

For the grain weight, 6-8 of the mature and ripened cowpea pods from each randomly chosen individual plant within a row was chosen. The UCR 368 had between 16-21 pods/plant with 9-15 seeds/pod while JUBA1 had between 10-15 pods/plant with 7-13 seeds/pod. One hundred seeds per plant from each of the varieties were later counted, oven dried at 100°C for 2-3 hours and weighed. The 100seed-weight/plant was determined and expressed for all plants within a plot in kg/plot (*or area in* m^2). Total weight per unit area was then expressed as kg/ha.

For the sensitivity test, the soil moisture content was conducted by extruding soil samples from experimental plots at 0-10cm depth on a 3-4 day basis due to the presumably high evapotranspiration rates (*average daily temperatures of about 33°C as from October to*

March) irrespective of the irrigation schedules. The soil samples were weighed and oven dried at 105°C for 24 hours. The measured soil water content was then calibrated against the predicted values for the three simulation years.

2.1.2 Experimental treatments

A single crop management file was created in DSSAT 4.5 for the rain-fed treatments. Under rain-fed conditions, the amount of water was not controlled as the experiments were conducted under natural conditions and the dry season between October to March had already began with erratic or hardly any rainfall.

2.1.3 DSSAT Model description and simulation

The DSSAT (Decision Support System for Agro-technology Transfer) model is particularly well suited for simulating agricultural practices [12]. The DSSAT v4.5 model integrates several crop system models, two soil carbon and nitrogen models, a daily water models and a range of crop/land management options to simulate crop growth/yield and environmental impacts. The model has been widely and successfully used throughout the world [12,13,17,18,19] and was recently used by [20] to simulate corn yield and nitrogen cycling on a 50-year corn production experiment in southwestern Ontario, Canada. CROPGRO is a generic model that can be used to simulate a range of grain legumes like soya-bean [21] and faba- bean [22] in both dry-land and irrigated environments across a range of latitudes in both northern and southern hemispheres.

Daily weather data as well as edaphic and crop management information were used as input data for the model. Due to lack of original and consistent weather data set over the last two decades for Juba, daily weather input variables from Morogoro, Tanzania were chosen because they at least matched the poor data obtained in Juba. The flow chart on the modeling sequences is shown in Fig. 1.

2.1.4 Statistical assessment and model performance

The best fit between the predicted phenological stages of vegetative weight or biomass change, dry matter increase, LAI and grain yield and the observed values were evaluated using three statistical parameters: Root Mean Square Error (RMSE), Index of Agreement *d* and Relative Error (RE) [23] and were computed using equations:

$$\text{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(P_i - O_i)^2} \qquad \text{Eqn. (1)}$$

$$d = 1 - \left[\frac{\sum_{i=1}^{n}(P_i - O_i)^2}{\sum_{i=1}^{n}\left(|P_i^{\circ}| + |O_i^{\circ}|\right)^2}\right], \qquad 0 \leq d \leq 1 \qquad \text{Eqn. (2)}$$

$$\text{RE}\ \% = \left(\frac{P_i - O_i}{O_i}\right) \times 100 \qquad \text{Eqn. (3)}$$

Where *n* is the number of observed values, P_i and O_i are the predicted and observed values respectively for the *i*-th data pair, $P_i^{\circ} = P - \bar{O}$ and $O_i^{\circ} = O - \bar{O}$ and $\bar{O}$ is the mean of the observed values. The departure from 0 of the index agreement *d*, can be used as a measure of under- or over prediction of the observed values by the model. A value of 1 for the index of agreement (*d*) indicates a good agreement between the simulated and observed data [24].

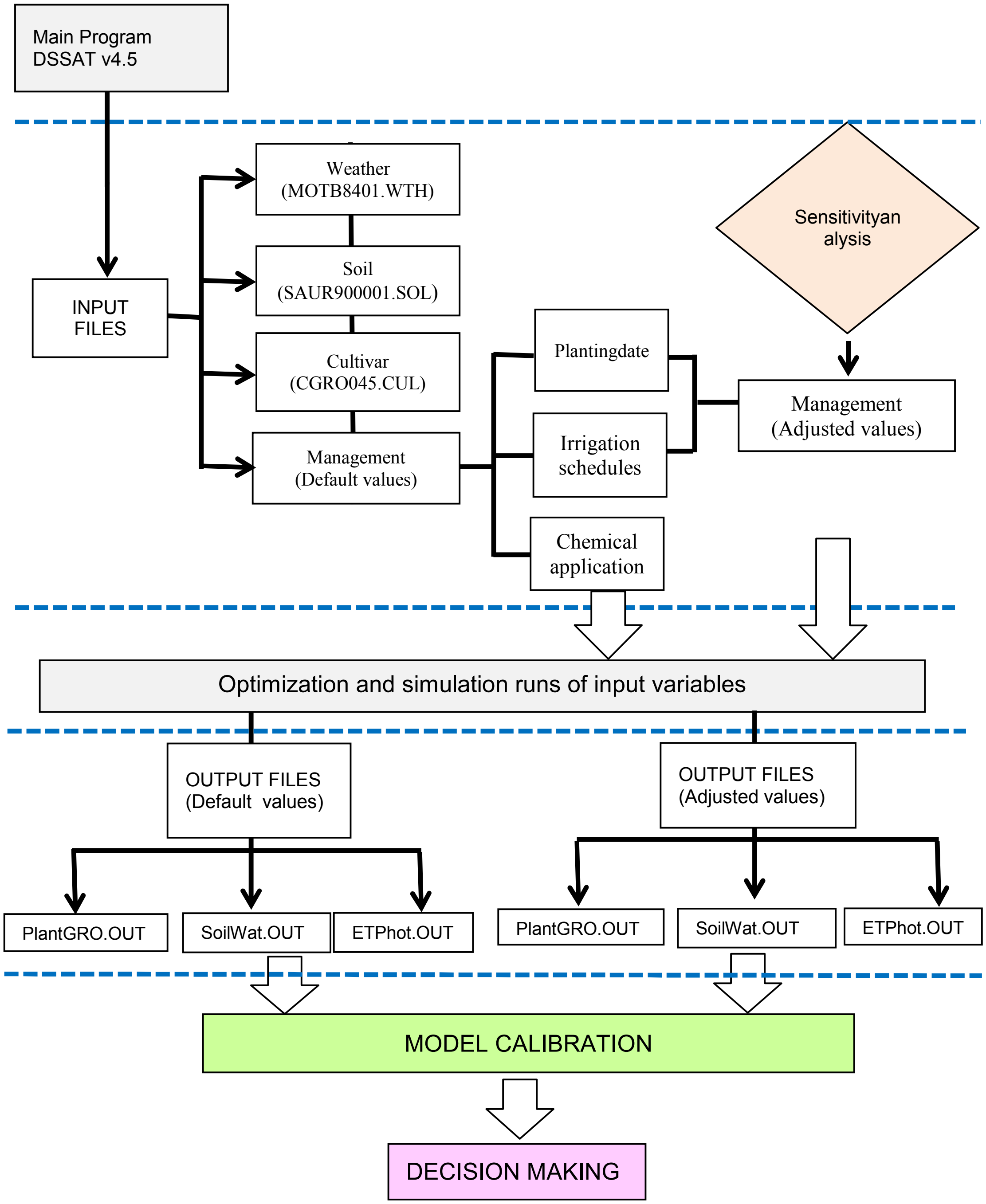


Fig. 1. Schematic representation of simulation program sequences used in the CROPGRO cowpea model of the DSSAT v4.5

2.1.5 Sensitivity analysis

Model stability and performance of the CROPGRO cowpea was examined by simulating increased water during irrigation schedules as well as altering the planting dates. Sensitivity analysis was obtained by computing the change in the output relative to changes in input parameter for the: planting date (*from 19 November 2012 to 10. June 2012*) and amount of water during each irrigation schedule as well as number of irrigation schedules (*from 5 to 35mm per each irrigation schedule and 11 irrigation schedules for entire vegetation period*) and how these impacted on: grain weight (kg/ha); Leaf Area Index (LAI); vegetative weight or biomass (kg/ha) and water content (cm^3/cm^3) in the first 0-10 cm soil layer.

3. RESULTS

3.1 Calibration and Evaluation of CROPGRO Cowpea Model

Calibration of the CROPGRO-cowpea model was done by using parameters: LAI, vegetative weight or aboveground biomass (kg/ha) obtained from measured observations of the local variety JUBA1 (unpublished data). No data on genetic coefficients of the black-eyed local variety JUBA1 used in this experiment were available, however, inference on specific genetic coefficients were done by visual observation of each individual phenology stages of the local variety JUBA1 and compared to that of the UCR 368 cowpea cultivar (Table 3).

Table 3. Genetic coefficients of both UCR 368 and local variety JUBA1 used in this study

Parameter/variable	Simulated UCR 368	Measured UCR 368	Measured JUBA1
Anthesis day (dap)	36	30	28
First pod day (dap)	40	37	31
First seed day (dap)	43	40	37
Yield at harvest maturity (kg [dm]/ha)	111	219	105
Leaf area index, maximum	0.68	0.7	0.52
Canopy height (m)	0.78	0.52	0.52
Harvest maturity day (dap)	106	99	120
Emergence day (dap)	4	5	5

The results of the CROPGRO cowpea calibration on vegetative weight or aboveground biomass (kg/ha) is shown in Fig. 2. Good agreements between the observed and simulated values of vegetative weight during the different phenology stages for the three simulation years were evident as indicated by the high regression coefficients (r^2). The simulated vegetative weights were best for Year 2 and 3 at r^2=0.96 and r^2=0.94 respectively while this was r^2=0.86 in Year 1.

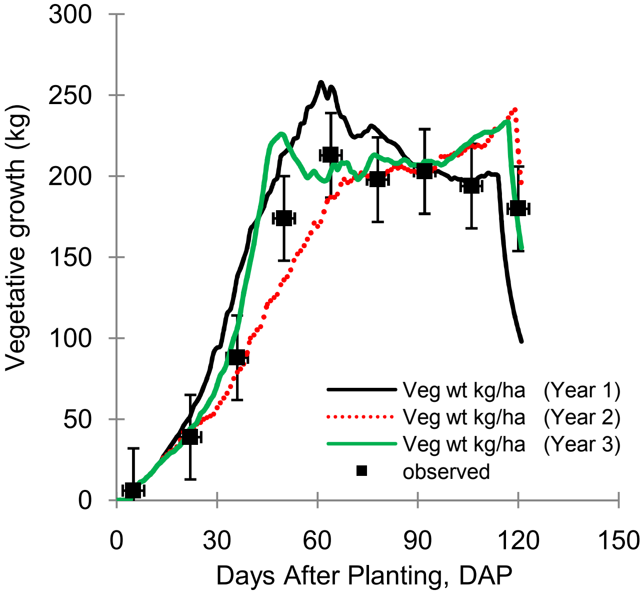


Fig. 2. Comparison between the observed and the simulated vegetative weight or biomass using default treatments
(under rain-fed conditions and unchanged planting dates)

3.2 Vegetative Weight or Biomass

Vegetative weight or biomass was simulated fairly well for all the three years with maximum values between 200-230 kg/ha, 30 and 60 DAP (Fig.3). Vegetative weight was consistently under-predicted especially 0 to 50 DAP for Years 1 and 3 but slightly over-predicted in Year 2 over the same period. Similarly, the model slightly over-predicted the vegetative weight for all three years 60-90 DAP. It appears that the model did not take into account the water stress caused by erratic rainfall during this time of the year which inevitably would have resulted in lower simulation values that those observed.

The relationship between the observed and predicted vegetative weight is shown in Fig.3. Year 3 showed the highest regression coefficient at r^2=0.96 followed by Years 2 and 1 at r^2=0.94 and 0.86 respectively

In addition, the agreement index (*d*) showed values as high as 0.99 for both Years 2 and 3 whereas this was low at 0.18 in Year 1. Similarly, the mean square error (RMSE) was large in Year 1 at 34.47 whereas this was low at 20.16 and 20.47 for Years 2 and 3 respectively.

These findings show that the CROPGRO-cowpea model effectively simulated the phenology of the UCR 368 cowpea cultivar in the three years as in Table 4.

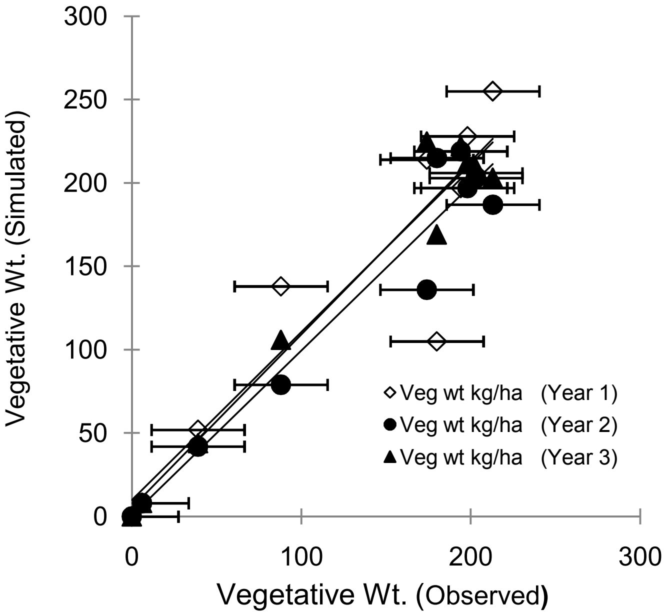


Fig. 3. The relationship between the observed and simulated vegetative weight or biomass using default treatments (*under rain-fed conditions and unchanged planting dates*)
(Year 1: y = 1.0069x + 9.9009; r² = 0.86), Year 2: y = 0.9897x + 0.4305; r² = 0.94),
(Year 3: y = 1.039x + 5.2524; r² = 0.96)

Table 4. Observed and simulated vegetative weight or biomass of cowpea cultivar UCR 368 at the research facility of Dept. of Agricultural Sciences, University of Juba (2012)

Total Vegetative weight or biomass (kg/ha)					
Simulation Year	**Observe**	**Simulated**	**RMSE [1]**	***d* [2]**	**RE (%) [3]**
1	1295	1403	34.47	0.183	14.27
2	-----	1286	20.16	0.996	2.86
3	-----	1398	20.47	0.995	10.96

[1]RMSE: Root Mean Square Error, [2]d: Index of Agreement, [3]RE: Relative Error

3.3 Leaf Area Index, LAI

The progress of the simulated and observed LAI is shown in Fig. 4. The LAI time course simulated by CROPGRO for the three years was nearly identical at 0 to 25 DAP and only began to show accentuated differences at 27 to 100 DAP. The model under-predicted the LAI in Year 2 with maximum value at around 0.24, 45 to 60 DAP as well as during the entire phenology. However, the model over-predicted the LAI with maximum values of about 0.35, 45-60 DAP for both Years 1 and 3 but predicted the LAI fairly well 75-120 DAP during seed setting and towards harvest maturity for all three years. This was to be expected as the model captured leaf senescence that initiated leaf abscission partly also caused by heat stress and intermittent water deficit during this time of the year.

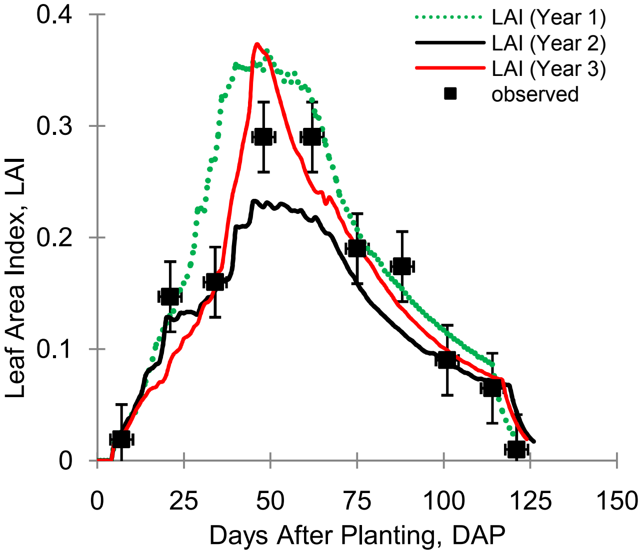


Fig. 4. Comparison between the observed and the simulated Leaf Area Index, LAI using default treatments (*under rain-fed conditions and unchanged planting dates*)

Fig. 5 illustrates simulated vs. observed LAI for the three simulation years. The model as aforementioned slightly overestimated LAI in Years 1 and 3 (RMSE=0.043, *d*=0.75 and RMSE=0.037, *d*=0.59 respectively). For Year 2, it under-estimated the LAI (RMSE=0.039, *d*=0.49) as in Table 5.

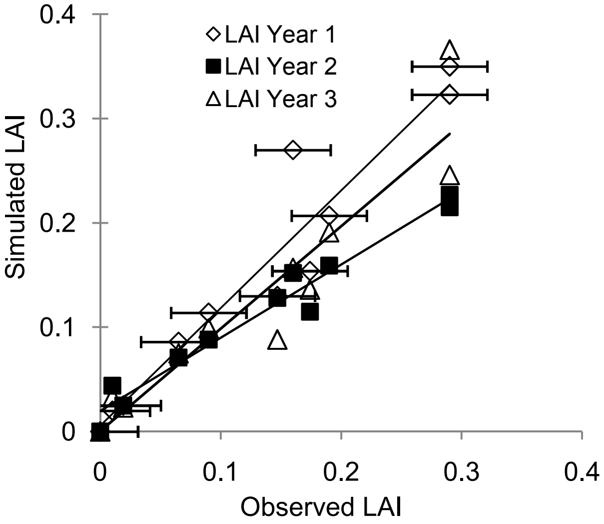


Fig. 5. Relationship between the observed and the simulated Leaf Area Index, LAI using default treatments (*under rain-fed conditions and unchanged planting dates*)

(Year 1: y = 1.1279x + 0.0055; r² = 0.92), (Year 2: y = 0.7014x + 0.0198; r² = 0.96),
(Year 3: y = 0.9833x + 0.0003; r² = 0.89)

Table 5. Observed and simulated *Leaf Area Index,* LAI of cowpea cultivar UCR 368 at the research facility of Dept. of Agricultural Sciences, University of Juba (2012)

	Leaf Area Index				
Simulation Year	**Observed**	**Simulated**	**RMSE** [1]	***d*** [2]	**RE (%)** [3]
1	0.134	0.153	0.043	0.751	20.205
2	-----	0.111	0.039	0.491	22.605
3	-----	0.129	0.037	0.599	20.377

[1]RMSE: Root Mean Square Error, [2]d: Index of Agreement, [3]RE: Relative Error

3.4 Grain Weight

The cowpea grain weight for three simulation years are compared in Fig. 6. The model accurately predicted the cowpea grain weight for all three years with Years 2 and 3 at around 220 kg/ha and a slight 16% over-prediction to the observed grain weight in Year 1 at 250 kg/ha. The deviations between predicted and observed grain weight were not significant as shown by the high regression coefficient values of r²=0.99 (Fig.7).

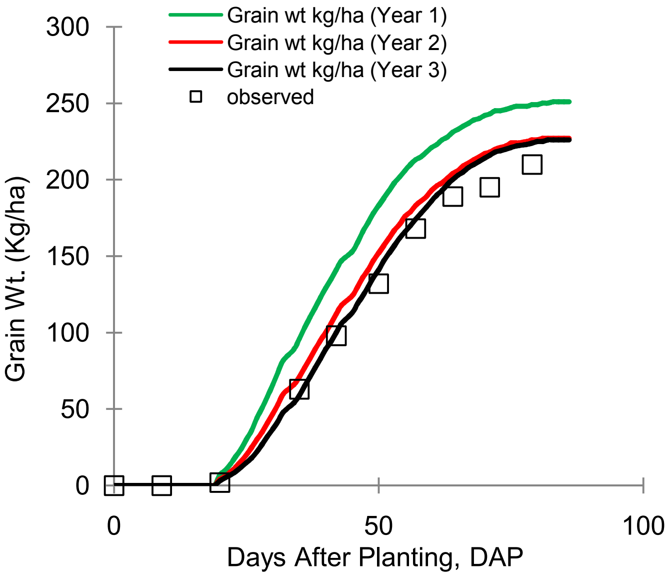


Fig. 6. Simulated and observed grain weight kg/ha) of cowpea cultivar UCR 368 under rain-fed conditions

The relationship between the observed and predicted grain weight is shown in Table 6. All three simulation years showed high regression coefficients of r²=0.99 but varying RMSE. Year 1 showed high RMSE and *d* followed by Years 2 and 3 respectively which both gave better fits.

Table 6. Observed and simulated grain weight (kg/ha) of cowpea cultivar UCR 368 at the research facility of Dept. of Agricultural Sciences, University of Juba (2012)

	Grain weight (kg/ha)				
Simulation Year	**Observed**	**Simulated**	**RMSE**[1]	***d*** [2]	**RE (%)** [3]
1	119.88	152.75	37.63	0.99	54.15
2	-----	132.25	14.59	0.99	20.52
3	-----	127.13	10.56	0.99	9.66

[1]RMSE: Root Mean Square Error, [2]d: Index of Agreement, [3]RE: Relative Error

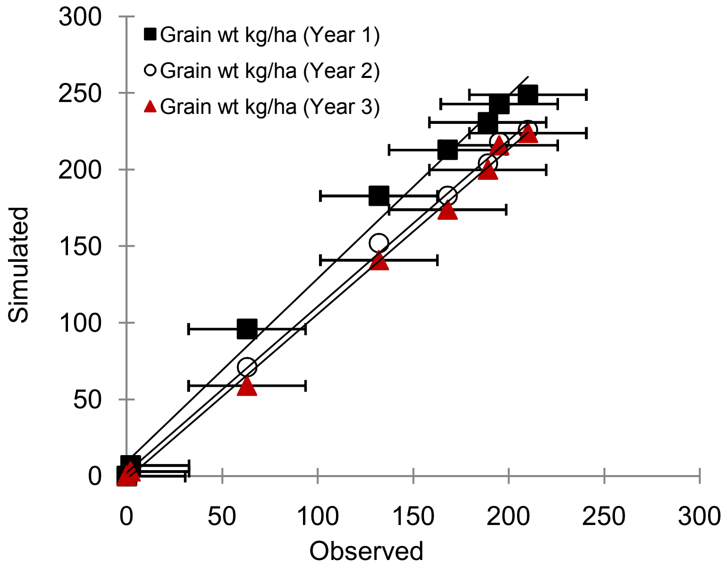


Fig. 7. Relationship between the observed and the simulated grain weight using default treatments (*under rain-fed conditions and unchanged planting dates*)
(Year 1: $y = 1.197x + 9.2641$; $r^2 = 0.99$), (Year 2: $y = 1.0853x + 2.1461$; $r^2 = 0.99$), (Year 3: $y = 1.0782x - 2.127$; $r^2 = 0.99$)

The water contents in the soil layer 0-10 cm during phenology of both UCR 368 cultivar and the local variety JUBA1 were also simulated predicting the rise and decline of soil water. The significance of water deficit in influencing LAI can be better understood by assessing the temporal changes of water regime in the soil during vegetation growth. Fig. 8 showed progress of the soil water content in the 0-10 soil layer for the three simulation years. For comparative purposes, soil water data based on measurements of Year 1 were used. Model results showed good estimate of the soil water dynamic in the first 0-10 cm of the soil layer in Year 2, but over-predicted this between 60 to 100 DAP during seeding and towards harvest maturity.

The performance of the model after changing the default treatments is shown in Fig. 9. After changing the planting date from default value (*19 November 2012 to 10 June 2012*), the model still showed no sensitivity in the three simulation years for the output variables. However, the model showed more sensitivity to water supply during and after eleven irrigation schedules. Leaf area index was highest in Year 3 at 1.6 and was threefold higher than under default values, whereas Years 1 and 2 were at 0.6 and 0.8 respectively. Similarly, increased water supply resulted into increased grain weight to maximum 1000 kg/ha in Year 3, this was tenfold more than under default values. Grain weight also increased by three-fold in Year 2 whereas it remained unchanged for Year 1. Our model simulation also showed that increased water supply increased vegetative weight in Year 3 to 3500 kg/ha with Years 1 and 2 at 1800 and 2000 kg/ha respectively.

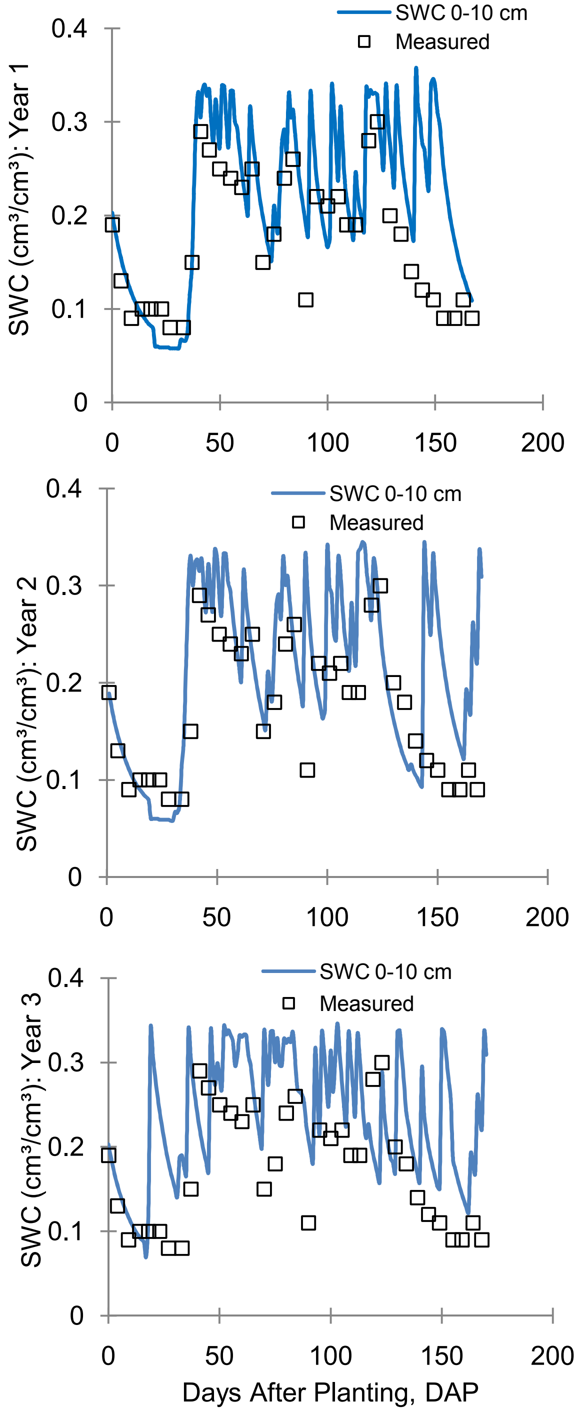
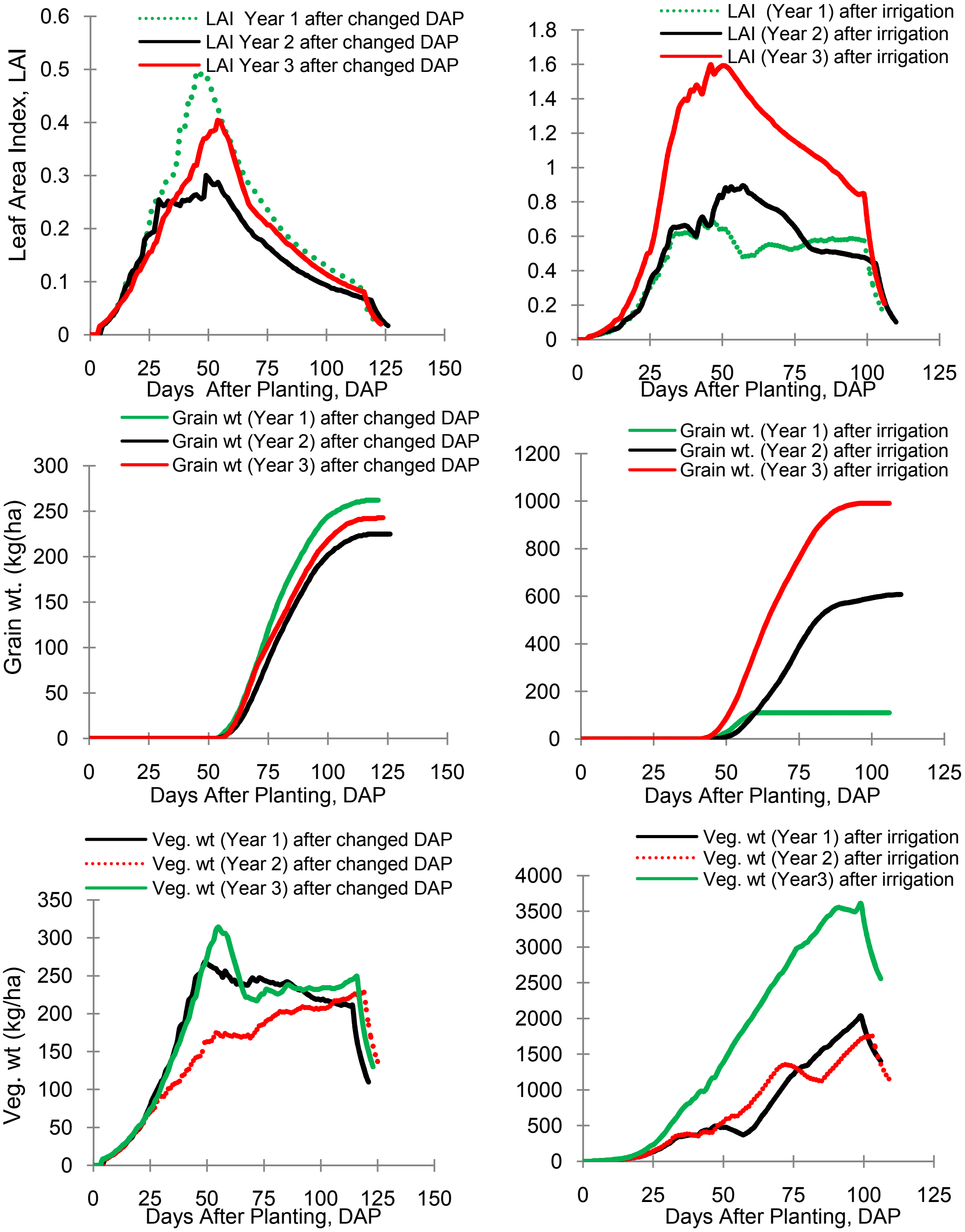


Fig. 8. Simulated and observed soil water content (cm²/cm³) in the first 0-10 cm of the soil profile with the available soil water set at 0.18cm³/cm³ during simulation



(A) (B)

Fig. 9. Changes in the LAI, vegetative and grain weights after sensitivity analysis (A) under rain-fed and (B) irrigation conditions. Dept. of Agric. Sciences, University of Juba (2012)

Crop yield versus water relationships provide information that can be used in making decisions on the appropriateness of crops in production systems, through a consideration of the expected water supply conditions. According to [25] the decision when to irrigate is controlled by two parameters: the lower and upper fractions f_{lower} and f_{upper} respectively and the condition to start irrigation is $zS \leq f_{lower}\,\phi D$ and to end irrigation is $zS \geq f_{upper}\,\phi D$, where z is the soil moisture expressed as a fraction of the total root zone storage D and the plant available water content (PAWC) coefficient ϕ (*the ratio of the depth of water to the depth of wetted soil*). Irrigation water application is then calculated as: I = [min (I_{max}, f_{upper}, ϕD-zS] where, I_{max} is the maximum available irrigation.

Results in Fig. 10 of the model showed that simulated irrigation schedules in Year 1 had no significant effect on cowpea yield which was constant at 111 kg/ha. Year 2 showed significant increase in yield relative to Year 1 at between 608-714 kg/ha especially between 5 and 8 irrigation schedules. Irrigation schedules 1- 4 and 6-11 showed no increase on yield at 608 kg/ha. The highest yield in Year 3 was at 1033 kg/ha during the first irrigation schedule and decreased to 871 kg/ha between 2-4 irrigation schedules. This was a 16% yield reduction. Yield marginally decreased to 869 kg/ha between 5-7 irrigation schedules and slightly increased to 943 kg/ha and subsequently 991 kg/ha after eleventh irrigation schedule.

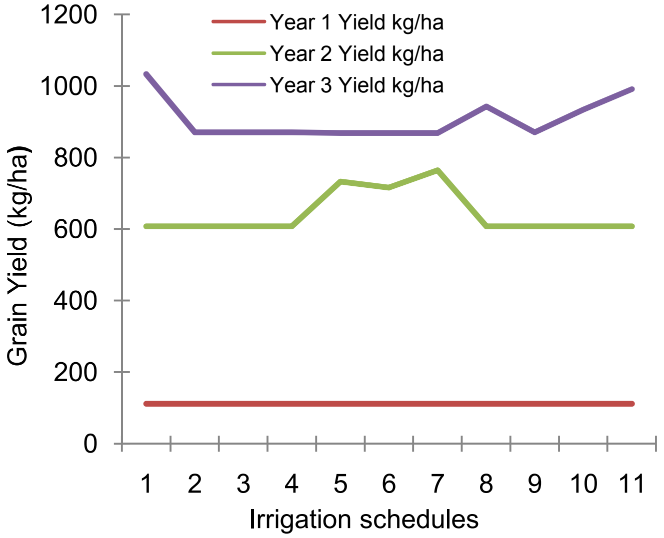


Fig. 10. Effect of irrigation schedules on grain weight (kg/ha) for three simulations years

Fig. 11 shows the relationship between the measured soil water content and the water stress in photosynthesis days (WSPD) for the three simulation years after some selected irrigation schedules. All three simulation years during the first phenology of germination and vegetative growth (1 to 20 DAP) showed low WSPD value of 0.2 with soil water content at around 0.20 cm^3/cm^3. Year 1 showed that WSPD increased to peak values between 0.4 and 0.5pre- and during anthesis (30 to 40 DAP) and first pod day respectively with decrease in soil water between 0.12 and 0.15 cm^3/cm^3. Second highest peak showed 50-60 DAP and remained insignificant until harvest maturity with a drop in the soil water content below 0.1 cm^3/cm^3 90 DAP. Year 2 showed several maximum WSPD peaks between 04-0.6, 30-40 DAP and 50-60 DAP with varying soil water contents between 0.1 and 0.3 cm^3/cm^3. A high WSPD maximum peak 0.4-0.7 occurred 70-90 DAP towards physiological maturity. Year 3 showed several WSPD maximum peaks between 0.4-0.75, 65-100 DAP after seed filling and towards physiological maturity.

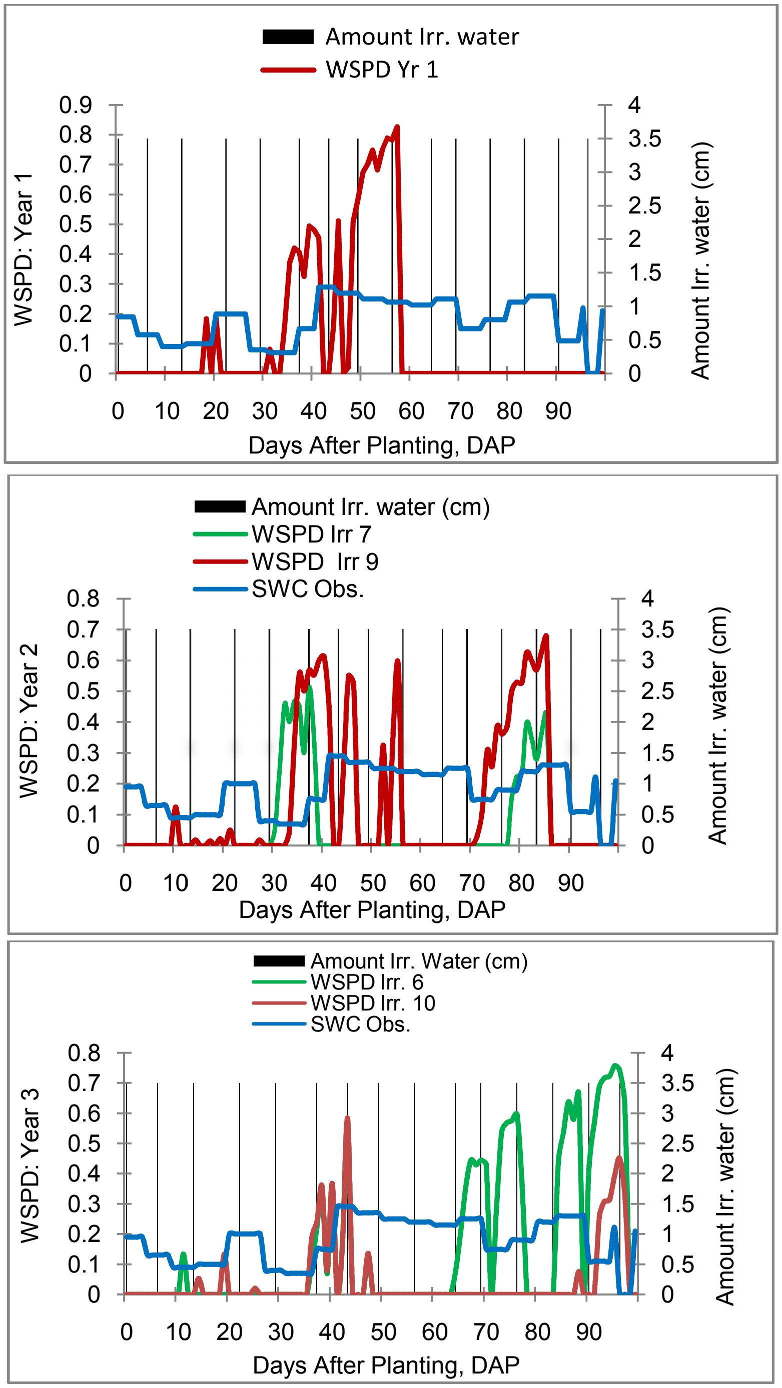


Fig. 11. Relationship between the amounts of irrigation water (cm) and Water Stress in Photosynthesis Days (WSPD)

4. DISCUSSION

4.1 Phenology Prediction

The linear regression coefficients between the observed and estimated values of the LAI, vegetative and grain weights as well as the respective RMSE and *d* values indicated accurate cowpea phenology prediction for the three years under both default treatments and after sensitivity test. However, it is significant to highlight some inconsistencies especially the estimated low LAI at 0.24 in Year 2, 30-60 DAP (Fig. 4) and grain weight (Fig. 6) that was invariable to Year 3 under default treatment (*rain-fed conditions and initial planting dates*). The comparatively low LAI in Year 2 was under-predicted and suggested the inability of the model to accurately predict leaf senescence. Such low LAI values on average 15% lower than the observed values suggested low leaf area coverage per unit plant and therefore implied reduced light interception and photosynthesis. Water stresses especially during the dry months of November to March are critical as this may have reduced vegetative growth and accelerated leaf senescence and leaf abscission thereby reducing the net assimilation. Similar findings were also reported by [26] and amount of dry matter accumulated in the seeds [27,28]. The UCR 368 cowpea cultivar is adapted to water stresses. Here, the high WSPD in Year 2 (Fig. 11) was corroborated by a correspondingly reduced LAI (Fig. 4) conversely, the high WSPD in Years 2 and 3 showed correspondingly high LAI. This however, was an exception rather than the rule and did not have any significance on the long term WSPD-LAI predictions. Our study here underscores the general positive correlation between LAI and WSPD under default treatments as well as after sensitivity analysis and showed thatthe ultimate assimilate accumulation in cowpea expressed as grain weight is a function of the LAI.

The correspondingly high values of the measured soil water content are attributable to timing of soil sample collection that took place immediately after an irrigation schedule. Admittedly, the time step for soil sample collection was too large and should have been done on a 3-day basis to give a more accurate prediction of the soil water, incorporating all measurements between two successive irrigation schedules. For the three simulation years, the model gave better estimates for soil water content only in the first 45 DAP with poor estimates 75 DAP until the time to physiological maturity. The high irrigation levels (*35 mm or (3.5 cm) flood irrigation*) after each schedule inevitably led to increased soil water content within the 0-10 cm, decreasing with each progressing day. However, the relatively constant soil water content at 0.2-0.3 cm^3/cm^3 50-70 DAP in the 0-10 cm soil layer was not captured by the model during simulation runs and therefore the possible role of evapotranspiration despite the high dry-season temperatures of October to March of about 34°C on average, was neglected. The model therefore, did not account for the soil water fluctuations and dynamism attributable to the intense water uptake and evapotranspiration should inevitably have led to reduced water content within the 0-10 cm soil layer.

Over-prediction of soil water content between 0.2-0.3 cm^3/cm^3 50-75 DAP in all three simulation years can be traced back to input soil parameter during model runs. DSSAT sequential simulation runs assumed that, the input soil parameter was constant for the three years and did not consider any soil management practices that may have led to creation of preferential flow pathways and hence increased water infiltration to lower soil layers. The textural composition of the soil sandy loam *Eutric Leptosol* also had a significant effect on water infiltration into the lower layers thus reducing the water content in the first 0-10 cm soil layer.

For the grain weight, the model simulation was not influenced by the soil water deficit and dynamism especially during this time of the year. The consistency in grain weight could be associated with the drought resistant nature of the UCR 368 and its ability to assimilate nutrients under water stress conditions. Given the stress-tolerant nature of UCR 368 cultivar, such moderate WSPD values appeared not to have affected pre-anthesis and pod setting with soil water within the manageable allowable depletion (MAD), slightly below the field capacity. The significance of soil water stress during pre-anthesis and grain filling by wheat was also reported by [29,30] and on pearl millet by [31] on bean by [32] on seed weight of sunflower by [33] on reduction in number of pods per cowpea plant [34]. Years 1 and 2 showed relatively high WSPD values of between 0.6 to 0.8 with soil water at 0.20 cm^3/cm^3, 50 to 60 DAP from beginning seed filling and development. This phenomenon is attributable to the inability of the cowpea cultivar to cope with excess soil water especially during post-anthesis, pod setting and towards harvest maturity. Years 2 and 3 showed high WSPD values of 0.7 (60 to 90 DAP) during the final stages of physiological maturity as soil water decreased to as low as 0.09 cm^3/cm^3. It appears, high WSPD values did not affect the final grain weight as much assimilate was already incorporated. Our results showed that WSPD can be perceived as the state of soil with either water deficit or water excess that could negatively influence cowpea phenology. For an environmentally-friendly and cost-effective use of water resources, the numbers and timing of irrigation schedules for maximum cowpea yield had to be effectively planned.

Although our study focused much more on the impacts of water stress on cowpea phenology, the causative and synergistic implications of heat stress during the experimental period was not overseen. Although no adverse effects of both heat and water deficit was recorded during the test trials, a combination of both high temperatures between 34 to 37°C and water deficit especially during non-irrigation intervals can otherwise cause considerable pre-harvest damages including leaf sunburns, enhanced leaf senescence and abscission as those reported in sugar-cane by [35], increased water loss coupled with reduced growth and biomass production in biofuels by [36],in sorghum by [37], reduced stomatal conductance by [38], reduced fruit setting in *Phaseolus vulgaris* by [39].

5. CONCLUSION

In the present work, we used the CROPGRO model distributed with DSSAT 4.5 to simulate the phenology of UCR 368 cowpea variety for three consecutive years under rain-fed conditions. Our research interest focused on the simulation of three genetic coefficients that are critical for cowpea: grain weight, vegetative growth and leaf area index. Using local variety JUBA1 grown locally especially in Equatoria, South Sudan, we calibrated and tested our model modifications in terms of varied planting dates and increased water amounts during each irrigation schedule. Default values prior to sensitivity analysis showed that the leaf area index was under-predicted in Year 2 whereas it gave good estimates for Years 1 and 3. The grain weight was adequately predicted in both Years 2 and 3 except with slight over-prediction in Year 1. Vegetative growth contrastingly was adequately predicted in all three years. Upon readjustment of default variables on water supply (*irrigation*), the cowpea model gave very high grain weight in Years 2 and 3 than under Year 1 and underscored the need for customized water supply. However, we only tested UCR 368 cowpea phenology under both adequate and limited water supply without considering the implications of heat stress. Combined effects of heat and water stresses whether in terms of deficit or excess supply may have an impact on overall cowpea phenology (Fig. 3) and thus affect the ultimate leaf area index, vegetative growth and grain weight.

Our results indicated the need to further examine the simulation of cowpea especially before and during the onset of early rainy season as well as during the dry season, especially when water is a limiting factor. DSSAT v.4.5 has the ability to simulating and predicting bountiful cowpea yield in the short term (3 years) as influenced by planting dates, rainfall and irrigation schedules in *Eutric Leptosol.* Nevertheless, further studies are needed to confirm that the model can equally be usefully when applied to a wide range of crops (e.g. maize, cassava, beans), as well as to other soil types within the agro-ecological zones of South Sudan.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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