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Assessment of Static Crop Water Production Functions of Plantain (*Musa Sp*. AAB) under a Tropical Climatic Condition

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ABSTRACT---- ***Static Water Production Function Models were used in assessing and predicting crop growth and yield for plantain. The regression analysis between the crop water use and yields showed that the relationships continued to improve from the linear function to the third degree polynomial functions.***

Fundamental water production function equations were drawn from the regression equations of each treatment when the relative yield decrease and relative evapotranspiration deficits were compared. The crop yield response factor values obtained in the study for plantain crop ranged from 0.61 – 1.35. The linear yield prediction models established for the crop gave positive slopes and thus exhibit some measure of reliability for predicting crop yields. The coefficient of correlation were significantly high varying from 0.66 – 0.87 for all treatments. Crop growth model is a very effective tool for predicting possible impacts of climatic change on crop growth and yield and also useful for solving various practical problems in agriculture.

Keywords--- Models, Crop water, evapotranspiration, static, growth, yield

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1. INTRODUCTION

Crop response to water can be described by crop-water-yield functions. It is important in defining the marginal crop production for maximum profit. Crop water production functions (CWPF) provide important basis not only for the planning and design of irrigation system, but also for the determination of water allocation scheduling of deficit irrigation for an area. In the last decades, researchers have developed a large number of models from different points of view since the early twentieth century. These models can be basically divided into two types. These are the static and dynamic crop water production functions. In the case of dynamic crop models, dry matter accumulation of the crop is expressed as a function of available soil moisture content in root zone. This indicates that dry matter accumulation is dependent on available soil moisture content. In view of its dynamic characteristics, model of this type is named as DYNAMIC MODELS.

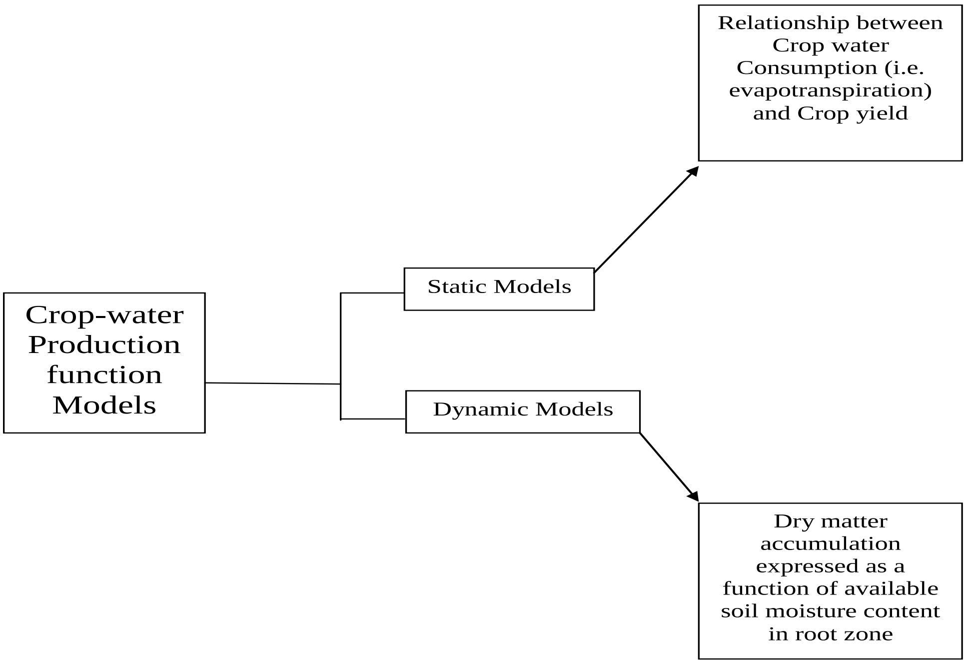


Fig. 1: Conceptual framework of **Crop Water Production Function Models (**CWPFM)

However static model is about the relationship between crop water consumption (evapotranspiration or transpiration) and the crop yield. In this type of models, crop yield is represented as a function of crop water consumption. It reflects the crop yield response to the degree of water stress at different growing stages. Models of this type can be called **static models**.

The Crop water yield function (CWYF) has been used to evaluate the economic viability of irrigation management schemes decades back. De Wit (1958) suggested the following CWYF, based on transpiration *[Y(T)]:*

$$Y = M\left(\frac{T}{E_0}\right) \qquad (1)$$

where Y is the dry matter yield, T is seasonal transpiration, E_0 is evaporation from free water surface, and M is the slope of the straight line representing the function. The term M accounts for crop variety, soil type, water availability and weather conditions not accounted for by E_0. Based on the de Wit function, Hanks (1974) suggested the following function:

$$Y = \left(\frac{T}{T_{MAX}}\right) Y_{MAX} \qquad (2)$$

where T_{MAX} is maximum seasonal transpiration and Y_{MAX} is the yield at T_{MAX}.

Stewart *et al.*, (1977) suggested a function based on evapotranspiration *[Y(ET)]:*

$$1 - \frac{Y}{Y_{MAX}} = B\left(1 - \frac{ET}{ET_{MAX}}\right) \qquad (3)$$

where ET is the actual seasonal evapotranspiration, ET_{MAX} is the maximum seasonal evapotranspiration and B is an empirical coefficient.

The above three relations are linear functions. The crop yield as a function of water applied (IRR) can be described generally as:

$$Y = F\,(IRR), \qquad (4)$$

The relation in this case is curvilinear. It coincides with the Y (ET) up to a point and deviates from linearity with increased water application. This departure occurs because the irrigation efficiency decreases. Y (ET) and Y (IRR) are identical as long as the irrigation efficiency is 100%. The departure from linearity is a non-ET contribution and results from deep percolation, runoff, drainage, change of soil moisture content or other components of the soil water balance equation.

This relation is important for irrigators since the water applied is the water paid for. It is a variable under their control as compared to T or ET. Transferability of Y (T) or Y (ET) to Y (IRR) is an interesting issue which represents a bottleneck.

The growth stage effect was taken into account by Jensen (1968) who developed a function which divided the growing season into stages with ET in each stage having a unique effect on yield:

$$\frac{Y}{Y_{MAX}} = \sum_{i-1}^{n}\left(\frac{ET}{ET_{MAX}}\right)^{b_i}, \qquad (5)$$

where bi is the relative sensitivity of the crop to water stress in the *ith* growth stage and n is the number of growth stages.

(f) Similarly Hanks' model can be written as:

$$\frac{Y}{Y_{MAX}} = \frac{T^{b_1}}{T_{MAX1}}\,\frac{T^{b_2}}{T_{MAX2}}\cdots\frac{T^{b_n}}{T_{MAXn}}, \qquad (6)$$

$$= \frac{Y}{Y_{MAX}} = \prod_{n-1}^{n}\left(\frac{T}{T_{MAX}}\right)^{bn} \qquad (7)$$

where b_n is the sensitivity to water stress in the n growth stage.

(g) Stewart's model can also be used to include the growth stage effect as follows:

$$Y = Y_{MAX} - Y_{MAX}\frac{\left[b_1 ET_1 + b_2 ET_2 \cdots + b_n ET_n\right]}{ET_{MAX}}, \qquad (8)$$

where ET_{MAX} is the ET for the whole season.

(h) Salinity affects the CWYF. Therefore, under saline conditions present in soil or irrigation water, the CWYF takes the following form (Maas and Hoffman, 1977):

$$\frac{Y}{Y_{MAX}} = 1 \quad \text{for } EC_e \le A_s, \qquad (9)$$

$$\frac{Y}{Y_{MAX}} = 1 - b_s(EC_e - A_s) \quad \text{for } EC_e \ge A_s, \qquad (10)$$

where A_s is the salinity threshold in ds m^{-1}, b_s is sensitivity of the crop to salinity above the threshold value in ds^{-1} m^{-2} and EC_e is the electrical conductivity of the soil solution of the saturation extract in ds m^{-1}.

(i) Van Genuchten and Hoffman (1984) suggested the following model:

$$Y = \frac{Y_{MAX}}{\left[1 + OP/OP_{50}\right]^b}, \qquad (11)$$

where OP is the current soil osmotic potential in J kg^{-1} and OP_{50} is the soil osmotic potential in J kg^{-1} when yield is reduced by 50% and b is an empirical constant. This was found to be around 3 for some crops.

Crop growth models can be used to produce daily CWYF. Its accuracy depends on the accuracy of the input to the model (Ragab *et al.*, 1990). The assumptions and limitations of the model will be reflected in the output similar to those of the empirical models.

The empirical relations based only on *T* or *ET* are usually valid for a single crop at a specific location. Using a relative transpiration or relative evapotranspiration ratio would make the CWYF a more generalized function and, therefore, transferable to different sites. Field values of *T*, unlike *ET*, are difficult or nearly impossible to determine or estimate accurately and, therefore, *ET* is more reliable.

From an economic point of view the *Y* (*IRR*) is the most important function for growers because it reflects better the cost of irrigation water, although it does not represent the actual water used by the crop as well as the *ET*. The relationship between *ET* and *IRR* applied is not well understood but it is known to depend mainly on irrigation system design and management. Soil water stress will usually have an inconsistent effect on yield under field conditions. The relation is also affected by the soil permeability (Ragab and Cooper, 1993), soil moisture uniformity within fields and other factors. The effect of variation in spatial application of irrigation and the spatial uniformity of *ET* over the field is an unresolved issue. Integrating all the factors affecting the CWYF is difficult. There is no universal relation between *Y* and *IRR*. This work studies some Static crop water production functions of plantain (*Musa* AAB) grown under a tropical climatic condition of South western Nigeria.

2. MATERIALS AND METHODS

2.1. Experimental site

Experimental site is the Agricultural Engineering Research farm of the Federal University of Technology, Akure, Nigeria. It is located within the humid region of Nigeria at latitude 7° 16’ N and longitude 5° 13’ E. It lies in the rainforest zone with a mean annual rainfall of between 1300-1600 mm and with average temperature of 27.5°C. The relative humidity ranges between 85% and 100% during the rainy season and less than 60% during the harmattan period.

2.2 Soil Physical and Chemical Properties of the Experimental Field

Soil samples were collected from 0 – 60cm depth at five different locations on the experimental field to determine the soil mineralogical, chemical and physical properties such as the particle size distribution (i.e. sand, silt and clay contents), organic matter present, soil pH, bulk density, percentage composition of nitrogen, sodium, potassium, calcium, phosphorous and magnesium using standard procedures. The soil at the experimental field belongs to category of sandy loam soil, skeletal, Kaolinitic, iso-hyperthermic, oxic paleustalf (Alfisol) or Ferric Luvisol.

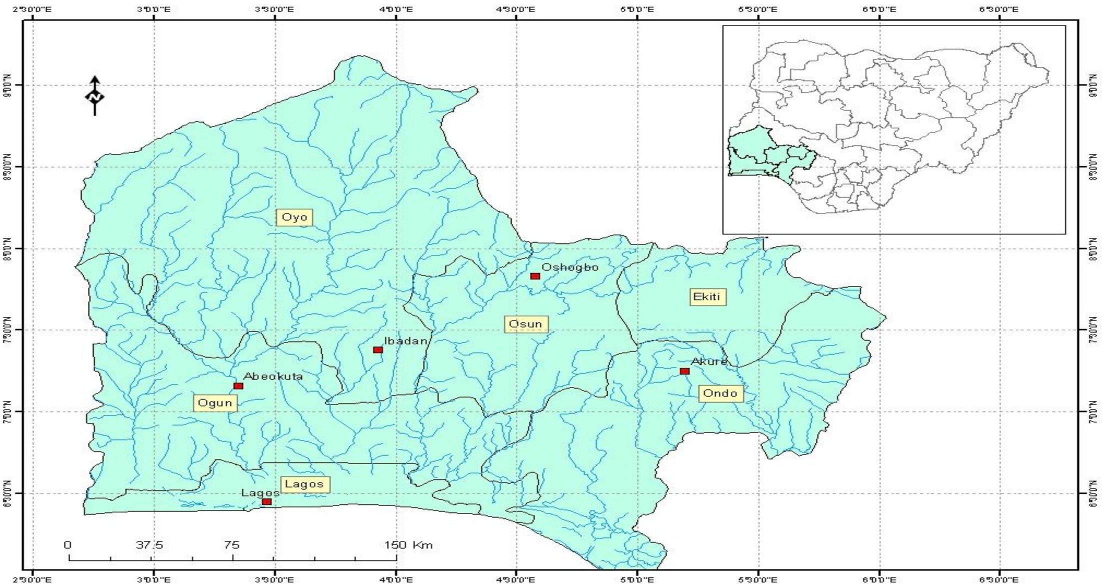


Fig 2: Map of Nigeria showing South Western Nigeria and the geographical location of the study area.

2.3 Planting and other cultural practices

Suckers of plantain, cultivar Agbagba (*musa* sp. AAB) were planted at the Teaching and Research farm site of the Department of Agricultural Engineering, Federal University of Technology, Akure between July 2006 - November 2007 and August 2007 – November 2008. The planting density was 1,921 plants ha^{-1} at 2 x 2 m spacing. A preliminary investigation was carried out on the soil physical and chemical characteristics, climate variations and water resource of the study site to determine its potentials for dry season farming. Low gravity drip irrigation system was designed for the 16 x 40 m^2 experimental farm. There were four irrigation treatments: no deficit irrigation, T_{100}, (i.e. maintained at near field capacity or 100% available water); 50% deficit irrigation, T_{50}, (i.e. maintained at 50% available water); 75% deficit irrigation, T_{25}, (i.e. maintained at 25% available water) and the control treatment, T_0, which was not irrigated except during crop establishment. The experimental design was a Randomized Complete Block Design (RCBD) with four replicates.

Table 1: Summary of Irrigation Treatments

Treatment	**Code**	**Definition**
High (Full)	T_{100}	0% Deficit Irrigation
Moderate	T_{50}	50% Deficit Irrigation
Low	T_{25}	75% Deficit Irrigation
Control	T_0	Control experiment

Measurements taken on the field during experiments included soil moisture content using the gravimetric method, soil bulk density, overland flow during occasional rainfalls in the field by use of runoff meter and deep drainage from the field using hydraulic lysimeter. Measured crop parameters included the plant height, the leaf area and the number of leaves and crop yield. The leaf area index (LAI) was determined weekly, a representative plant was selected weekly for the measurement of LAI. The length L and the maximum width W of each leaf were measured from which the leaf area was computed following the method of Obiefuna and Ndubizu, (1979)

$$\text{Leaf Area (LA)} = 0.83LW \tag{12}$$

Leaf area index was then estimated from the relationship below (Gong *et al.*, 1995):

$$\text{Leaf Area Index (LAI)} = \frac{\text{Area of leaf per plant}}{\text{Area of soil covered per plant}} \tag{13}$$

Bunch yield and dry matter yield were determined at maturity.

The consumptive use of water by the crop was estimated using the water balance equation:

$$\mathbf{ET = I + P \pm \Delta S \pm R \pm D} \tag{14}$$

where ET = actual evapotranspiration in mm; I = amount of irrigation water (mm); P = effective rainfall (mm); ΔS = change in soil water storage (mm); R = surface runoff, (mm) and D = amount of drainage water (mm)

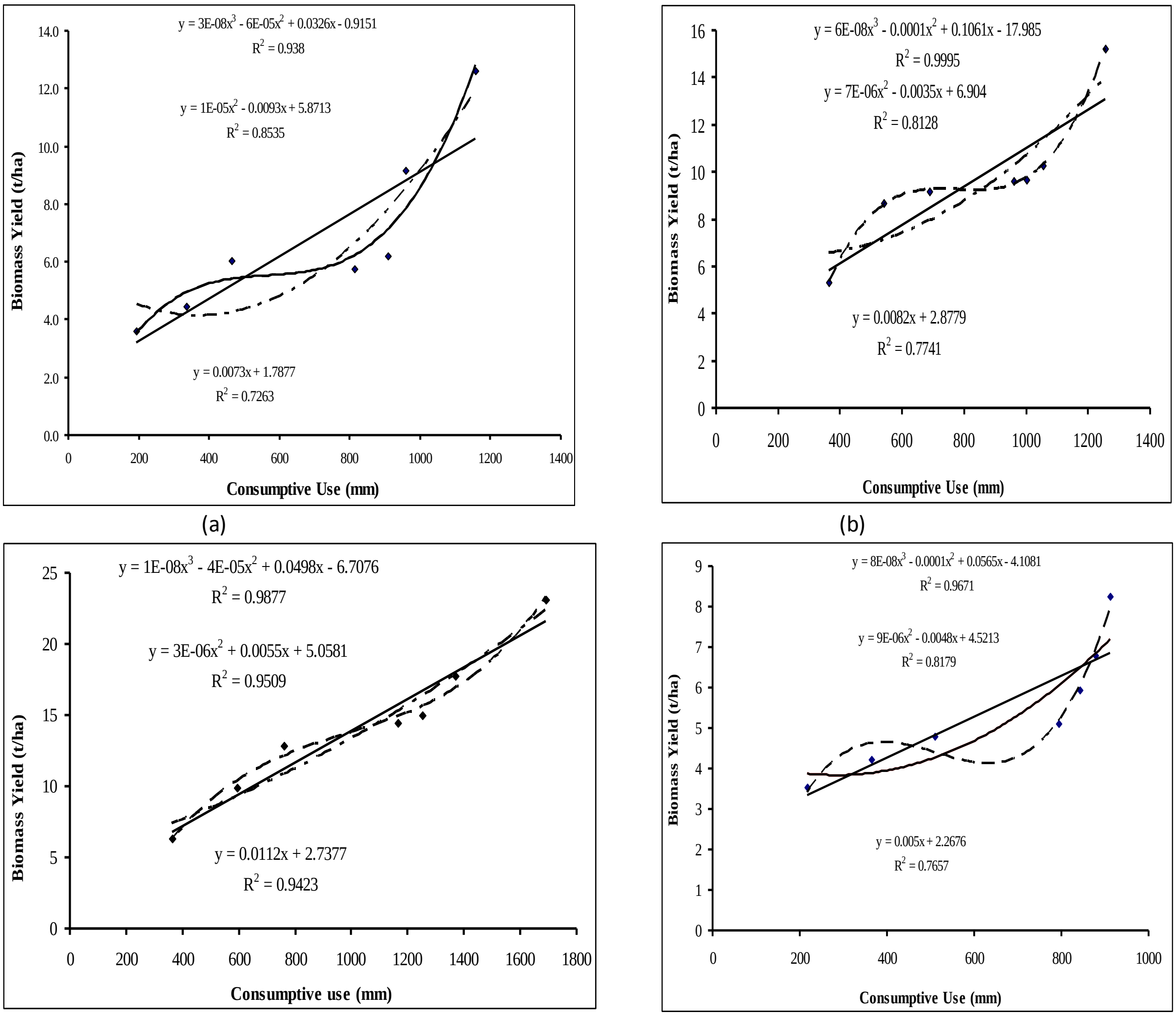
Plate 1: Runoff Meter Installed on T_{100}

Plate 1: Runoff Meter Installed on T_0

3. RESULTS AND DISCUSSIONS

3.1 Biomass Yield – Consumptive Yield

The relationship observed between the measured consumptive use and biomass yield for each treatment are presented in fig.3. Estimated water consumed ranged from 900 mm to 1700 mm from planting to harvest in the order of T_0, T_{25}, T_{50} and T_{100} treatments respectively. For example, in the fully irrigated treatment, (fig. 3c), crop consumptive use at 413DAP (at harvest) was 1691.5 mm while crop consumptive use was 910.7 mm at same period for treatment T_0 (fig. 3d). Correspondingly, highest biomass yield was 23.2tha^{-1} at harvest for T_{100} treatment while lowest value of biomass yield was 8.3 tha^{-1} in T_0 treatment. This confirms that supplemental irrigation had significant effect ($p<0.05$) on biomass yield.



(a) (b)

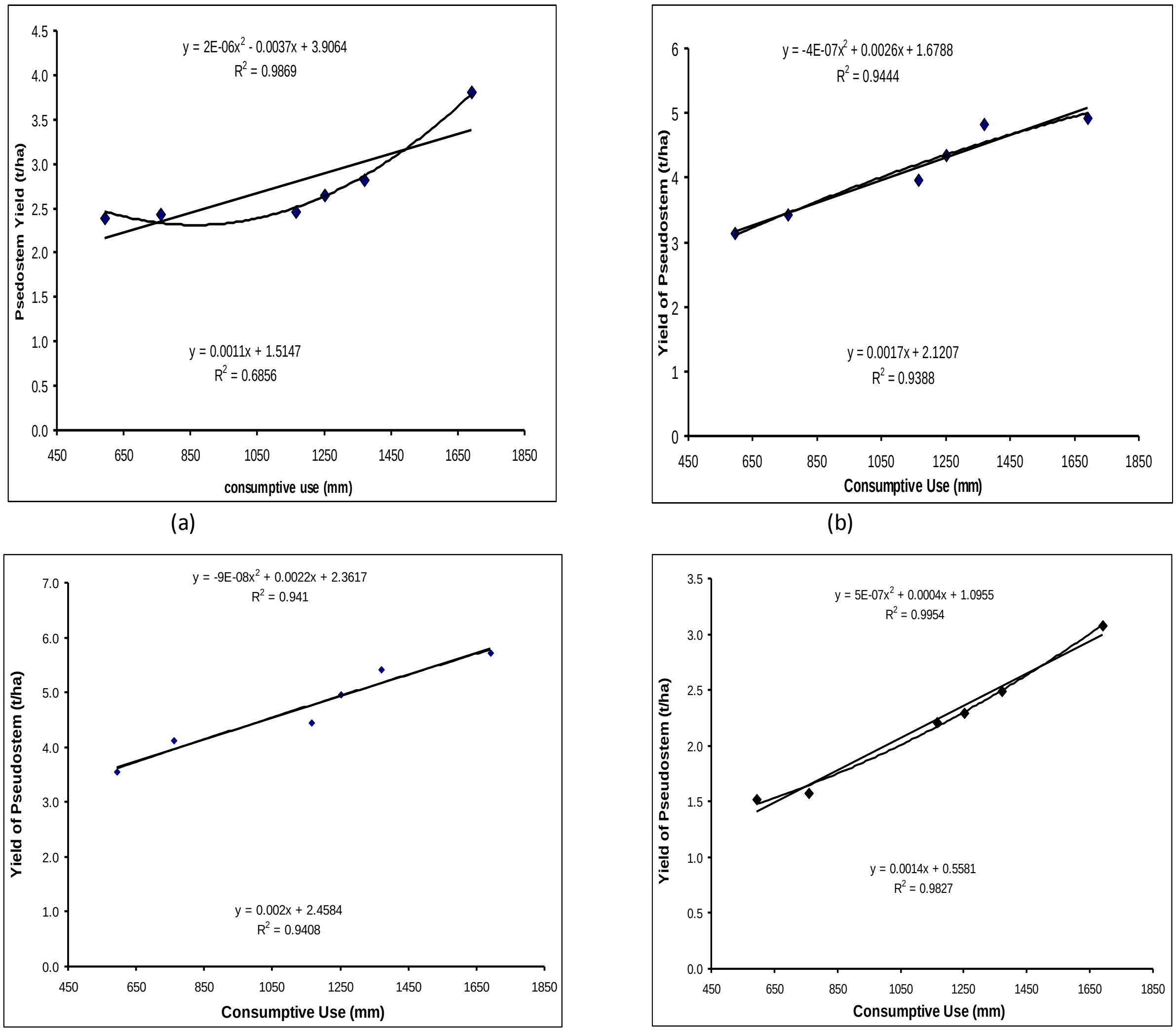
(c) (d)

Fig 3: Biomass Yield vs Seasonal Consumptive use for (a) T_{25} (b) T_{50} (c) T_{100} and (d) T_0

When crop consumptive use and biomass yield were fitted to a linear model, R^2 values obtained were 0.94, 0.77, 0.73 and 0.77 for T_{100}, T_{50}, T_{25} and T_0 respectively. On third degree polynomial model, R^2 values were 0.99, 1.0, 0.94 and 0.97 for T_{100} down to T_0 treatments respectively

3.2 Pseudostem Yield and Consumptive Use

The pseudostem yields and consumptive use relationship (fig. 4) for each treatment were examined. Results showed that T_{100} treatment (fig. 4c) was highest in each case. The value for the highest yield of pseudostem was 5.73 tha^{-1} while the corresponding ET was 1691.5 mm at maturity. T_0 (fig. 4d) had least pseudostem yield of 3.08 tha^{-1} at harvest. The R^2 value for the linear regression equation for T_{100}, T_{50}, T_{25} and T_0 treatments were 0.94, 0.94, 0.69 and 0.98 respectively.



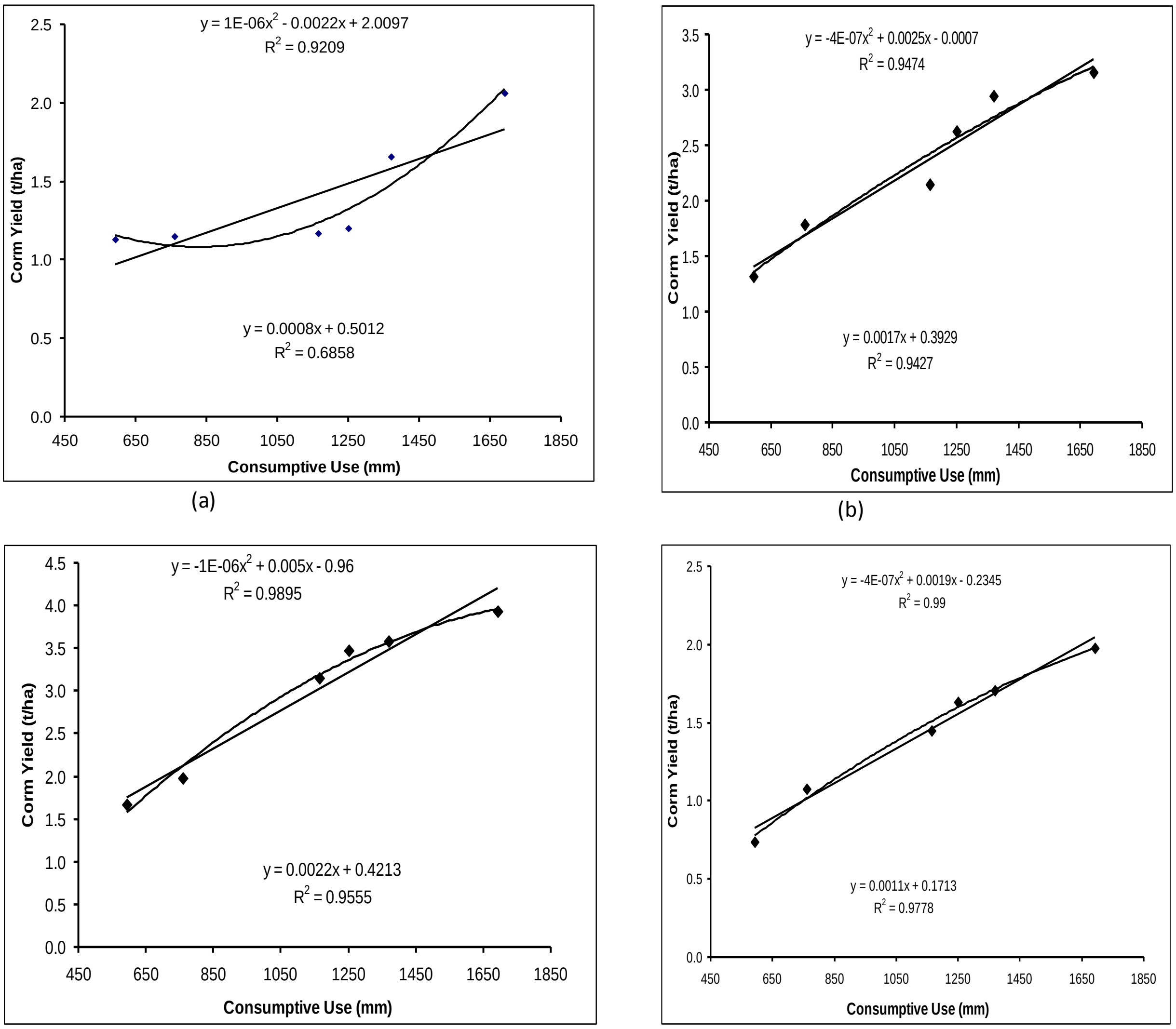
(a) (b)

(c) (d)

Fig 5: Yield of Pseudostem vs Consumptive Use for (a) T_{25} (b) T_{50} (c) T_{100} and (d) T_0

3.3 Corm Yield and Consumptive Use

The relationship between the corm yield and consumptive use are shown in fig. 5 On the average corm yield was highest for T_{100} treatment (fig. 5c) with a value of 3.93 tha^{-1} which occurred during the maturity stage. The corresponding consumptive use at this period was 1691.5 mm. The lowest yield was in the T_0 treatment (fig. 5d) with a value of 1.98 tha^{-1} also at the maturity stage. The R^2 values for T_{100}, T_{50}, T_{25} and T_0 were 0.96, 0.94, 0.69 and 0.98 respectively.



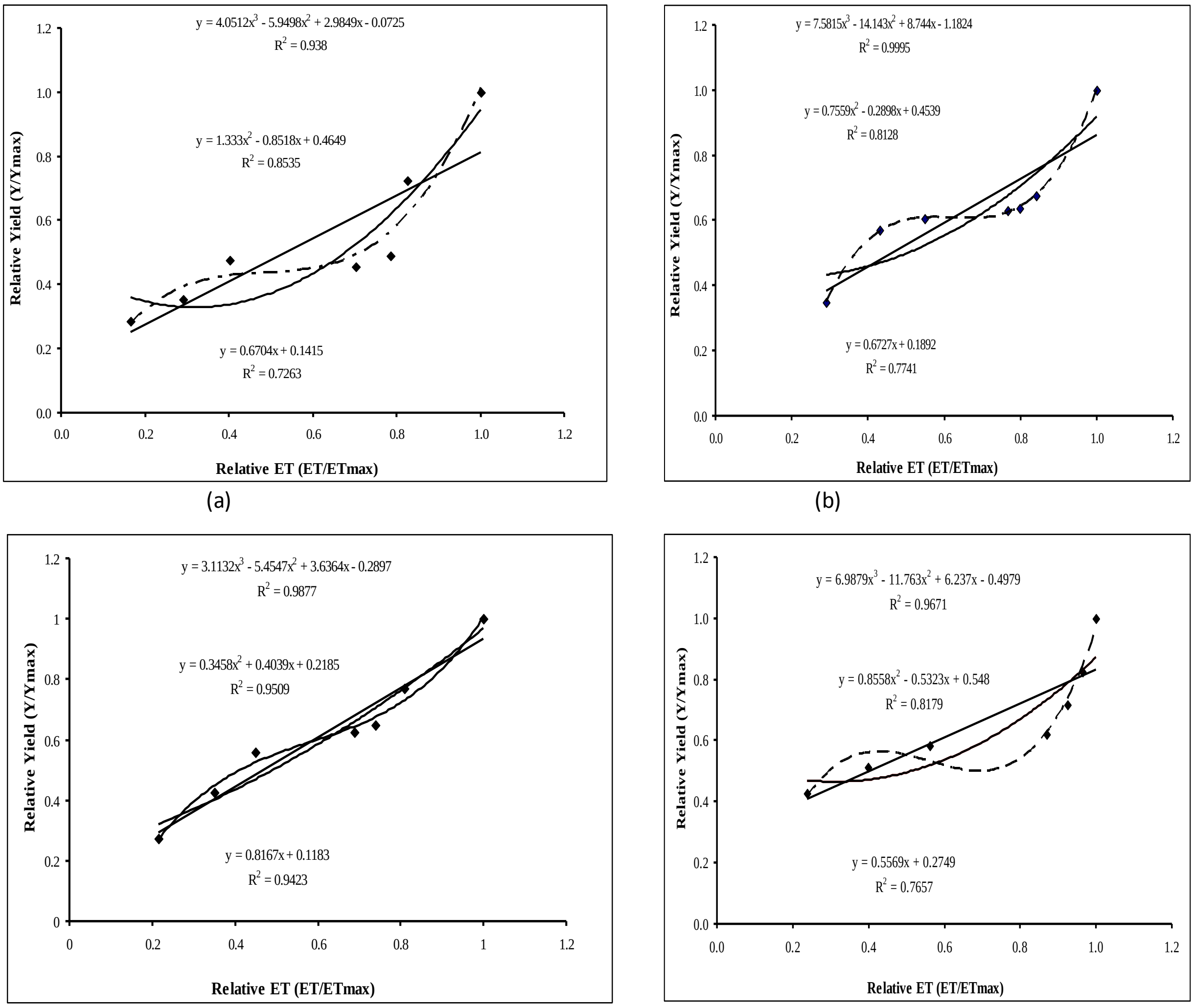
(a) (b)

(c) (d)

Fig 5: Yield of Corm vs Consumptive Use for (a) T_{25} (b) T_{50} (c) T_{100} and (d) T_0

3.4 Relative Yield and Relative Evapotranspiration

When actual evapotranspiration (ET_a) is less than the maximum evapotranspiration (ET_{max}), evapotranspiration deficit occurs which consequently leads to a reduction in yield. According to Stewart *et al.*, (1976), the effect of evapotranspiration deficit is associated with some minimum fractional reduction in yield below the maximum yield (Y_{max}), and the reduction is a measure of crop sensitivity to water stress. Fig. 6 shows the relationship between relative yield and relative evapotranspiration. The relative relationship "yield – evapotranspiration" varied with variation in water supply to crop and also to variations in rainfall. The coefficient of correlation R^2 between relative yield and relative evapotranspiration expressed with linear function were significantly high, between 0.73 and 0.94 for all treatments.



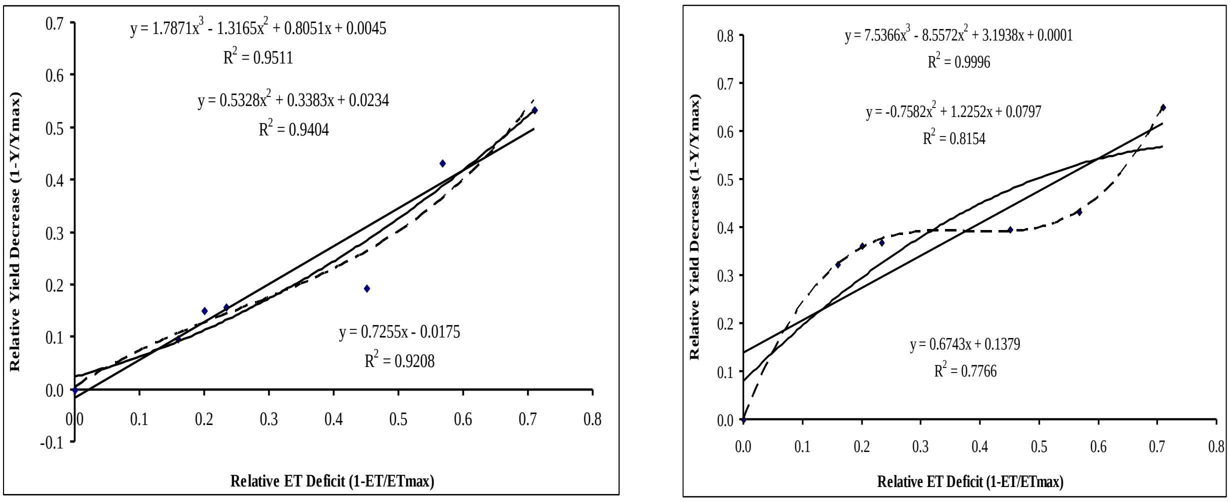
(a) (b)

(c) (d)

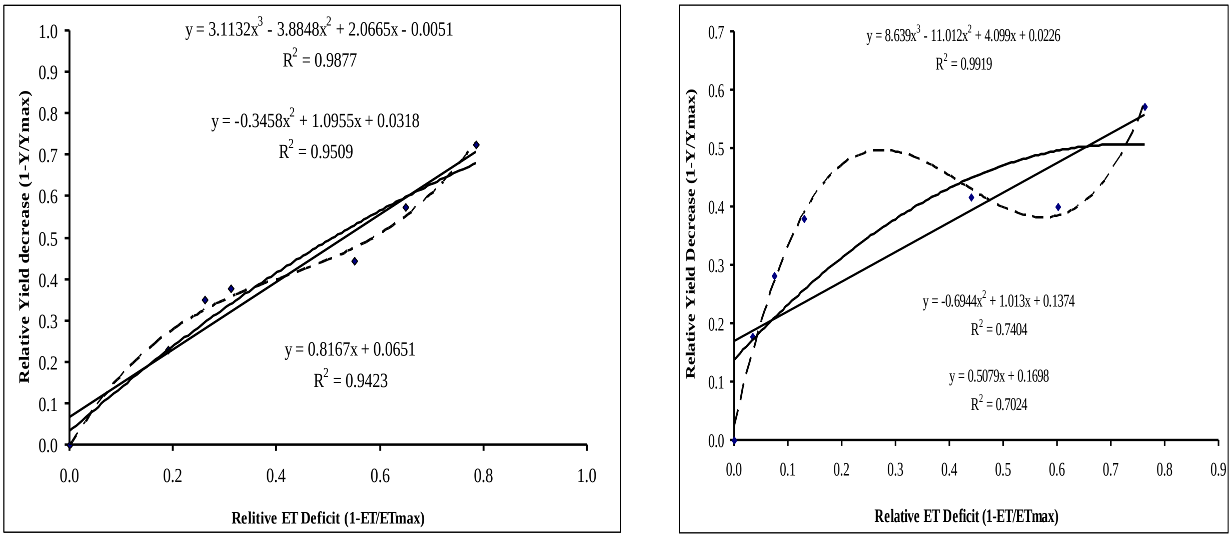
Fig. 6: Relationship between relative yield (Y/Y_{max}) and relative evapotranspiration (ET/ET_{max}) - Global function for (a) T_{25} (b) T_{50} (c) T_{100} and (d) T_0

3.5 Relative Yield Decrease – Relative Evapotranspiration Deficit

The relationship between yield decrease and relative evapotranspiration deficits are shown in fig 7.



(a) (b)



(c) (d)

Fig. 7: Relationship between Relative Yield Decrease (1-Y/Ymax) and Relative Evapotranspiration Deficit (1-ET/ET$_{max}$) for (a) T$_{25}$ (b) T$_{50}$ (c) T$_{100}$ and (d) T$_0$

The linear regression equations of the relationships for each treatment were as follows:
For T$_{25}$

$$\left(1-\frac{Y_a}{Y_m}\right) = 0.73 \text{ x } \left(1-\frac{ET_a}{ET_{\max}}\right) \qquad 16$$

for T$_{50}$

$$\left(1-\frac{Y_a}{Y_m}\right) = 0.67 \text{ x } \left(1-\frac{ET_a}{ET_{\max}}\right) \qquad 17$$

for T$_{100}$

$$\left(1-\frac{Y_a}{Y_m}\right) = 0.82 \text{ x } \left(1-\frac{ET_a}{ET_{\max}}\right) \qquad 18$$

and, for T$_0$

$$\left(1-\frac{Y_a}{Y_m}\right) = 0.51 \text{ x } \left(1-\frac{ET_a}{ET_{\max}}\right) \qquad 19$$

where Y_a = actual yield obtained for the treatment
Y_m = maximum yield obtained for the treatment
ET_a = actual ET for the treatment
ET_{max} = maximum ET obtained for the treatment

Equations 16-19 above are the well known water production functions of Doorenbos and Kassam, (1979). Doorenbos and Kassam, (1979) referred to the slope of the expression as the crop yield response factor, K_y. The K_y values obtained in this study ranges from 0.51 to 0.82. In Kenya, values of K_y for *musa* varied from 1.3 to 1.35 (Molua and Lambi, 2006). K_y values greater than unity is an indication of severe moisture stress (Igbadun *et al*., 2006). The result in this study confirmed that the rate of relative yield decrease resulting from moisture stress is relatively proportional to the relative evapotranspiration deficit for all treatments. This is in agreement with the works of Prieto and Augueira, (1999), Anac *et al*., (1999). When the relationship between yield decrease and relative evapotranspiration deficits were fitted to a linear model, R^2 values obtained ranged from 0.70 – 0.94 for all treatments. On third degree polynomial model, R^2 values were between 0.95 – 1.0.

3.6 Water Stress Factor (Ks) for *Musa paradisiaca*

The FAO revealed the plausibility of "linear crop-water production functions" to predict the reduction of crop yield when crop stress is caused by a shortage of soil water according to the relationship in equation 20:

$$K_s = 1 - \frac{1}{K_y\left(1-\frac{Y_a}{Y_m}\right)} \qquad 20$$

where K_s is the water stress factor and other terms as previously defined. Hence water stress factor for the various treatments as revealed in this study are given in Table 2. The water stress factor was high for both fruit filling/bulking and maturity stages of *musa* for all treatments (0.82-0.97) and low during the vegetative period. The mean water stress factor for the combined treatments ranged from 0.44 to 0.95 for the various stages of growth. When compared with bananas grown in Kenya (Karanja, 2006), the K_s factor was 0.506 for the variety of banana grown. The nature of treatment applied was not however mentioned in the report and neither was the K_s value for the crop stages given.

A high value of stress factor is an indication of the severity of water stress in a plant and the need to supplement with water. The standard deviation for combined K_s was 0.11, skew was -0.399 and kurtosis 1.43.

Table 2: Water Stress Factor Ks for the Plantain Crop during the 2006-2007 Growth Season

STAGES	TREATMENT				Summary for Combined Treatment			
	LOW	**MEDIUM**	**HIGH**	**CONTROL**	**Mean**	**STD**	**Skew**	**Kurtosis**
Vegetative	0.46	0.3	0.57	0.44	0.4425	0.111	-0.399	1.430
Floral	0.64	0.9	0.75	0.61	0.725	0.131	0.955	-0.420
Flowering	0.82	0.92	0.9	0.83	0.8675	0.050	0.103	-5.027
Maturity	0.91	0.95	0.97	0.96	0.9475	0.026	-1.443	2.235
Mean	0.7075	0.7675	0.7975	0.69				
STD	0.1996	0.3123	0.1773	0.2308				
Skew	-0.4816	-1.9790	-0.6788	-0.1806				
Kurtosis	-1.6995	3.9151	-1.0797	-2.3064				

4. CONCLUSION

Static water Production Function Models were used in assessing and predicting crop growth and yield for plantain. The regression analysis between the crop water use and yields showed that the relationships continued to improve from the linear function to the third degree polynomial functions.

Fundamental water production function equations were drawn from the regression equations of each treatment when the relative yield decrease and relative evapotranspiration deficits were compared. The crop yield response factor values obtained in the study for plantain crop ranged from 0.61 – 1.35. The linear yield prediction models established for the crop gave positive slopes and thus exhibit some measure of reliability for predicting crop yields. The coefficient of correlation were significantly high varying from 0.66 – 0.87 for all treatments. Crop growth model is a very effective tool for predicting possible impacts of climatic change on crop growth and yield. Crop growth models are useful for solving various practical problems in agriculture. One should however trust contemporary models particularly those concerned with yields. Wide variations may be found in the yield predicted by different models for specific crop in a defined environment. There is a need to develop, test and improve the models with similar basis till they achieve comparable success for use by farmers, extension workers industry, etc. The reason is that the farmer needs them for decision-making, because It was found that the model can be used to identify new sites suitable for development of crop which finally results in generation of income to them. Adequate human resource capacity has to be improved to develop and validate simulation models across the globe.

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