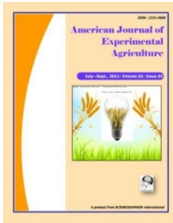

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Dynamic Crop Water Production Model of Plantain Yield Response to Water

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Authors' contributions

This work was carried out in collaboration between all authors. Author OAA designed the study, performed the statistical analysis, wrote the protocol, and wrote the first draft of the manuscript. Authors AAO and PGO managed the analyses of the study. All authors read and approved the final manuscript.

Original Research Article

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ABSTRACT

Crop Water Production Function Model (CWPFM) has been studied for quite few decades and since recent years developing a non- time specific and non-site-specific CWPFM has been receiving more and more attentions. A dynamic model of plantain bunch yield response to daily available soil moisture is presented. Using a priori information on dry matter accumulation in the plant when water is not limiting and using a piecewise linear regression, functions of crop response to soil moisture from experimental test plot data were estimated. With the estimated model, the bunch yields for various irrigation schedules were predicted. The predictions demonstrate the sensitivity of the model to the timing of irrigations.

Keywords: Dynamic model; static model; sigmoidal function; piecewise regression; dry matter accumulation.

1. INTRODUCTION

Most irrigation scheduling studies have been limited to scheduling irrigations based on some criteria regarding the level of soil moisture depletion [1]. The ultimate objective of an irrigator

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is to schedule his irrigations so as to maximize his profits from irrigated production. To do that requires knowledge both of the cost of applying each increment of water and the additional revenue resulting from the increased yield associated with each increment of water applied [2,3]. Scheduling models with such capabilities use synthesized crop response functions instead of empirically estimated function [4,5,6]. Synthesized response functions are used because empirically estimated dynamic response relationships are not available. Dynamic response relationships are needed because with irrigation scheduling the decision of when to irrigate depends upon the crops response to water, which depends upon the condition of the crop when irrigated. But the condition of the crop when it is irrigated is a function of growing conditions previously encountered by the crop.

Present crop response functions are static. Static models are about the relationships 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. They do not take into consideration the dynamics of the continuous growth process of the plant. In production function studies of water use and crop yield, harvested yield is correlated to total water use or to total water applied during the growing season. A discussion of several evapotranspiration-based yield models are presented by [7]. [8,9] reported greater yield reductions when moisture stress occurred near silking. The number of stress days during this critical period was highly correlated with yield. These approaches do not capture the dynamics of the plants response to the time path of the available moisture levels during the growing season.

The work of [4] is an example of such an approach. Burt and Stauber's model is an improvement because it identifies five separate periods for which water is critical and because the effect on yield of irrigation water and precipitation in one period is affected by the conditions in the other four periods. Specifying corn yield as a function of the composite variables provided that interdependence among the periods.

While the Burt and Stauber model exemplified the improvement that has been made by dividing the growing season into periods, its deficiencies are also typical of models of this type. Only in an indirect fashion does it represent the physiological functions of plant growth and development. It fails to specify explicitly the dynamic nature of growth and development where a plant's growth depends on current growing conditions and on the current status of the plant itself. It fails to recognize directly the importance to growth of available soil moisture. It is a model that can be estimated efficiently only when the number of periods in the growing season is kept small. When one divides the growing season into periods sufficiently short to be useful for irrigation scheduling, the number or periods is more than what such a model can handle when estimating the coefficients. [3] Successfully developed a dynamic model of corn yield response to water. The model measured crop response to daily available soil moisture. Because it incorporates certain physiological knowledge of the plant, it does not require a prohibitively large number of observations to estimate the response function.

A valuable dynamic crop-water production function must be stable and sensitive, variables contained in this model and experimental treatments required for this model development must be as less as possible, and this model must be capable of being used easily. Based on the above, an empirical dynamic crop-water production function model for plantain is developed. Although many attempts have been made to develop dynamic crop-water production function model for crops such as grain crops [3,10], no literature has been found on the development of dynamic crop-water production function models for plantain and banana.

Based on these an empirical dynamic crop – water production function model of plantain, (*Musa sp*), AAB subgroup is evaluated and explored in this present paper. The model does not deal with the impact of soil fertility on plant response to water stress. Subsequent modifications of the model should explicitly include the element.

2. MATERIALS AND METHODS

2.1 Location of Field Experiments

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. Akure, the region of study is the capital of Ondo State, Nigeria. It is located in a humid tropical climate of Western Nigeria. The Irrigation experimental field lies at latitude 7.16º North, and longitude 5.13º East, at an altitude of 351m above sea level. Two wells were sunk at the experimental site for the purpose of the research work. Average depth of wells was about 4.5m.The quality of the wells water was analyzed and was found suitable for irrigation. Some chemical characteristics of irrigation water are shown in Table 1.

The soil at the experimental field belongs to category of sandy loam soil, skeletal, Kaolinitic, iso-hyperthermic, oxic paleustalf (Alfisol) or Ferric Luvisol [11]. Some physical characteristics of the experimental soil are shown as Table 2.

Table 1. Some chemical characteristics of irrigation water

Conductivity (μmhos)	pH	Cations (ppm)				Anions (ppm)			SAR	CEC	ESP
		Na	**K**	**Ca**	**Mg**	**SO_4**	**NO_3**	**Cl**			
$1.2x10^2$	5.9	60.1	64	11.3	18	ND*	ND	0.18	15.7	0.05	19.06

**not detected*

Table 2. Some physical characteristics of experimental soil

Bulk density (gcm^{-3})	1.50
Field capacity (%)	20.60
Wilting Point (%)	3.43

2.2 Experimental Treatments and Field Measurements Description

Plantain suckers were planted between July 2006 and November 2007 and between August 2007 and December 2008. The experimental design was a Randomized Complete Block Design (RCBD). There were four blocks with four plots in each block. The plots represent the treatments while the blocks represent the replications. There were four treatments based on different levels of water application: high irrigation called T_{100} (maintained at near field capacity i.e. 100% available water), medium irrigation, T_{50}, (maintained at 50% available water), low irrigation, T_{25}, (maintained at 25% available water) and the control treatment, T_0, which was not irrigated except during crop establishment. Summary of irrigation treatments on the field during both seasons is shown as Table 3.

Water stored between the field capacity and the permanent wilting point is the maximum available water (i.e. 100%AW) and it is expressed as:

$$\text{Total Available Water (AW)} = \sum_{d=0}^{d=50} S_{up} - \sum_{d=0}^{d=50} S_{lo} \quad (1)$$

Where S_{up} and S_{lo} are the upper and lower limits soil storage.

Table 3. Summary of Irrigation treatments on the field

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

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

$$ET = I + P \pm R_o \pm DP + CR \pm \Delta SW \quad (2)$$

Where Irrigation (I), Rain fall (P), Surface runoff (R_o), deep percolation (DP), capillary rise (CR) and change in soil water content (ΔSW) were obtained during the experiment. All terms in Eq. 2 are expressed in millimeter of water per day.

Water was applied using low gravity bucket irrigation system and emitters were spaced along polyethylene lines with stopcock controls at each end of the line to control the timing and quantity of water applied. Irrigation amount was recorded at every water application. The change of soil water storage, ΔS was estimated from moisture content readings up to a depth of 50 cm which was assumed to be the root zone. Runoff was estimated using runoff meters. The drainage below root zone was estimated using Darcy's equation. A Watermark Soil Moisture Sensor and the Multipurpose Temperature Probe used with the Vantage Pro2 wireless soil moisture /Temperature station was installed on the experimental field to monitor the soil moisture and soil temperature. Soil moisture contents were also determined by gravimetric method. This was measured in each treatment plot to depths of 50 cm at 10 cm interval starting from the soil surface. Rainfall data were collected using standard rain gauges installed at various points of the experimental farm. The rain gauges were regularly raised above crop canopy to avoid errors due to rainfall interception. Reference evapotranspiration (ET_{ref}) was calculated using monthly temperature, humidity, solar radiation and wind speed according to the FAO Penman Monteith Method [12].

Growth analysis was carried out monthly by harvesting plant material from randomly selected plots of each treatment. Samples were taken in all replicates. Plants were harvested and separated into dry leaves, wet leaves, pseudostem, corm, and fruits. The fresh and dry mass of each sample were determined. Dry matter of plants organs were determined by drying samples in an oven at 65ºC for 48hrs. Weekly measurements of plant height, girth, circumference, fruit size, of *musa* were made beginning from the vegetative stage to the maturity stage. The leaf area index (LAI) was determined weekly from a selected representative plant. Length (L) and the maximum width (W) of each leaf were measured from which the leaf area was computed following the method of [3]

$$\text{Leaf Area (LA)} = 0.83\text{LW} \tag{3}$$

Leaf area index was then estimated from the relationship below [13]:

$$\text{Leaf Area Index (LAI)} = \frac{\text{Area of leaf per plant}}{\text{Area of soil covered per plant}} \tag{4}$$

Bunch yield and dry matter yield were determined at maturity.

Analysis of data was carried out using statistical softwares such as the Statistical Package for Social Sciences (SPSS), Stat graph, MS Excel and Sigma plot 10.0.

2.3 Development of the Model

Our purpose was to design a model that would estimate plantain bunch yield response to available soil moisture. Since plant growth is dynamic in nature, that is, growth in any period is dependent on growth in previous periods [14], we propose a dynamic model. This various elements in the dynamic model are represented by the following conceptual framework:

2.3.1 Analysis of the relationship between dry matter accumulation and bunch yield

The process of crop growth from emergence to maturity is a dynamic process, in which the crop dry matter accumulation increases monotonically. In general, the rate of dry matter accumulation has a pattern of slow – quick – slow, the rates of dry matter accumulation in the early and later stages of crop growth season are smaller than those in the middle stages [10]. The relative dry matter accumulation for plantain varying with time was fitted to a sigmoidal function of the elongated *S* shape as follows:

$$f = \frac{a}{(1 + \exp(-(x - x_o)/b))} \tag{5}$$

Where f =RDM (the relative dry matter accumulation of plantain, x = the days after planting, a, b and x_0 are constants. This shape is normally observed for most crops e.g corn [10,14,15].

Dry matter yield reflects the effect of soil moisture, soil nutrient, and climatic factors on crop growth throughout the growing season. Plantain bunch yield also affected by soil moisture, soil nutrient, etc., is an important part of dry matter yield. In general, the higher the dry matter yield, the higher the bunch yield. The relationship between dry matter yield and bunch yield at harvest for plantain was fitted with a linear regression model of the form:

$$Y_b = \beta_1 Y_{dm} + CY \tag{6}$$

Where Y_b and Y_{dm} are the bunch yield and the dry matter yield for plantain respectively, and *CY* is a constant.

2.3.2 Dry matter accumulation and available moisture content

According to the pattern of relative dry matter accumulation described with eq.5, the ratio of relative dry matter accumulation was represented as

$$\frac{RDM_y(t)}{RDM_y(t-1)} = \Gamma(t) \tag{7}$$

Where *Γ(t)* represents proportional growth of relative dry matter accumulation when soil moisture is not limiting, *Dy(t-1)* and *Dy(t*) are relative dry matter accumulation at initial and end of the period t. According to eq. 7 the dry matter yield at harvest was written as

$$YDM = YDM_o \prod_{t-1}^{n} \Gamma(t) \tag{8}$$

In which *YDM(T)* is the dry matter yield at harvest, YDM_o is the initial dry matter yield (dry matter accumulation at the initial time of calculation), n is the total number of time intervals of calculations, when an interval is equal to a day, then n is the total number of days from the initial date of calculation to the date of harvest.

When the soil nutrients supply and farming measures are normal, soil moisture content is the key factor affecting the crop growth. Eq. 7 must be modified by a soil moisture factor when soil moisture stress occurred, that is

$$\frac{S(t)}{S(t-1)} = \Gamma(t) * f(AMC_t) \tag{9}$$

This is similar to the works of [16] and [17].

In eq. 9, S(t), S(t-1) are the actual relative dry matter accumulation at the initial and end of time period t respectively, $f(AMC_t)$ varies with the available soil moisture content AMC_t,

$$AMC_t = \frac{(MC_t - MC_p)}{(MC_f - MC_p)} \tag{10}$$

In which MC_t is the average soil moisture content in crop root zone at period t, MC_p, MC_f are wilting point and field capacity respectively (the moisture content values in this respect are normalized). When $MC_t > MC_f$, AMC_t takes the value 1. Comparing the eq. 9 with eq. 7, function $F(AMC_t)$ must be subjected to increasing monotonically.

By substituting eqs. 9 and 10 into eq.8, the crop dry matter yield can be written as:

$$Y = YDM_o \prod_{t-1}^{n} \Gamma(t) * f(AMC_t) \tag{11}$$

Where Y is the dry matter yield (having moisture content factor).

Except that the soil moisture stress is so severe as to cause crop to die, substituting the eqs. 6 into eq. 11, an expression for the plantain bunch yield can be obtained thus:

$$Y_b = YB_o \prod_{t-1}^{n} \Gamma(t) * f(AMC_t) + CY \tag{12}$$

Where YB_o is the plantain bunch yield potential at the initial time of calculation, *CY* is a constant.

2.3.3 Evaluation of function *F(amc$_t$)*

From the above analysis, it can be seen that $f(AMC_t)$ is not only affected by AMC_t, but also depends on $\Gamma(t)$. Here it is assumed that $f(AMC_t)$ is expressed as a function of the ratio of relative dry matter accumulation as:

$$f(AMC_t) = \Gamma(t)^{\alpha} \tag{13}$$

Where α is a parameter, which also depends on AMC_t [14].

2.3.4 α as a Piecewise Linear Function of AMC_t

(16) Used a piecewise function to describe the relationship of α and AMC_t

$$\alpha = \sigma(AMC_t) - 1 \tag{14}$$

Substituting eq. 14 into eq. 11 and eq. 12, yields

$$Y = YDM_o \prod_{t-1}^{n} \Gamma(t)^{\sigma(AMC_t)} \tag{15}$$

$$Y_b = YB_o \prod_{t-1}^{n} \Gamma(t)^{\sigma(Am_t)} + CY \tag{16}$$

Where $\alpha(AMC_t)$ is a piecewise linear function of AMC_t referred as response function of yield to available soil moisture content, and can be written as follows:

$$\sigma(AMC_t) = \begin{cases} \dfrac{a_1(T_1 - t) + a_2(t - t_1)}{T_1 - t_1} & (\mathrm{t}_1 \le t \le T_1) \\ \dfrac{a_2(T_2 - t) + a_3(t - T_1)}{T_2 - T_1} & (\mathrm{T}_1 \le t \le T_2) \\ \dfrac{a_3(T_3 - t) + a_4(t - T_2)}{t_3 - T_2} & (\mathrm{T}_2 \le t \le t_3) \end{cases} \tag{17}$$

Where t_i (i = 1, 2, 3) is the jointing value of available soil moisture content between two consecutive moisture intervals i-1 and i.

2.4 Model Calibration

2.4.1 Analysis of dry matter accumulation for musa

The dry matter accumulation for plantain, grown during the 2006/2007 and 2007/2008 shown in Figs. 1 and 2 were fitted with (a.) cubic polynomial regression function:

$$y = 5*10^{-8}x^3 - 5*10^{-5}x^2 + 0.0171x - 1.0953 \qquad R^2 = 0.9177 \tag{18}$$

And (b) 3-parameter sigmoidal function respectively.

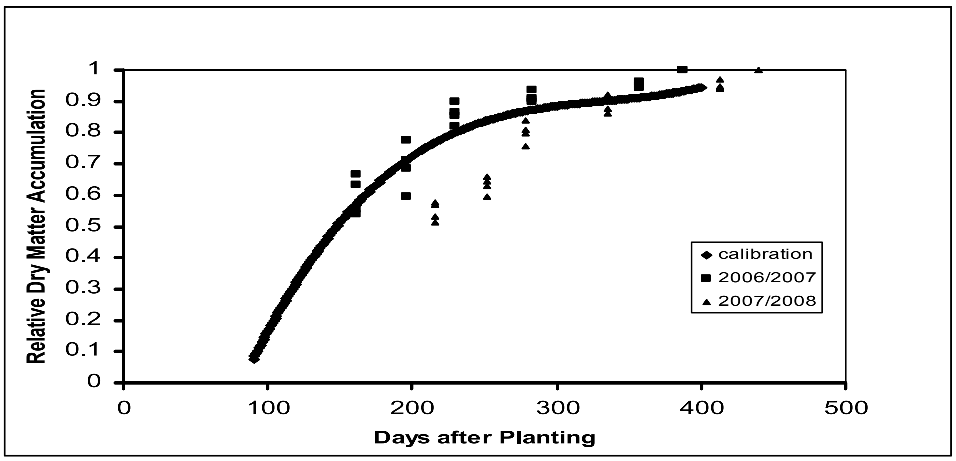

Fig. 1. Relative dry matter accumulation of plantain using polynomial function

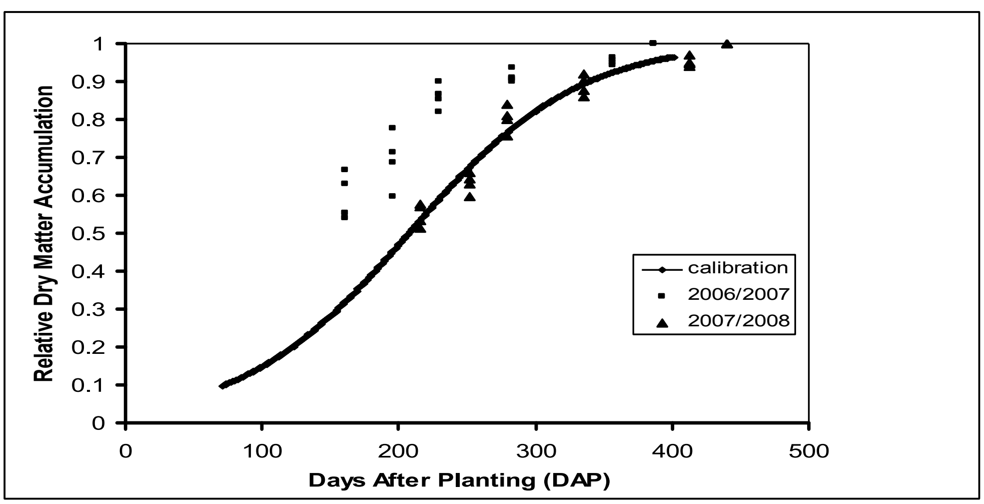

Fig. 2. Relative dry matter accumulation of plantain using 3-parameter sigmoidal function

Comparing both functions, the graphs fitted well with the polynomial model having R^2 value of 0.9177 while the 3-parameter sigmoidal model has an R^2 value of 0.9591 (see Table 5). However when the calibrated values were plotted, polynomial graph produced negative values between 1-82 days after planting which is illogical. The 3-parameter sigmoidal plot on the other hand produced positive values from day one although values were near zero at the earlier days and began to pick up as the days increase. The relative dry matter accumulation for plantain varying with time was thus calibrated with a 3-parameter sigmodal function of the form shown in eq. 5. The corresponding coefficients of a, b and x_o and other best fit solutions are shown in Table 4.

Table 4. Coefficient values and other statistical parameters for the overall best-fit for the 3-parameter sigmoidal function

R	Rsqr	Adj Rsqr	Standard Error of Estimate		
0.9793	**0.9591**	**0.9552**	**0.0359**		
Coefficient		**Std. Error**	**T**	**P**	**VIF**
A	1.0070	0.0211	47.7018	<0.0001	5.4979<
B	61.6239	7.4805	8.2379	<0.0001	6.1042<
x0	208.3285	4.2259	49.2981	<0.0001	2.3078

Putting these coefficients into equation (5) yields:

$$RDM = \frac{1.0070}{(1+\exp(-(t-208.3285)/61.2239))} \tag{19}$$

Where f =RDM (the relative dry matter accumulation of plantain, x = t (the days after planting).

According to [10,18], the process of crop growth from emergence to maturity is a dynamic process, in which the crop dry matter accumulation increases monotonically. In general the rate of dry matter accumulation has a pattern of slow-quick-slow; the rates of dry matter accumulation in the early and later stages of crop growth season being smaller than those in the middle stages. It can be found that the dry matter accumulation in 2006/2007 and 2007/2008 for plantain were approximately the same. Dry matter yield reflects the effect of soil moisture, soil nutrient, and climatic factors on crop growth throughout the growing season.

2.4.2 Dry matter yield and bunch yield

Plantain bunch yield also affected by soil moisture, soil nutrient, etc., is an important part of dry matter yield. In general, the higher was the dry matter yield, the higher was the bunch yield. The relationship between dry matter yield and bunch yield at harvest for plantain measured in 2006/2007 shown in Fig. 3 was calibrated with a linear function as follows:

$$Y_b = 0.2332Y_{dm} - 297.88 \tag{20}$$

In which Y_b, Y_{dm} are bunch yield and dry matter yield for plantain (tha^{-1}) respectively. The R^2 value for this fix was 0.9318. This is similar to the works of [10].

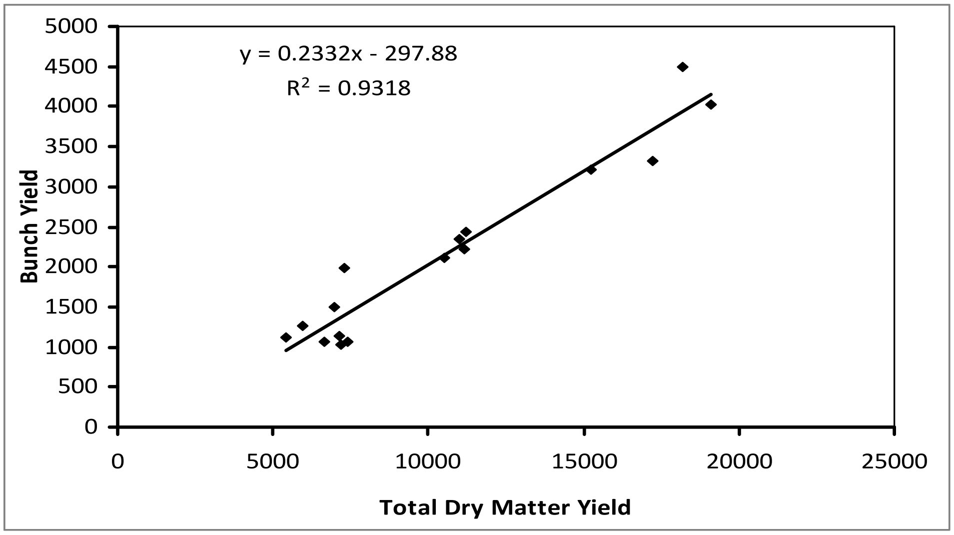

Fig. 3. Relationship between measured bunch yields and dry matter yields for plantain during 2006/07 experiment

Based on the data of soil moisture content in the root zone and data of the dry matter accumulation of the 2006/07, the parameters of the piecewise linear regression were estimated with eq. 17.

Three available soil moisture intervals of (0, 0.374), ((0.374, 0.85), (0.85, 1.0) were adopted, they represent the light moisture stress interval, medium moisture interval, and heavy moisture interval respectively. Two jointing available soil moisture content among the three intervals were 0.374 and 0.85. The parameters a_1, a_2, a_3, T_1, T_2, and T_3 are parameters of the piecewise response function σAMC_t estimated as shown in Table 5 while the relationship between σAMC_t and AMC_t can be seen from Fig. 4. The coefficient of determination (R value) is 0.804.

Table 5. Coefficients and other statistical values for the overall best-fit for piecewise regression

R		Standard error of estimate			
0.8040		**0.0921**			
Parameters	**Coefficient**	**Std. Error**	**T**	**P**	**VIF**
a1	0.1833	0.0541	3.3854	0.0011	1.1399
a2	0.2334	0.0562	4.1540	<0.0001	10.4107<
a3	0.5380	0.0306	17.6063	<0.0001	2.3718
a4	0.6946	0.0683	10.1766	<0.0001	1.1469
t1	0.3740	0.0995	3.7603	0.0003	10.7408<
t2	0.8520	0.0187	45.4506	<0.0001	2.1176

2.4.3 Analysis of variance

Uncorrected for the mean of the observations

	DF	SS	MS
Regression	6	12.1330	2.0222
Residual	74	0.6272	0.0085
Total	80	12.7602	0.1595

Corrected for the mean of the observations

	DF	SS	MS	F	P
Regression	5	1.1465	0.2293	27.0552	<0.0001
Residual	74	0.6272	0.0085		
Total	79	1.7737	0.0225		

The above calibrated response function is for the whole growth season of plantain. It could be observed from the graph that crop sensitivity to moisture is distinctive throughout the growth stages of plantain. Any moisture stress occurring at any of the growth stage of the crop may considerably influence the dry matter yield or bunch yield.

2.4.4 Model validation

According to the data of moisture content in root zone measured in 2006/2007 and 2007/2008, the bunch yields were predicted for 2007/2008 as shown in Fig. 5 using the dynamic crop water production function model (Eq. 16) for alpha being piecewise linear function . The bunch yields predicted by the model agree well with those measured, with R^2 value being 0.8449.

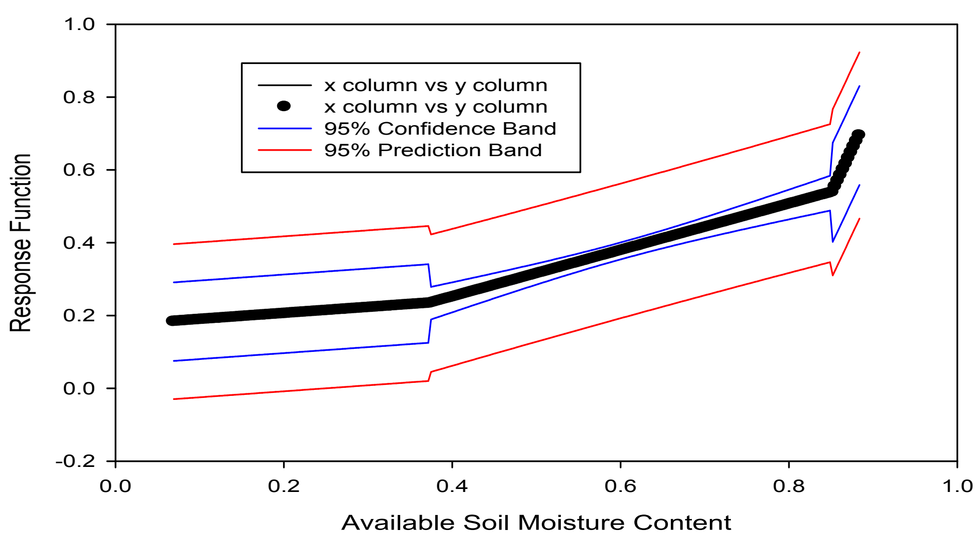

Fig. 4. Piecewise linear function of whole growth season for plantain

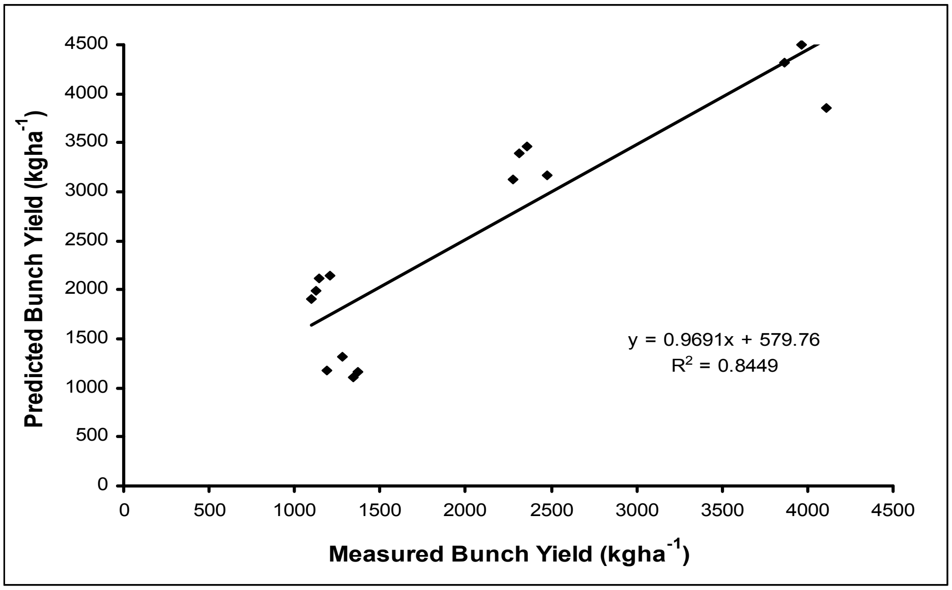

Fig. 5. Comparison of the measured and predicted bunch yields for plantain. Yields predicted with model (16) for alpha being piecewise linear function for whole growth season

The dynamic crop water production function model can also be used to evaluate bunch yield under different water supply conditions.

3. CONCLUSION

The dynamic crop response model presented here can be estimated without elaborate data collection procedures. The model estimated here was used to predict the effects of various irrigation schedules. The predicted results indicate that the above empirical dynamic crop-water production function model is capable of predicting the bunch yields in years with different moisture stress levels.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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