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Modelling Yield Gap Trends of Maize (Zea mays L.) Production under Soil Fertility Stress for Uasin Gishu Plateau Climate

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Abstract: Results of maize yield under fertility stressed conditions were predicted using AquaCrop model by comparing a reference non- fertility stressed field with a stressed condition for levels of soil stress from 5% to 95% corresponding to biomass production levels of 95% to 5% respectively. Fertility stress level in the field reduces the amount of biomass produced and maximum canopy cover attained. Soil fertility module in AquaCrop model derives and calibrates specific level of stress crop parameters as a proportion of the reference plot data. Maize crop yield findings indicate a general decrease with increase in the soil fertility stress under the three weather conditions of dry, normal and wet categories. Similarly canopy growth coefficient (CGC) parameters decreased from 7.92% to 4.0% and an increase in the length of growth to maximum canopy cover from 109 to 134 (DAS). Maximum canopy cover (CC_x) achieved was lower than that of the reference plot value of 81% and vary from 75% to 11% (model minimum value) applied under conditions of dry, normal and wet climate of Uasin Gishu plateau. Prediction of maize dry grain yield under dry weather condition recorded values below controlled demonstration plot ($F_{100}W_{100}$). Results of normal and wet weather conditions recorded positive yield gap values for soil fertility stress below 15% and 25% respectively, and all other levels of predictions are below$F_{100}W_{100}$ yield level. Maize dry grain yields reduction vary gently for soil fertility stress range from 0% to 50% levels but greater variation occurs for values above 50% in all the weather conditions. Comparison of grain yield results simulated under soil fertility stress and soil nutrient application levels used in the demonstration plots are given in Table 4.33 for similar range of 20% to 80% maize nutrition levels.
Keywords: Climate, Canopy cover, soil fertility, water productivity, yield gap, modeling, AquaCrop

I. INTRODUCTION

Soils vary in type and their properties from one location to another and possess different storage capacities for maize production nutrients and moisture. Maize is a staple crop in Kenya and its production is not enough to meet the demand hence deficit amount is covered through import. Knowledge of nutritional level in the soil is important for optimal yield management in maize production. Sadras *et al.* (2015) documented that inputs contribute to variable crop productivity. Soil fertility stress is a form of soil degradation that cause stagnation or decreasing crop yields (FAO, 2006) and variations in yield gaps. The problem is experienced in the field as a result of multiple activities in the soil that include; plant nutrient depletion due to soil erosion, inactivation of nutrients, reduced retention and loss of organic matter, soil acidity and toxicity. The level of inputs in plant nutrients held in the soil reserve describes fertility level in a given ecological zone.

Different soils exhibit different storage capacity and result in varied productivity categories. Higher yields and good quality maize is achieved through application of the right amounts of nutrients demand and at appropriate stage of growth. Soil scan guide on the right maize production nutrient assessment that lead to efficient resource use and help in the decision on appropriate level of production. Variable soil fertility stress result in different productivity of maize that inform the farmer on the rate of fertilizer application devoid of the general recommendation of pre-formulated rations. Yield gap productions of maize at varying levels of soil fertility provide an impetus on accurate analysis of opportunities of investment that are profitable and consider untapped capacities under spatial variability and climatic conditions.

AquaCrop model was calibrated for non-stressed condition to simulate biomass production under fertility stress between 5% (near optimal production) and 95% (very poor production). Van Gaelen *et al.* (2015) reported similar model calibration and effect of soil nutrient reservoir levels on yield.

II. MATERIALS AND METHOD

The research was located at Saroiyot farm about 2km South-East of Kapsoya Meteorological Station and about 5km from Eldoret Town along the Eldoret-Plateau Road (Figure 1). Grid referencing of the experimental plots lie at an average elevation of 2,117m above mean sea level at a latitude of 0°30'52"North of the equator, and a longitude of 35°18'2"East.

The study involves calibration of AquaCrop model algorithms specified as input parameters specific to prevailing local conditions using reference field data from non-stressed controlled plot with application of 100% N:P:K fertilizer (F) and moisture (W) levels recommended for optimal growth ($F_{100}W_{100}$). The model was validated using data from demonstration plots of moisture application levels at 90%. 80%, 65% and 50% and nutrient fertilizer at F_{100} level. The parameters are stored and tuned during calibration in the following model files: climate, crop, soil, field and irrigation management. Running the model simulates the effect on the output generated biomass, crop yield, canopy cover, soil water content and its performance indicator of water productivity (FAO, 2016).

Climate data collected using a mini-weather station at Saroiyot farm experimental site was used during calibration and validation of the model. Crop parameters comprise of real time field measurements during the research period from date of sowing the maize crop (DOS) up to the period of grain harvesting and were fine tuned in the model to their most influencing parameters respectively.

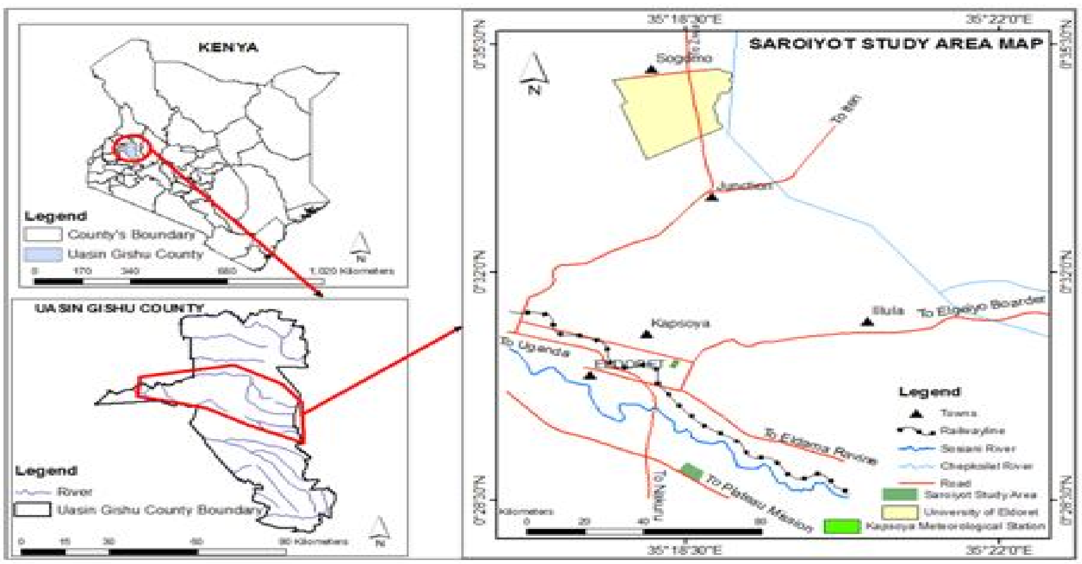

Figure 1: Location map of the study area

Canopy cover development was monitored by the rate of expansion controlled by canopy growth coefficient (CGC) and its rate of dying off at the end of the growing season controlled by the canopy decline coefficient (CDC). The two coefficients were fine tuned until the simulated canopy cover (CC) was closely comparable with the field observed values. crop coefficient for transpiration at full canopy cover, soil water depletion thresholds for inhibition of leaf growth and stomata conductance, and acceleration of canopy senescence (Heng et al 2009, Hsiao et al 2009).Water productivity and transpiration crop coefficients were used to calibrate biomass and crop yield by comparing the simulated water use efficiency (WUE) with the observed data from the field experiments.

Soil fertility module in AquaCrop model derives and calibrates specific level of stress crop parameters by comparing a reference non- fertility stressed field with a stressed condition based on the proportions of their measurable parameters. Both fields are well watered to avoid the effect of soil water stress on crop development and production and the crop response only to limited soil fertility (FAO, 2017). Maize crop yield prediction is achieved by tuning the model for maximum canopy cover (CCx), days after sowing (DAS), water productivity (WP*), coefficient of canopy growth (CGC) and coefficient of canopy decline (CDC) due to soil fertility stress on the reference plot. The model predicts the amount of biomass produced as a difference between the potential value at 100% and the level of soil fertility stress and the amount of predicted maize grain yields follow the model regression.

Forecast of Uasin Gishu plateau climate trend and analysis for the maize cropping season (March – October) rainfall was studied using 34 years daily historical climate data (1981-2014) from Kapsoya meteorological station. The data subjected to frequency using RAINBOW software (Raes *et al.*, 1996) is found normally distributed with mean statistic of 898.2 and standard deviation of 189.8. Probability of exceedance limits of 20% and 80% in the frequency analysis is considered to categorize the climate presented in dry, normal and wet weather conditions and predict Uasin Gishu plateau climate. AquaCrop model is used to predict maize yield for each weather condition.

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III.RESULTS AND DISCUSSION

A. Calibration Of Crop Parameters Due To Soil Fertility Stress

The study results on calibration of crop parameters considered the effect of soil fertility stress on the reference plot data and prediction of dry maize grain yield. Results of each parameter trend calibrated against the level of soil fertility stress in the soil are presented in Fig. 2 to Fig. 6. Individual parameter function show distinct variations and imply that soil fertility levels strongly govern elements of biomass production and the ultimate yield and yield gap predictions of AquaCrop model.

AquaCrop model does not simulate directly soil nutrient deficiency balances recorded in the model as soil fertility stresses (FAO, 2017) but indirectly consider the effect of available soil fertility level on green canopy cover (CC) development and the amount of biomass water productivity (WP*). Results of maximum canopy cover (CC_x) trend attained when maize growth is at mid-season are presented in Fig.2. The effect of soil fertility deficiency clearly indicates that maximum canopy cover experienced in a non-stressed reference plot is never attained but continue to decrease reflecting a stressed condition as the nutrient level in the soil diminishes. The rate of decrease of canopy cover trend indicate a partition separating lower and higher levels of soil fertility deficiencies marked by a transition of near constant maximum canopy cover at 50% for stress levels between 40% and 60% range. Explanation of the result is based on the canopy cover (CC) development equation given in Eqn.1 (FAO, 2017) where crop transpiration (T_r) is directly proportional to the prevailing area reference evapotranspiration (ET_o) but modified by products of coefficients of water stress (K_s), cold stress (Ks_{Tr}) and crop transpiration stress (Kc_{Tr}). Crop aging and senescence is controlled by the adjustment of Kc_{Tr}.

$$CC = \frac{T_r}{[Ks_{Tr} \times Kc_{Tr}]\, ET_o} \qquad (1)$$

Effects of water stress and cold stress during analysis of the soil fertility deficiency are avoided by considering sufficient moisture in the soil at all levels equally but monitor only one independent variable of the outcome predicted maize grain yield.

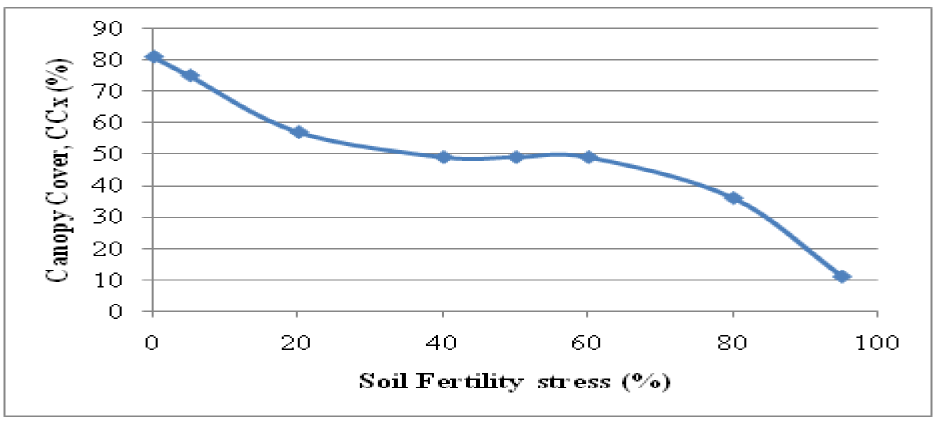

Figure 2: Maximum Canopy cover (CC_x) trend

The crop transpiration coefficient (KcTr) become the main influence of green canopy cover (CC) development and influences the resultant trend of CC_x given in Fig.2. At the transition range the rate of change in maize crop transpiration, T_r is similar to the change in its coefficient, KcTr and result in near constant CC_x level obtained. Fertility stress above 60% increases the rate of aging and senescence in canopy development and result in a less dense canopy cover and lower attainable CC_x.

When canopy cover is small, unit area of photosynthesis and assimilation of nutrients is low and does not exhaust sufficient amounts left available in the soil and therefore daily biomass production is equally low for both the adjusted and the non-limited soil fertility water productivity (i.e $WP^*_{adj.}$ = WP*). Similar analogy is replicated when considering occurrence of soil nutrient deficiency. Adjusted biomass water productivity ($WP^*_{adj.}$) trend fall into two levels of soil fertility categorized as low (0% to 50%) and high (above 50%) as presented in Fig.3. Development of canopy expansion is minimally reduced by fertility stress during the initial stage and the rate of biomass production and its biomass water productivity remains high and near constant at its maximum value from nil to 50% soil fertility stress level when its rate change to an inverse negative decrease with a uniform correlation value of R^2=0.962. The change in biomass water productivity (WP*) is further explained by Eqn. 2 described by a proportionality decrease in the biomass production as the effect of stress levels increases.

$$WP^* = \frac{B}{\Sigma \frac{Tr}{ET_o}} \qquad (2)$$

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Increased fertility stress above 50% result in a less dense canopy cover affecting area of plant food manufacture through transpiration and therefore result in poor crop development and reduction in the biomass production level. Biomass is directly proportional to cumulative amount of water transpired and its reduction causes the coefficient of proportionality (WP*) to decrease with an increase in the fertility stress level.

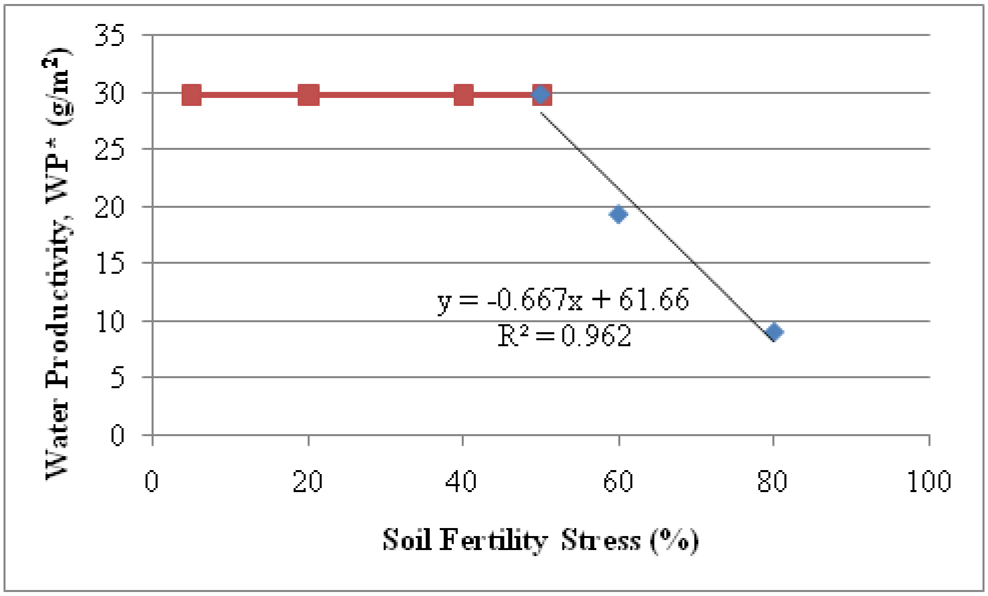

Figure 3: Biomass Water Productivity (WP*) trend

Canopy growth coefficient (CGC) is a conservative crop characteristics parameter (Hsiao et al., 2009; Heng et al., 2009) that is derived by the duration of canopy cover growth to reach its maximum canopy. The index decreases uniformly with a negative correlation (R^2=0.954) from 0.08 (%/day) at zero stress to 0.05 (%/day) at maximum stress of 100% as the soil fertility stress level increases (Fig.4). The trend indicates reduction at constant rate of canopy cover expansion (%/day) for every increase in fertility stress level. This effect is reflected in the variation in the age of maize crop from date of sowing (DAS) to attain maximum canopy cover (CC_x) peak for the different levels (Fig.5).

Canopy decline coefficient (CDC) is considered conservative in a similar manner specified for canopy growth coefficient (CGC). The index has a positive correlation (R^2=0.929) rate determined for every increase in the soil fertility stress and applied for the duration, in days when maize crop achieve maximum senescence (Fig.6).

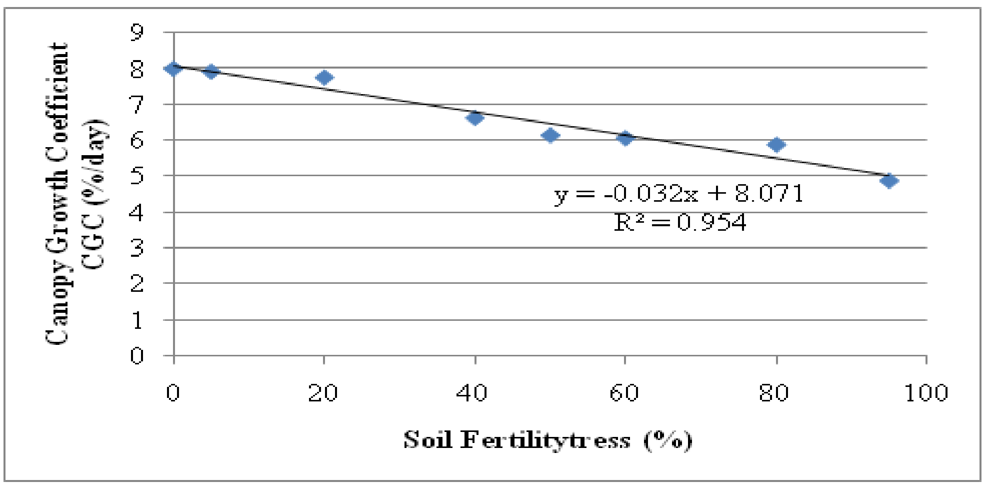

Figure 4: Canopy Growth Coefficient (CGC) trend

Senescence of maize crop leaves occur at the rate of 0.4 %/day from zero at the beginning to a maximum value of about 0.4 at the end of maturity or when fertility stress is at its maximum (100%).

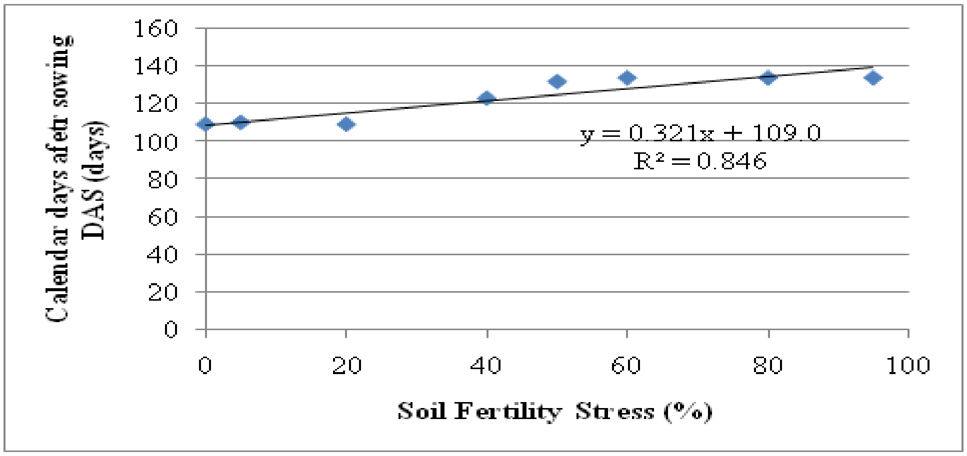

Figure 5: Calendar days after sowing (DAS) trend

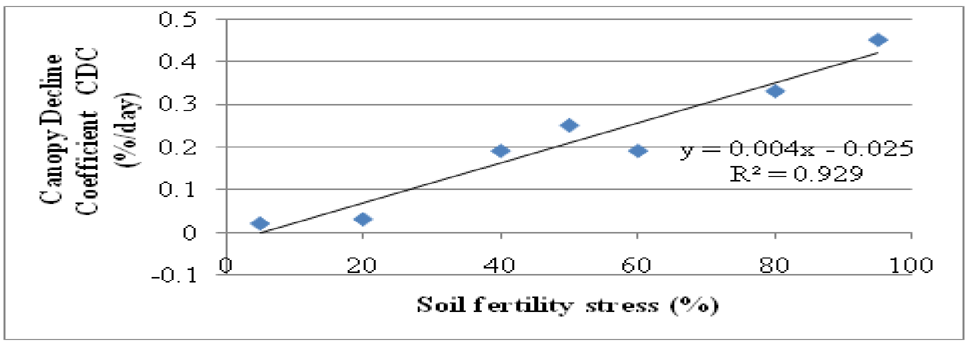

Figure 6: Canopy Decline Coefficient (CDC) trend

B. Results Of Soil Fertility Stress Prediction For Uasin Gishu Plateau Climate

Comparative prediction of maize yield gaps for various soil fertility stresses and weather conditions are given in Figure 7. The findings indicate that maize yields and yield gaps drop as fertility stress increases. AquaCrop model simulation partitioned maize yields under fertility stress grouped into dry, normal and wet season conditions. Normal weather results are approximately the average of both dry and wet season data. The differe +nce in yield gap results for the three weather conditions above 50% soil fertility stress are closer with smaller margins than for stress less than 50%. This is attributed to stronger influence of reduced nutrition levels compared to the effect of the amount of water and weather conditions.

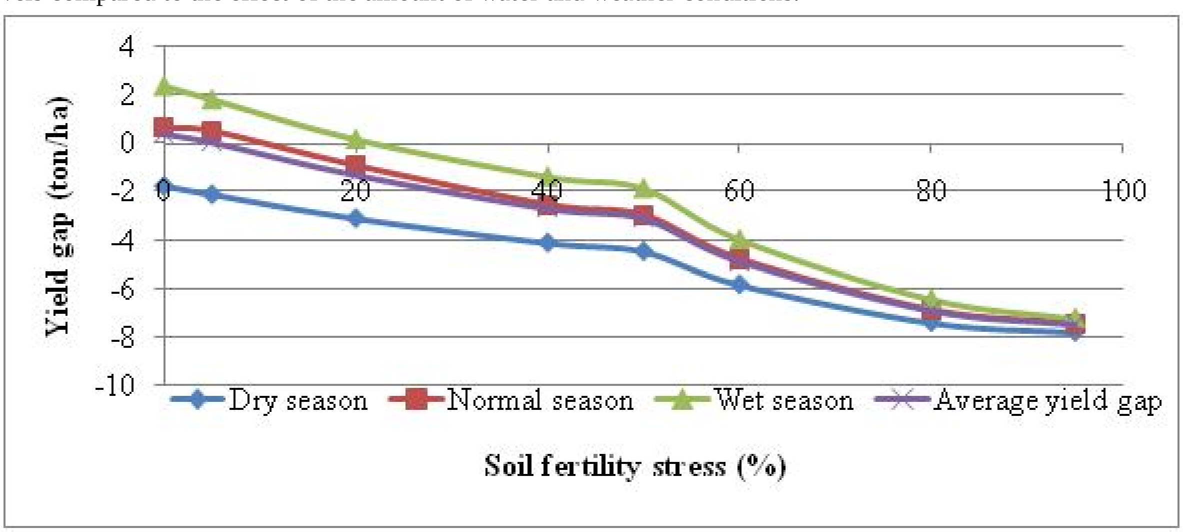

Fig. 7: Effect of soil fertility stress and climate on prediction of maize yield gaps in Uasin Gishu plateau

IV. CONCLUSION

The findings suggest that maize yields and yield gaps as affected by soil fertility stress are influenced by the crop canopy cover growth, the levels of biomass water productivity and duration taken to maturity.

Recommended optimal level of soil fertility nutrition for maize crop application when the soil does not have any residual nutrient content is approximately 85% and 75% under normal and wet weather conditions respectively. Dry weather conditions does not supply sufficient moisture level in the root zone and lead to increased concentration of available residual nutrients and maize crop experience difficulty imbibing root zone moisture. Low moisture result in stomata closure and reduce leaf expansion as senescence sets in and ultimately diminish biomass manufacture and lower maize grain yields.

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