Simulations Of The Potential Yields Of Jenguma Soybean Variety In The Upper West Region Using Aquacrop Model

Ibrahim Denka Kariyama

Abstract: The potential yields of Jenguma soybean (110 calendars days) a medium maturity variety recommended for northern Ghana were simulated using the AquaCrop model with daily climatic data taken from the Wa Meteorological Station. The climate was delineated to be the only constraint limiting the potential yields with the soil serving only as a reservoir to store the rainfall while other factors affecting the potential yields were assumed non-limiting. The simulations were done in growing degree days (GDD) which is about 2275 °C-days rather than in calendars days. The average potential yields of Jenguma soybean planted in the recommended planting period in mid-June to July on uniformly deep clay loamy were 4.6 tons/ha, 4.4 tons/ha and 4.6 tons/ha for the 2009, 2010 and 2011 farming year respectively. For any of the generated planting dates the yields were more than the yearly averages recorded in the region. The climate of the region is therefore suitable for the production of Jenguma soybean variety and hence with adequate investment and best agronomic practices to provide constraint free environment, the yields will be improved from the current average of about 1.2 tons/ha hence increasing the productivity and improving the livelihoods of soybean farmers in the region.

Index Terms: AquaCrop model, Jenguma Soybean, potential yield, simulations.

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1 INTRODUCTION

Crop yields are direct response to the prevailing climatic condition, the soil condition and the cultivation practices to ensure the crop have the favourable unlimited environment for growth. Hence, to simulate the yield of crops, local climatic data are required to determine crop response to the climate of the area. Climate influences the crop water requirement, the crop development and the growth stages and the yield. The soil type and its characteristics determines its' ability to provide favourable non-limiting soil environment for optimum crop growth such as soil water holding capacity, soil fertility and productivity. Cultural practices such as mulching, manure and fertilizer application, weeds control, pests and diseases control, irrigation also ensures that the crop have the favourable non-limiting environment for optimum growth and optimum yield. Hence for maximum crop yield, the crop must be a high yielding variety, grown in a favourable climatic condition, in a soil with non-limiting water availability and soil nutrient and diseased free with non-limiting economic environment to restrict proper cultural practices. The climate is one most important resource in crop production. The selection of the crop types and varieties for a particular locality are strictly based on first the suitability of the climate among other factors such as the soil requirement; the know-how, socio-economic constraints and just to mention a few. In the Upper West Region, soybean is relatively a new cash crop grown by smallholder farmers under rainfed agriculture mainly. One commonly grown soybean variety in the region is the "Tax 1448-2E" variety which has been given the name "Jenguma" in the Lobi dialect which literally means "stay and wait for me" [7]. This variety is a medium maturity variety (110 calendar days) recommended for Northern Savanna ecological zone of Ghana because of its adaptability to the climate. The variety have very good and attractive grain colour, have high oil content, is low in shattering and also best in striga hermonthica control in Ghana [4]. There are governmental and non-governmental interventions in the region to support out-grower farmers to increase the productivity. While there are evidences of increases in the hectares, the average yield remains relatively low (Table 1).

TABLE 1
SOYBEAN PRODUCTIVITY IN THE UPPER WEST REGION

Year	Area(Ha)	Production (Mt)	Mt/Ha
2009	14,370	19,870	1.20
2010	14970	21,219	1.42
2011	15630	17736	1.13

(Source: SRID of MoFA)

This research therefore uses the AquaCrop model to simulate the potential yields of the commonly grown Jenguma soybean variety under rainfed agriculture considering the climate as the only limiting factor that affects the relative yield loss with the soil serving only as reservoir to store the rainfall while other factors mentioned above are assumed non-limiting. The AquaCrop model which is a water-driven model integrates all the above mentioned factors except the model assumed a disease free crop growing environment. With the AquaCrop model, the climate can be delineated as the only limiting factor affecting the potential yield. The simulation runs of AquaCrop are executed with daily time steps, using either calendar days or growing degree days (GDD). The duration of a particular variety depends on the day length and the growing degree days (GDD) which is influence by the sunshine hours and air temperature respectively, but the GDD alone can be used to determine the duration of the

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growth stages and the crop development. Crop growth duration have effect on the growth and development parameters and the crop consumptive water use, the biomass accumulation and hence the yield. The simulations were therefore done using the GDD rather than the calendar days. The GDD influences the duration of growth stages, the total duration of the crop that is from planting to maturity. The GDD also influences flowering and pollination. The general objective of this paper is to simulate the potential yields of Jenguma soybean variety grown under rainfed using local climatic data with generated planting dates. The results will provide information of the potential yields of soybean in the region.

2 RESEARCH METHODOLOGY

2.1 Climate Data

Daily climatic data was taken from the Wa Meteorological Station located at the Wa township on latitude 10.04°N, longitude 2.30°W and at altitude 322.7 m above sea level. The data comprises the daily rainfall, daily air temperature (maximum and minimum), the daily air relative humidity (maximum and minimum), the daily wind speed and the daily sunshine hours for the period of 2009-2011.

2.2 AquaCrop Model

Soybean yields were simulated using the AquaCrop Model Version 3.1, the Food and Agriculture Organization (FAO) crop model to simulate yield response to water stress [10]. The AquaCrop Model environment consist of sub-model components that includes: the soil, with its water balance; the crop, with its development, growth and yield; the atmosphere, with its thermal regime, rainfall, evaporative demand and carbon dioxide concentration (CO_2); and the management, with its major agronomic practice such as irrigation and fertilization. For potential yields simulations it is assumed that only the atmosphere (climate) is the limiting factor for crops growth, development and yield formation all other factors are non-limiting. Under the climate, five weather input parameters required to run the simulation were inputted. These are daily maximum and minimum air temperatures, daily reference crop evapotranspiration (ETo), daily rainfall and the mean carbon dioxide concentration. The mean carbon concentration data was taken from the Mauna Loa Observatory record in Hawaii which is included in the model structure, while others input variables were taken from the Wa Meteorological Station. The yields simulations were run for three cropping years (2009-2011). The statistical summary of the climate input variables are presented in Table 2.

TABLE 2
STATISTICAL CHARACTERISTICS OF CLIMATE VARIABLES USED FOR MODEL SIMULATION (2009-2011)

Variables	Tmax	Tmin	ETo mm/day	Rainfall mm/day
2009				
Max	43.50	28.00	7.50	65.10
Min	25.00	16.30	2.00	0.00
Mean	33.87	22.65	4.65	3.09
Std	3.34	5.89	1.11	8.67
Cov	11.12	2.43	1.23	75.21
2010				
Max	42.00	30.50	9.60	88.20
Min	22.10	16.60	1.90	0.00
Mean	34.39	23.44	4.74	2.83
Std	3.49	2.48	1.20	9.80
Cov	12.19	6.16	1.45	96.07
2011				
Max	41.00	28.10	7.60	72.80
Min	25.00	17.00	2.00	0.00
Mean	34.12	23.13	4.79	2.64
Std	3.17	2.30	1.02	7.61
Cov	10.08	5.28	1.04	57.98

The daily reference crop evapotranspiration (ETo) was determined using the ETo Calculator Version 3.1 software [3]. The ETo Calculator (EToCal) was developed by the FAO in 2009 and employ's the FAO Penman-Monteith (FAO-PM) method for calculating the ETo. In determining the ETo for the model input, using the FAO-PM method, measurable agro-meteorological weather input variables are required: the daily maximum and minimum air temperature, daily maximum and minimum air relative humidity, daily air wind speed and the daily sunshine hour. The station data such as the altitude, latitude and longitude and other location characteristics that are also required were inputted. The FAO-PM equation for the hypothetical reference crop evapotranspiration is expressed as below in (1), [1]. For detailed calculation steps, consult FAO Irrigation and Drainage Paper N^{o} 56 [1].

$$ETo_{FAO-PM} = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad \textbf{(1)}$$

where ETo_{FAO-PM} ET_o estimated by the FAO-PM [mm/day]; R_n net radiation at the crop surface [MJ m^2/day]; G soil heat flux density [MJ m^2/day]; T mean daily air temperature [^{o}C]; u_2 daily wind speed at 2 m height [m/s]; e_s saturation vapour pressure [kPa]; e_a actual vapour pressure [kPa]; $e_s - e_a$ vapour pressure deficit [kPa]; Δ slope of the saturation vapour pressure temperature curve [kPa/^{o}C]; and γ psychrometric constant [kPa/^{o}C].

2.3 Conceptual Framework of AquaCrop Model

Crop responses to water deficits are simulated using empirical production functions as the most practical option to assess crop yield response to water. The empirical approach developed by [2] presents an important source to determine the yield response to water of herbaceous crops (field, vegetable) and tree crops, through the expression (2) below.

$$\left(1 - Y_a / Y_m\right) = k_y \left(1 - ET_a / ET_m\right) \qquad (2)$$

Where Y_m and Y_a are the maximum (potential) and actual yield, $\left(1 - Y_a / Y_m\right)$ the relative yield decline, ET_m (ETo) and ET_a are the maximum and actual evapotranspiration (dependent on soil moisture availability), $\left(1 - ET_a / ET_m\right)$ the relative water stress and k_y is the proportionality factor between relative yield loss $\left(1 - Y_a / Y_m\right)$ and relative reduction in evapotranspiration. The AquaCrop model evolves from (2) [7, 10]. AquaCrop model divides the ETa into soil evaporation (Es) and crop transpiration (Tr) as below.

$$ET_a = Es + Tr \qquad (3)$$

The division of evapotranspiration (ET) into Es and Tr avoids the confounding effect of the non-productive consumptive use of water (Es). This is important for growing periods when canopy cover is incomplete. The actual yield (Ya) is express as the product of biomass (B) and harvest index (HI).

$$Y_a = B \times HI \qquad (4)$$

The expression of yield (Ya) in terms of B and HI allows a distinction of the basic functional relations between environmental conditions and B, and environmental conditions and HI. The biomass (B) is obtained from the product of water productivity (WP) and cumulated crop transpiration which is the core of the AquaCrop growth engine (5). The crop water productivity (WP), expresses the aboveground dry matter (g or kg) produced per unit land area (m^2 or ha) per unit of water transpired (mm).

$$B = WP \times \sum Tr \qquad (5)$$

The Tr is normalized with reference evapotranspiration (ETo). The normalization of Tr makes the B-Tr relationship general, applicable to different climatic regimes. The AquaCrop model (Fig. 1) focuses on the fundamental relation between B and Tr (5) rather than yield (Y) and ET (2), relying on the conservative behaviour of WP. The (2) and the AquaCrop (5) model is water-driven, meaning that the crop growth and production are driven by the amount of water consumptively used (Tr).

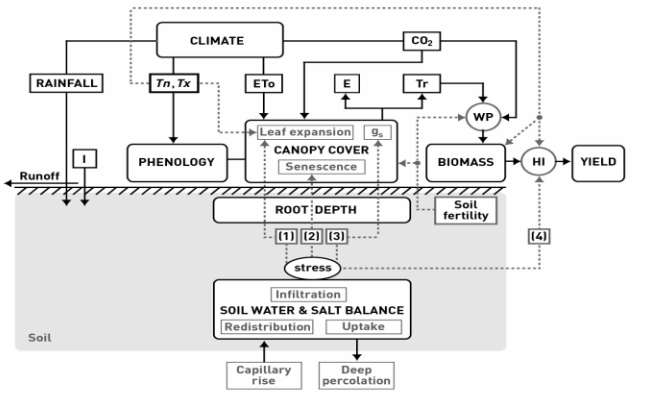

Fig. 1. AquaCrop flowchart indicating the main components of the soil-plant-atmosphere continuum

Simulation runs of AquaCrop are executed with daily time steps, using either calendar days or growing degree days (GDD). In this study the GDD was employed. The simulation of water use and production in daily time steps permits a more realistic accounting of the dynamic nature of water stress effects and crop responses.

2.4 Generation of Planting Dates for yields simulations

The simulations were done for three cropping years (2009-2011). The generation of the planting dates were done using the AquaCrop model. Once the climate data is provided, the software is able to generate the planting date using given selected generation criteria. Since the amount of soil moisture stored during rainfall is lost to the atmosphere to meet the environmental (climatic) demand through the ETo, the planting dates were generated using two criterion to generate enough planting dates for the simulations. The first criteria selected was that, planting should begin when rainfall in decade (10-day period) exceeds 0.5ETo in decade. This was to ensure that within that period there are not droughts and that there are enough soil moisture for good germination. The second criteria selected was that planting starts when the rainfall in five successive days is at least 25 mm, since the average daily ETo during the rainy season is about 4.7 mm/day, and the emergence for soybean is about 7 days with the required soil moisture temperature, the second criteria for the planting was found to be justified.

2.5 Model Calibration for Jenguma Soybean Variety

The dynamic growth and development of the variety was run under growing degree days (GDD) (°C day) rather than on calendar month (days). The GDD allows for the effect of the temperature to effluence the growth and development of the crop dynamically. Different crop developmental stages are completed once a given number of GDD are reached. The GDD is determined by the expression below:

$$GDD = Tavg - Tbase \qquad (6)$$

Where, $Tavg$ is the average temperature in °C and $Tbase$ is the based temperature in °C. The temperature file which contains the minimum and maximum temperatures is required to calculate the GDD using the method 2 for calculating the average temperature and hence the GDD as presented by [5]. The base temperature is the temperature below which crop development does not progress. An upper threshold temperature (*Tupper*) which is the temperature above which crop development no longer increases with an increase in air temperature is also provided which forms the bases for determining the GDD. The $Tbase$ of 5 °C and *Tupper* of 30 °C were used. Cultivar specific crop parameters and less-conservative crop parameters were adjusted such as the planting distance and growth periods. The planting spacing of 75 cm by 50 cm, with a plant population of 266,667 plant/ha was used and the GDD from sowing to maturity was about 2275 °C. Conservative crop parameters where maintained and used for the models simulations.

3. RESULTS AND DISCUSSIONS

3.1 Generated Planting Dates

The results of the planting dates generated for the three farming seasons, indicates that planting starts in early April and ends in either late July or early August in the region (Table 3).

TABLE 3
GENERATION OF PLANTING DATES (2009-2011)

Occurrences	2009		2010		2011	
1st	1	April	1	April	1	April
2nd	1	May	2	April	2	April
3rd	2	May	3	April	3	April
4th	3	May	4	April	4	April
5th	4	May	5	April	1	May
6th	21	May	11	April	2	May
7th	22	May	12	April	3	May
8th	23	May	13	April	4	May
9th	27	May	14	April	5	May
10th	1	June	15	April	6	May
11th	2	June	21	April	11	May
12th	3	June	22	April	20	May
13th	5	June	26	April	26	May
14th	7	June	23	May	4	June
15th	14	June	25	May	13	June
16th	19	June	5	July	20	June
17th	26	June	17	July	24	June
18th	30	June	23	July	13	July
19th	14	July	7	August	17	July
20st	17	July	10	August	20	July

Even though the planting period spans for about 4 to 5 months, the effective planting days did not span for the total numbers of days in that period. This is as a result of the fact that intermittent drought period occurs in the rainy season.

A total of twenty (20) planting occurrences were generated for each season. For each criteria selected the software is able to generate only the 11th occurrence of planting from the onset of the rains or selective period, some dates were repeated and used only once. The result shows that, farmers that planted in April 2009 faced drought period (Table 3 and Fig. 2). Also in April 2011 water deficit occurred even though the rainfall is higher than 0.5ETo as in Fig. 2, the simulation is on daily and hence Fig. 2 is just a guide. Also not all the rainfall is available in the root zone for plant use, some runoff and depercolate and also, the soil storage capacity is limited; hence the software takes care of the soil-water balance and on daily time steps. The effects of planting in such periods are poor germination hence low plant population per hectare, permanent wilting of young plants, stunted growth and delay in fertilizer application in some cases. In 2010 the rainfall in April was exceptional but in June there was intermittent drought by the generation criteria and the soil-water balance. Generating planting dates and using these planting dates to simulate yield provide enough information for decision support of when to plant and which variety to plant since the rainfall in the region ends in October (Fig. 2.).

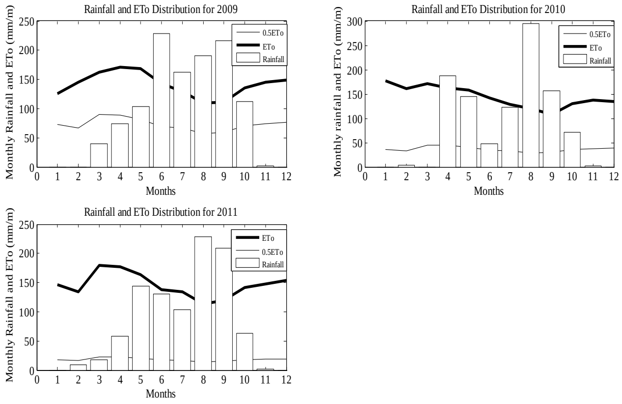

Fig. 2. Monthly Rainfall and ETo distribution for 2009-2011

3.2 Simulated potential yield of Jenguma variety

The results of the simulations are presented in the Fig. 3, 4 and 5 below. The yields obtained are the total effects of the climate on the growth and development of the crop. Soybean is highly sensitive to soil moisture stress. The reference harvest index was set at 40% with allowance for adjustment, of the potential accumulated biomass. Potential accumulated biomass of about 11.626 ton/ha is achievable under rainfed agriculture in the region. The results as presented in Fig. 3 revealed that only few planting dates achieve sufficient green canopy cover and hence maximum reference harvest index. In Fig 4 all the planting dates could not reach maximum reference harvest index due to insufficient green canopy cover. Also in Fig. 5 only few planting dates achieve sufficient green canopy cover and hence maximum reference harvest index. The rest of the planting dates could not reach maximum reference harvest index due to insufficient green canopy cover. Water stresses, short duration of grown stages and poor development of leaves, roots and plant height are causes of insufficient green canopy cover which is influence by climate only in this research. Seasonal climate variability and uncertainty therefore exist in the region hence planting of when to plant and the variety to plant is a critical decision to be made. Planting early results in short duration in the growth stages due to high temperatures and this affects the crop development such as leaf expansion, root development and the height notwithstanding the fact that water deficit would exacerbate the situation. Heat stresses as result of high temperatures above the thresholds for leaf expansions, flowering and pollination was not experienced. Also waterlogging stress as a result of high rainfall was not experienced for the simulations periods.

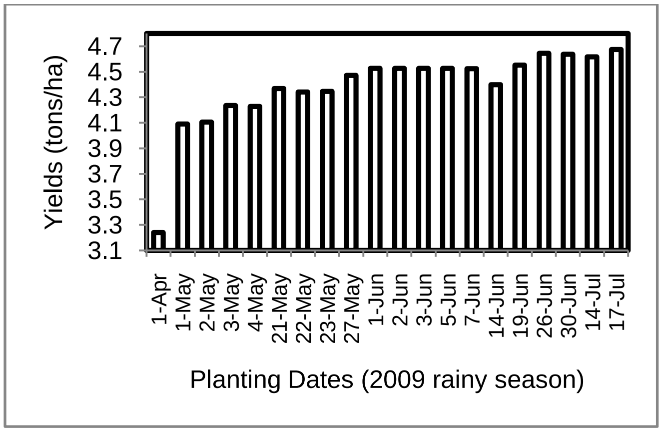

Fig. 3. Simulated yield of Jenguma Soybean (2009)

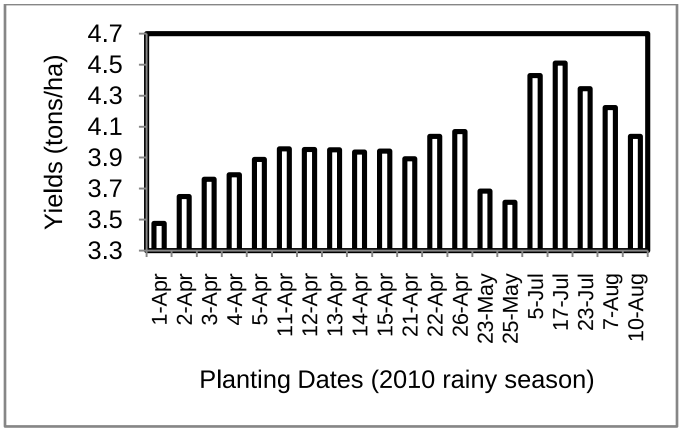

Fig. 4. Simulated yield of Jenguma Soybean (2010)

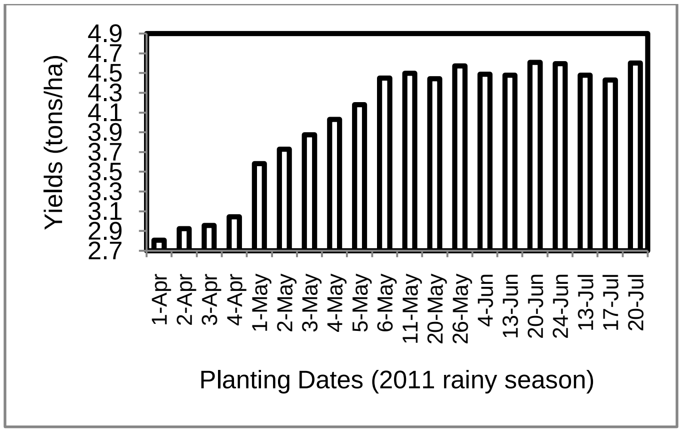

Fig. 5. Simulated yield of Jenguma Soybean (2011)

The simulations revealed that, even though seasonal climate variability exist, the thresholds for Jenguma soybean variety is within suitable levels. Therefore with best agronomic practices and investments to provide constraint free environment and planting at the right period, the variety have the potential yield of about 4.6 ton/ha achievable under rainfed agriculture in the region.

4. CONCLUSIONS AND RECOMMENDATIONS

4.1 Conclusions

The climate of Upper West Region is suitable for medium maturity Jenguma soybean production. Seasonal climate variability exists in the region which is typical of arid climatic zone but the thresholds are not above the required climate for soybean production. The results of the simulation of the potential yield of Jenguma soybean for the three seasons, shows that when to plant for a specific cultivar is an important decision to be made in other to obtain the full potential yield. Generating planting dates and modeling yield using local climate data is important in building decision support tool of when to plant and which variety to plant. Planting at the right planting calendar ensures that the agro-climate environment is favourable for optimum growth and development and hence optimum yield. Planting should avoid water stress, heat and cold stresses which are climate influenced assuming other factors are favourable. In general, water stresses during the mid-season (critical period) causes severe yield loss compared to the other growth stages. The average potential yields of Jenguma soybean planted in the recommended planting period in mid-June to July on uniformly deep clay loamy were 4.6 tons/ha, 4.4 tons/ha and 4.6 tons/ha for the 2009, 2010 and 2011 farming year respectively. For any of the generated planting dates the yields were more than the averages recorded in the region. The climate of the region is therefore suitable for the production of Jenguma soybean variety and hence with adequate investment and best agronomic practices to provide constraint free environment, the yields will be improved from the current average of about 1.2 tons/ha hence increasing the productivity and improving the livelihoods of soybean farmers in the region.

4.2 Recommendations

Simulation of potential yield using local climate data is important in planning when to plant for full potential yield. When possible, robust but simple predictive tools should be build for predicting the uncertainties of climate change variability and change for yearly updating and planning of planting calendar. Planting should be done at the recommended planting periods if maximum yield is required. Results of the simulated yield should act as a guide in planning planting calendar in the region. Efforts should be made to provide favourable or non-limiting environment for optimum yield. Investors should be encouraged to go into commercial soybean production in the region using the Jenguma soybean variety.

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