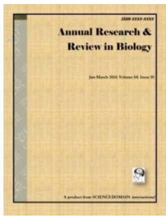

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Growth and Water-Yield Functions of Dry-Season Fadama-Grown Pepper (*Capsicum annuum* L.) Under Differential Irrigation in a Rainforest Zone of Nigeria

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Authors' contributions

This work was carried out in collaboration between all authors. Author SOA conceived of the study, and participated in its design and coordination and helped to draft the manuscript. Author IAA carried out the field study, soil and plant analysis, statistical analysis and helped to draft the manuscript. Authors IBF and SKO participated in the design of the study and performed the statistical analysis and helped to draft the manuscript. All authors read and approved the final manuscript.

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ABSTRACT

Field experiments were conducted to assess the effects of differential irrigation on the growth, stress development and water- yield functions of dry season fadama-grown pepper in a humid rainforest zone of Nigeria. The aims were to characterize water productivity of pepper (crop yield production functions) and develop the drought response factor K_y in relation to irrigation (*Ir*) and total crop water-use (ETc). Four irrigation treatments were studied based on the restoration of depleted soil moisture (the levels of cumulative pan evaporation: Epan). These were 100%, 80%, 60%, and 40% of EPan which indicate relative water deficit of 0, 0.2, 0.4 and 0.6 respectively in order to attain maximum and minimum plant water stress conditions. Irrigation was fixed at 5 days-interval at EPan coefficient (Kcp) of 0.70 and accumulated pan evaporation. The amount at each irrigation and seasonal sum of irrigation were 4.82 l/day; 127500 mm and 1.93 l/day; 20400 mm for the respective well irrigated control (DI_1) and the more stressfull (DI_4) treatment. Fruit yields of

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pepper plants declined with increasing soil moisture deficits. Highest fruit yields were obtained under the well watered control (DI_1; 11.2 t/ha) and lowest under the highest deficit irrigation (DI_4; 7.1 $t.ha^{-1}$). Maximum water use efficiencies (IWUE and WUE) were observed in $D1_1$ (0.88 and 1.52 kg. m^{-3}) and minimum in $D1_4$ treatments (2.73 and 1.33 kg. m^{-3}). The values of irrigation and crop water use (evapotranspiration) efficiencies were (IWUE; 0.80, 1.12, 1.81 and 2.73; WUE (ET_E;); 1.34, 1.54, 1.56 and 1.61 mm of water per ton dry matter respectively. The moisture stress sensitivity indices (drought response factor, k_y) were computed from a: the relative yield (Ya/Ym) and the relative evapotranspiration (ETa/ETm) and b: relative yield (Ya/Ym) and soil moisture deficit (SAWa/SAWm) relationships of the water production models. The mean ky were 0.92 and 2.25 for the respective a and b models and 1.79 and 2.30 for the respective DI_2 and DI_4 treatments. The results indicated that the adopted models (a and b) are valid to be used to predict pepper yield under different irrigation applications.

Keywords: Drought response factor; water productivity; irrigation; pan evaporation; pepper.

1. INTRODUCTION

In the humid tropics, the soil and water resources of inland valley swamps (inland floodplains) is important to the attainment of year round production (food and nutritional security) of crops especially vegetables. The agricultural potentials of tropical inland wetlands/flood plains (Fadama ecosystem) can be harnessed for improved agricultural livelihoods and contribute to productive wetland based farming via management of soil and water resources. It is imperative therefore, to develop management guidelines for sustainable exploitation of soil and water resources of inland valley swamps to meet year round crop production and for the attainment of food and nutritional security, improved agricultural livelihoods and contribute to productive wetland based farming. There is inadequate information on the management of soil and water resources of inland wetlands/flood plains via irrigation strategies for enhancing water productivity of dry season fadama grown vegetables especially pepper.

Crop yield completely depends on the available moisture to crops if climatic and agronomic conditions are adequate. There are strong relationships between crop yield and water use. Under normal condition, when environmental conditions do not restrict crop production, crop yield is at maximum when the crop water requirement is met [1].

Certain growth stages of crops are more sensitive to water deficits than others. In fruit vegetable crops, the vegetative and flowering stages are very sensitive to water deficit [1,2]. Crop water use depends mainly on the climate and the soil conditions of an area. The efficient use of evapotranspiration data in solving irrigation problems requires a satisfactory characterization of the effective soil moisture reserve or storage. Crop evapotranspiration (consumptive water use; ET) is the sum total of water lost through transpiration by crop and evaporation from the soil or exterior portion of the plant where water may have accumulated.

Crop water use efficiency (WUE) can be calculated as the ratio between total yield harvested (kg/ha) and crop evapotranspiration (ETc) as calculated using pan evaporation and also from the ratio between marketable yield (kg/ha) and crop evapotranspiration (ETc). Irrigation water use efficiency (IWUE) can be calculated as the ratio between total yield harvested (kg/ha) and total volume of irrigation water applied [1,3]. The knowledge of marginal productivity of water allocated to a crop is required in order to arrive at an optimal set of decision making with regard to irrigation water management.

The relationship between crop yield and water use is called the yield response factor (water production function). Numerous attempts have been made to develop production functions for irrigated crops. One of the most comprehensive studies of yield and transpiration relationship using wide range of data collected for common field crop grown in containers by De Wit [4]. The determination of crop water production function for a specific location is recommended [5,1,3]. Two approaches are adopted in the estimation of crop-water production function in literature. The approaches are based on the assumption that crop yields are directly influenced by quantity of the irrigation water applied and used by the crop (ETa). One approach synthesizes production functions from theoretical and empirical models of individual components of the crop water process [5,2]. The second approach estimates production functions by statistical inference from observations of the effect of different water applications on crop yield [6]. This approach estimates direct relationships between irrigation water applied and crop yield.

Regression analysis are also commonly used to evaluate the water use-yield relationships (yield response factor: ky) derived from seasonal crop evapotranspiration and yield data obtained from experiments. Crop water use function (known as crop yield water use models) in which crop yield is related to water inputs, provides the needed information for scheduling irrigation that promises a high economic return.

The yield response to water deficit for different crops is of major importance in production planning. The yield response factor (water production function) had been frequently used in the scheduling available but limited water supply in order to obtain highest yields [1,7,8]. The water production function is a useful input in planning, design and operation of irrigation projects and allows the quantification of water supply and water use in terms of crop yield and total production for the project area.

Crop water production function is expressed on a relative basis where actual yield (Ya) is divided by maximum yield under a given management condition (Ym) and actual evaportanspiration (ETa) is divided by crop evapotranspiration for non-limiting water condition (ETm). Doorenbos and Kassam [1] developed the most simple and common used model for quantifying water productivity. The yield response factor (ky) also represent the relationship between relative yield reduction [1- (Ya /Ym)] and relative evapotranspiration deficit [1-(ETa/ETm)].

$$\left(1-\frac{Ya}{Ym}\right) = ky\left(1-\frac{ETa}{ETm}\right) \quad (1)$$

Where, ETa and ETm are the actual and maximum seasonal crop evapotranspiration values (mm), respectively, and Ya and Ym are the corresponding actual and maximum yields (kg ha^{-1}) and ky is the yield response factor to water deficit.

Mathematical models such as Penman-Monteith are useful in the calculation of crop evapotranspiration (ETa) in water productivity models. The evapotranspiration models such as the FAO Penman-Monteith combination equations [9] are based on real-time weather data to be obtained from weather station close to a field. It means that crop evapotranspiration cannot be estimated in cases where no weather station close to a field. The seasonal values of the yield response factor (ky) can also be quantified using a modified version of FAO model for quantifying water productivity [10]. The modified model uses soil moisture data instead of meteorological data.

$$\left(1-\frac{Ya}{Ym}\right) = ky\left(1-\frac{SAWa}{SAWm}\right) \quad (2)$$

Where, SWa and SWm are the actual and maximum sea-sonal avaialble soil water (mm), respectively, and Ya and Ym are the corresponding actual and maximum yields (kg ha^{-1}) and Ky is the yield response factor.

The parameters to be estimated are the stress sensitivity factors (water yield function; ky) for a particular growth phase of the entire growth cycle.

Water stress is imposed at a given period by withholding irrigation either during a specific growth phase or entirely during growth in order to quantify threshold of crop water stress sensitivity indices. Crop water stress sensitivity indices is measured as the evapotranspiration deficit relative to the evapotranspiration of the non-stress treatment, and the maximum seasonal yield (Ym) is usually associated with the scheduling treatment that satisfies maximum evapotranspiration rate, which also accumulates the maximum seasonal evapotranspiration (ETm) [2,1].

Scarcity of water resources and growing competition for water in many sectors reduce its availability for irrigation hence the need for approaches to develop efficient management of water for crop production. Achieving efficient and effective use of water may be achieved via increased crop water productivity (WP) and drought tolerance either by genetic improvement or physiological regulation [11]. But only high water productivity values carry little or no interest if they are not associated with high or acceptable yields [11]. Thus, in the circumstances of increasing challenge of producing more food and fiber with limited or even reduced available water, it is imperative to improve the understanding of the factors affecting water productivity and the possible techniques for its improvement.

The effects of deficit irrigation on growth, yield, stress development and water-yield functions of dry season fadama-grown pepper (*Capsicum annuum* L.) in the rainforest zone of Nigeria was investigated. Four irrigation treatments based on the restoration of depleted soil moisture via evapotranspiration (ETa) were studied. Differential irrigation was therefore designed to evaluate pepper's response to irrigation applications, and to evaluate water- yield functions and the threshold of crop water stress sensitivity indices to schedule irrigation for pepper.

2. MATERIALS AND METHODS

A field experiment was conducted as part of a wide research programme to assess the effects of differential irrigation on the productivity of pepper in a humid tropical environment. The study was carried out in an inland valley swamp (inland flood plain) within the Teaching and Research Farm of the Federal University of Technology, Akure (7°51'N; 15°101'E), A rainforest zone of Nigeria. Irrigation was fixed at 5 days-interval at EPan coefficient (Kcp) of 0.70 based on the restoration of cumulative pan evaporation (EPan) [12,9,13]. The irrigation treatments examined were based on the restoration of depleted soil moisture via evapotranspiration (ETa) were studied between January to May, 2010 and 2011 respectively. Four levels of irrigation based on the restoration accumulated EPan were imposed. These were 100%, 80%, 60%, and 40% of EPan which indicate relative water deficit of 0, 0.2, 0.4 and 0.6 respectively in order to attain maximum and minimum plant water stress conditions. Pepper plants were therefore drip-irrigated based on levels of cumulative pan evaporation (Epan) values of 1.0 Epan (DI_1), 0.8 Epan (DI_2), 0.60 Epan (DI_3) and 0.40 Epan (DI_4). The amount of irrigation at each event and seasonal sum of irrigation amount were (4.82 l/day; 127500mm) and (1.93 l/day; 20400mm) for the respective well irrigated control (DI_1) and the more stressfull (DI_4) treatment. Treatment DI_4 had the maximum water deficit and was used to determine the fully stressed baseline while DI_1 suggest that the irrigation water applied was adequate to meet the full crop water requirements was selected in order to determine non-crop water stressed baseline.

The soil of the site of experiment is sandy-clay-loam with relatively high water holding capacity. Available soil water in the upper 0.60 m of the soil depth is 187mm. the percent soil moisture contents at field capacity and permanent wilting point are 21 and 10 % respectively. Mean bulk density was 1.25g.cm^{-3}.

One plant-pan coefficient was evaluated to determine the irrigation levels (K_{cp} = 0.70).

$$E_{Pan} * K_{cp} = ETO \tag{3}$$

Where Epan is Pan evaporation, kcp is pan coefficient

Daily irrigation amount (I_{amt}) was calculated as:

$$I_{amt} = K_{cp} * EPan * \text{irrigation interval (days)}$$

Where K_{cp} is pan coefficient and EPan is Pan evaporation. This corresponded to 7.14 mm (1.93 l/day), 10.7 mm (2.90 l/day), 14.28mm (3.86 l/day) and 17.85 mm (4.82 l/day) for the respective 0.4, 0.6, 0.8 and 1.0 EPan. The total amount (volume) of irrigation water applied per treatment was calculated using equation:

$$V = P * A * EPan * DI \tag{4}$$

Where, V, is the volume of irrigation water (L); P, wetting percentage (taken as 100 % for row crops); A, is plot area (m^2); $E_{pan,}$ the amount of cumulative evaporation during an irrigation interval (mm); DI, irrigation levels (0.40, 0.6, 0.8 and 1.0 EPan). Irrigations occurred on the respective treatments when Epan reached target values.

In order to attain good plant stand, a pre-treatment total of 135 mm of irrigation water was applied equally to all treatment plots in several applications. Thus soil water in the 0.60 m profile depth was replenished to field capacity in all treatments. The differential irrigation treatments which commenced on January 15th following the pre-treatments of 4.82 l/day for 4 days, was terminated on 10th of May, 2011. The amount of water applied per irrigation and seasonal irrigation amount varied from a maximum of 4.82 l/day and 127500 mm (DI_1 level) to a minimum of 1.93 l/day and 20400 mm (DI_4 level). Irrigations continued until one week before the final harvest.

Class-A evaporation pan (121 cm in diameter and 25.5 cm in depth) was used to determine evaporation during pepper growth cycle. Daily crop evapotranspiration was estimated using the pan evaporation data, pan factor and crop coefficient [14,12]. A drip irrigation system which supplied water to plant roots via drippers was used. One drip lateral served each plant row. Single drip lateral line was laid for each plant row, and inline emitters with discharge rate of 2 L h^{-1} were spaced at 0.40 m intervals on the lateral. The system was operated at 150 kPa throughout the growing season. A totalizing inflow meter was installed at the control unit to measure total flow distributed to all replications in each treatment.

Actual crop evapotranspiration (ET) of pepper plants under varying irrigation amounts was calculated with the water balance equation (equation 5) [2,15].

$$ET = I + P + \Delta S - Dp - Rf \quad (5)$$

Where, ET, is actual crop evapotranspiration (mm); I, the amount of irrigation water applied (mm); P, the precipitation (mm); ΔS, changes in the soil water content (mm); Dp, the deep percolation (mm); Rf, amount of runoff (mm). Since the amount of irrigation water was controlled, deep percolation and run off were assumed to be negligible.

2.1 Soil Moisture Determination

Soil water content was measured within the top soil layer (0 - 20 cm) by gravimetric method and at fortnight interval during pepper growth. Soil sample were taken from four sampling points per treatment and within the 0 – 20 cm depth for the determination of the moisture content using soil auger. As earlier assumed, soil moisture content would attain field capacity in two days since the soil is sandy clay to silty clay loam [15]. The samples were taken two days after and just before the next irrigation. The difference in moisture content between the two sampling periods was taken to be the moisture used. That is, the evapotranspiration by the crop for that period. Since it was assumed that drainage was negligible (no drainage), the moisture change was principally attributed to evapotranspiration.

2.2 Crop Yield as a Function of Water Use (Yield Versus Water Deficit) and Water Yield Functions

Seasonal values of the yield response factor (ky), which represent the relationship between relative yield reduction [1- (Ya /Ym)] and relative evapotranspiration deficit [1-(ETa/ETm)]. The yield response factor (ky) was therefore determined using equation 1 as: [1- (Ya /Ym)] = ky [1-(ETa/ETm)] (after 1) where, ETa and ETm are the actual and maximum sea-sonal crop evapotranspiration values (mm), respectively, and Ya and Ym are the corresponding actual and maximum yields (kg ha^{-1}) and ky is the yield response factor to water deficit.

The seasonal values of the yield response factor (ky) was also quantified using a modified version of FAO model for quantifying water productivity from the relationship between relative yield reduction [1- (Ya /Ym)] and relative soil water deficit [1-(SAWa/SAWm)]. The yield response factor (ky) was determined using equation 2 as: [1- (Ya /Ym)] = ky [1-(SAWa/SAWm)] after[10] where, SWa and SWm are the actual and maximum sea-sonal avaialble soil water (mm), respectively, and Ya and Ym are the corresponding actual and maximum yields (kg ha^{-1}) and Ky is the yield response factor. The modified model uses soil moisture data instead of meteorological data and the model was validated using dry season grown pepper in an inland swam (inland flood plain). For both models (equation 1 and 2), the relative yield (Ya/Ym) and the relative evapotranspiration/soil moisture deficit (ETa/ETm; SAWa/SAWm) terms of the models were obtained from the yields and evapotranspiration measured data while the stress sensitivity factor for the model was obtained by using multiple linear regression technique.

2.3 Irrigation (IWUE) and Crop Water Use (WUE) Efficiencies

Water use efficiency (WUE, kg/m3) can be calculated as the ratio between total yield harvested (kg/ha) and crop evapotranspiration (ETc, m^3/ha, as calculated using pan evaporation) and also from the ratio between marketable yield (kg/ha) and crop evapotranspiration (ETc). Irrigation water use efficiency (IWUE) can also be calculated as the ratio between total yield harvested (kg/ha) and total volume of irrigation water applied (mm). Water use efficiency (WUE) and irrigation water use efficiency (IWUE) was calculated as crop yield divided by seasonal crop evapotranspiration (ET) and total seasonal irrigation water applied, respectively [15].

Data collected were subjected to analysis of variance (ANOVA) while significant treatment means were separated using the Least Significance Difference (LSD) test at 5% level of probability. The results of each year's experiment were separately analyzed, and were not significantly different from one year to the other. Therefore, data collected o for the two-years of study were averaged and means are presented in tables and figures in the text.

3. RESULTS AND DISCUSSION

3.1 Weather Condition of the Site of Study

The weather conditions at site of study during pepper growth is shown in Fig. 1. November marks the onset of the dry season which span December of a year to April of the following year. The period of experiment (January to May) falls within the dry season which is characterized by low amount of rainfall from transplanting to fruit filling (1 - 10 weeks after transplanting, WAT) while the average temperature was 29°C with high air vapour pressure deficits.

3.2 Trends of the Soil Profile Moisture

The changes in profile (0 -20 cm depth) soil water storage during pepper growth for each irrigation level in comparison with field capacity and permanent wilting moisture contents is shown in Fig. 2. Across the irrigation treatments, soil water contents in the 0.60 m soil depth were kept fairly constant until 15 days after transplanting (DAT) during which 0.60 m depth was replenished to field capacity in all treatments, before the commencement of the differential irrigation treatments. The differential irrigation commenced on 15th January, 2011, thereafter, available soil water varied under the different irrigation levels. In the non-water stress (DI_1) treatment soil water contents remained fairly high as compared to water stress treatments (DI_3 and DI_4). Available soil water in DI_1 and DI_2 treatment plots remained above 50% throughout the growing season In the water stress treatments (DI_3 and DI_4) available water fell below 50% after 40 DAT during the growing season and hence the resultant lower yield presumably due to moisture stress occurring prior to flowering. Soil water contents in the 0.60 m profile decreased gradually from DAT 17 until 90 DAT then started to increase slightly until harvest period in growing seasons. The period at the beginning of the flowering period is most sensitive to water shortage and soil water depletion in the root zone during this period should not exceed 25%. For high yields, an adequate water supply and relatively moist soils are required during the total growing period.

Good water management practice is important at all stages of plant development due to the influence of water on establishment and yield [14,2]. Reduction in water supply during the growing period in general has adverse effect on yield and the greatest reduction in yield occurs when there is a continuous water shortage until commencement of fruit harvest [16]. Water shortage just prior and during early flowering reduces the number of fruits [1]. Jones et al. [17] stated that water deficit during this period would have the greatest negative impact on yield and quality. Optimum soil water content during flowering was at 60% of the available water and that either higher or lower water content resulted in suboptimal fruit yields. Soil water should be maintained between 65 and 80% of field capacity [17]. The gradually increasing water stress in the lower irrigation treatments caused significant reductions in fruit yield, whereas higher levels of irrigation created a favourable soil water environment for pepper growth resulting in higher yields [18].

3.3 Pepper Growth and Fruit Yield Characters

The occurrence of 50% flowering stage of pepper was earlier dates in the lower irrigation levels (DI_3 and DI_4) compared with the unstressed treatment (DI_1) (Table 1). This was most probably due to the lowest amount of irrigation water applied in this treatment. Irrigation levels significantly affected fruit yield of pepper. This observation agrees with those of [19] on onion and [20] on cucumber. As the irrigation level decreased pepper yields decreased significantly, the highest yield averaging, 11.2 t. ha^{-1}, was obtained in DI_1 and followed by declining order DI_2 (9.1 t. ha^{-1}), DI_3 (8.3 t. h a^{-1}) and the lowest minimum in DI_4 (7.6 t.ha^{-1}). Duncan grouping of pepper yields from the treatments indicated that yield from highest irrigation level (DI_1) was in the first group. Thus, an irrigation level of 0.4EPan (1.93 l/day) was found to be unsuitable for drip-irrigated pepper in the study area. Patanè et al. [21] assessed the effects of deficit irrigation upon water productivity and final biomass of pepper. Their results recommended 50% reduction of ET application to save water, improving pepper use efficiency, minimizing fruit losses and maintaining high fruit quality levels.

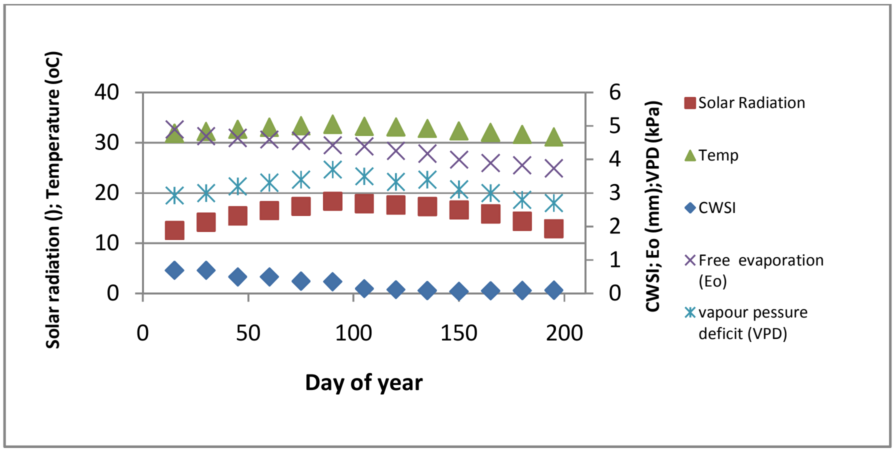

Fig. 1. Weather conditions during peper growth

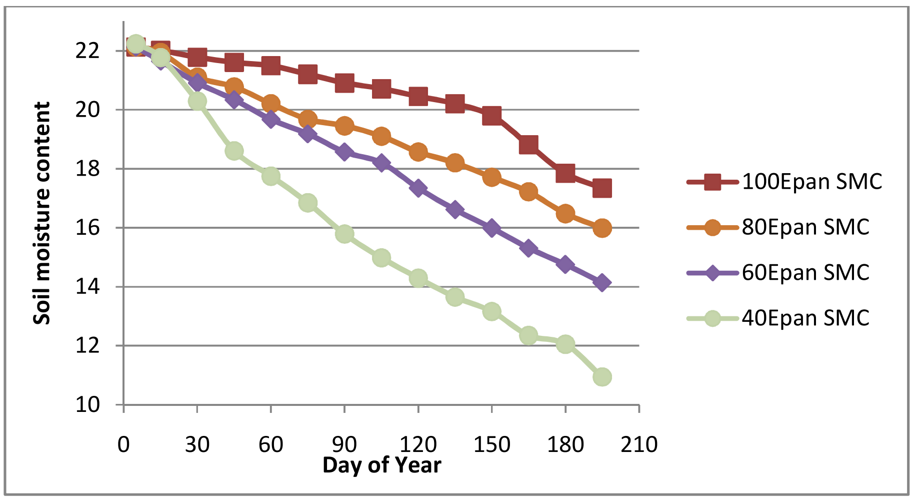

Fig. 2. Irrigation effects on the time trends of soil mositure storage during pepper growth

Table 1. Growth and yield characters of pepper as affected by irrigation levels

Irrigation regimes	Root length (cm)	Root dry weight (g)	Shoot dry weight (g)	Leaf area (cm^2)	Days to 50% flowering	No. of fruits harvested	Fruit yield (t/ha)	Harvest index
100 EPan	17.8	26.5	143.2	0.19	72	35	11.2	0.53
80 EPan	19.3	32.8	137,7	0.15	68	31	9.1	0.55
60 EPan	22.9	37.6	132.3	0.10	65	28	8.3	0.56
40 EPan	25.4	41.4	128.9	0.07	62	26	7.6	0.57
LSD (0.05)	3.7	6.4	5.1	0.04	4.1	1.8	2.1	0.03

3.4 Crop Evapotranspiration, Efficiencies of Irrigation and Crop Water Use and Crop Production Functions (ky: Yield Reduction – Evapotranspiration/Soil Moisture Deficit Relationships)

The trends in crop water use (ETa) which was determined using the water budget method is presented in Fig. 3. The values of seasonal crop water use (ETa) varied between 621 and 515 mm (Table 2). The highest seasonal evapotranspiration was recorded for the reference treatment (DI_1; higher amount of irrigation 612 mm) while the least was recorded for the highest water stress treatment (DI_4; limited irrigation 516 mm). Under the limited irrigation treatments, pepper plants had access to less available moisture in the rootzone than their requirements. The recorded values of seasonal evapotranspiration in the reference and in the water stress treatments were however higher than the range of seasonal water consumption for pepper given as 480 – 530 mm [13].

The levels of irrigation imposed significantly affected crop water use (WUE) and irrigation use (IWUE) efficiencies values (Table 2). Crop water use efficiency (WUE) values ranged from 1.34 g m^{-3} in DI_1 to 1.37 kg m^{-3} in the DI_4. Irrigation use efficiency (IWUE) decreased with increasing irrigation level, the values varied from a minimum of 0.88 kg m^{-3} in DI_1 to a maximum of 2.73 kg m^{-3} in DI_4. In general, water use efficiency on fresh yield basis increased under the more deficit irrigation (DI_1) and thus it decreased with increasing irrigation levels. Both the crop water use and irrigation use efficiencies values increased with increasing irrigation level. Dukes et al. [22] reported higher IWUE values for drip-irrigated pepper ranging from 16.0 to 52.6 kg m^{-3} for marketable yields in Florida, USA. Karam et al. [23] Reported WUE values for fresh pepper yield ranging from 5.9 to 7.8 kg m^{-3}.

The trends in the relationships between yield and the efficiencies of irrigation (IWUE) and crop water use (WUE) is presented in Fig. 4 and 5 The relationships between yield and the efficiencies of irrigation use (IWUE) as $y = -0.02x + 1.41$, $R^2 = 0.98$, and crop water use (WUE) as $y = -0.07x + 3.96$, $R^2 = 0.97$.

The effect of differential irrigation on pepper yield was quantified as the relationship between relative yield decrease and the relative evapotranspiration or soil moisture deficits deficit. The relationship gave the empirically derived yield response factor (the crop water production function; ky). Table 2 presents the percent yield, yield reduction and seasonal evapotranspiration and soil moisture deficit as measured from the experimental plot. The crop water production function relative values of K_y increased as soil moisture deficit stresses increased. For the respective a: (1 – (Ya/Ym) = ky (1 – (ETa/ETm) and b: (1 – (Ya/Ym) = ky 1 – SAWa/SAWm) models, the values of water production function (ky) were 0.84, 0.93 and 0.98 and 1.79, 2.30 and 2.60 for the DI_2, DI_3 and DI_4 while the mean ky values across irrigation levels were 0.92 and 2.25 for the respective a and b models .The yield response factor for pepper obtained from the two (a and b) models were close to those obtained by Datta et al [24] and Sezen et al. [13]. The relationships between relative yield decrease (1 – Ya/Ym) and relative evapotranspiration (1 – ETa/ETm) and between relative yield decrease (1 – Ya/Ym) and soil moisture deficit (1 – SAWa/SAWm).

The yield response factor (ky), which is the slope of the relative ET deficit versus relative yield reduction relation, for pepper was found to be 1.08 whole growing season Doorenbos and Kassam [1] reported the yield response factor for pepper as 1.1 for whole growing season. Sezen et al. [13] obtained Ky factor of 1.14 in Turkey. These values are similar to our findings. Treatment DI_4 had higher response values and appeared to suffer greater yield loss than those with a lower values (DI_1). The yield response to water deficit of different crops is of major importance in production planning and also important in the scheduling of available but limited water supply in order to obtain highest yields [1].

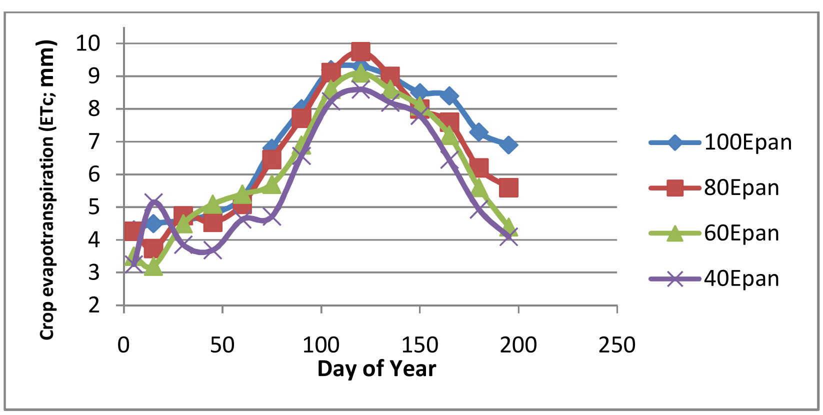

Fig. 3. Irrigation effects on the time trends in crop water use (ETa) during pepper growth

Table 2. Irrigation effects on fruit yield, crop evapotranspiration and efficiencies of irrigation and crop water use of pepper

Irrigation levels	Seasonal irrigation (mm)	Relative irrigation (%)	Crop ET (mm)	Relative ET (%)	Fruit yield	Water-yield function (ky)	Irrigation water use efficiency (Kg/ha/mm)	Crop water use efficiency (Kg/ha/mm)
100 EPan	127500 (4.82 l/day)	1.0	621.0	11.2	100	1.89 (1.79)*	0.88	1.52
80 EPan	81600 (3.86 l/day)	0.8	594.0	9.1	0.82	1.48 (2.60)*	1.12	1.39
60 EPan	45900 (2.90 l/day)	0.6	552.6	8.3	0.74	1.48 (2.28)*	1.81	1.35
40 EPan	20400 (1.93 l/day)	0.4	515.7	7.6	0.68	1.15 (2.28)*	2.73	1.33

**Values in brackets are the stress sensitivity factor (ky) for b model (1 – (Ya/Ym) = ky 1 – SAWa/SAWm)*

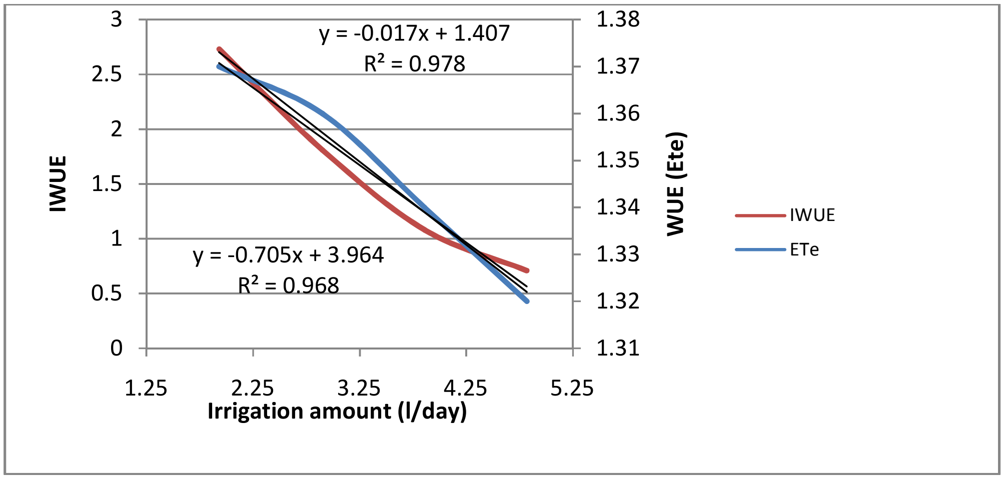

Fig. 4. Irrigation effects on efficiencies of irrigation and crop water use

Crop water production functions are very useful in determining irrigation strategies when water supply is limited. The determination of crop water production function for a specific location is recommended [25,1,3].

The yield reduction versus evapotranspiration deficit function was obtained as:

$$(1 - Ya/Ym) = 3.5743(1 - ETa/ETm) + 0.0832; \quad R^2 = 0.8935 \qquad (7)$$

The yield reduction versus soil available moisture deficit function was obtained as:

$$(1 - Ya/Ym) = 3.5743(1 - SAWa/SAWm) + 0.0832; \quad R^2 = 0.8935 \qquad (8)$$

It would be observed that the equations are close and linear which shows direct proportionality between relative yield and relative seasonal evapotranspiration. However, the relationship between relative yield and relative seasonal evapotranspiration is not strictly or entirely proportionate as to give a 1:1 fit graph that would have passed through the origin hence the intercept of 0.0832 which for practical purposes can be considered very small and real zero. This supports Hillel and Guron [26,27] argument on yield and evapotranspiration relationship. In some cases, the Ky values were more than one, which indicate the high sensitivity of pepper to soil moisture deficits. Allen et al. [9] found that the relationship considers only water stress as the factor affecting crop yield and assumes the other factors affecting crop yield as fixed. Moutonnet [28] found that when good environmental conditions are exist the slope is steeper than unfavorable conditions. Also, Rhoads and Bennet [29] indicated that soil physical properties and soil water contents directly affect evaporation from the soil and indirectly regulate crop transpiration through their influence on crop water status. The results indicated that both models adopted ((1 – Ya/Ym) = ky (1 – ETa/ETm); (1 – Ya/Ym) = ky (1 – SAWa/SAWm) are valid to be used to predict pepper yield under different irrigation applications. Omran [13] studied the relation between yield reduction and water deficit using two models depicted in equation 1 and 2, and concluded that both models and for scheduling irrigation based on crop evapotranspiration and soil moisture measurements. Therefore, it could be concluded that monitoring soil moisture content is relatively easier and reliable than ET calculated by mathematical models using a large number of meteorological data.

Linear relationships were found between yield and evapotranspiration, and also that between yield reduction and evapotranspiration/soil moisture deficits. These findings are in agreement with those of [1,24,30,13]. Based on the range of levels of irrigation application (0.4 to 1.0 EPan) evaluated, the results show that applying water more than 100% of soil available water is not logic from economic view, because it causes water losses without any improve in obtained yield [19,31]. Also, applying water less than 40% of available water causes potential reduction of crop yield and the relationship will change from linear to non-linear [32]. Moutonet [28] found that the linear relationship of the FAO crop response model is only valid within 50 percent water deficit, for most crops.

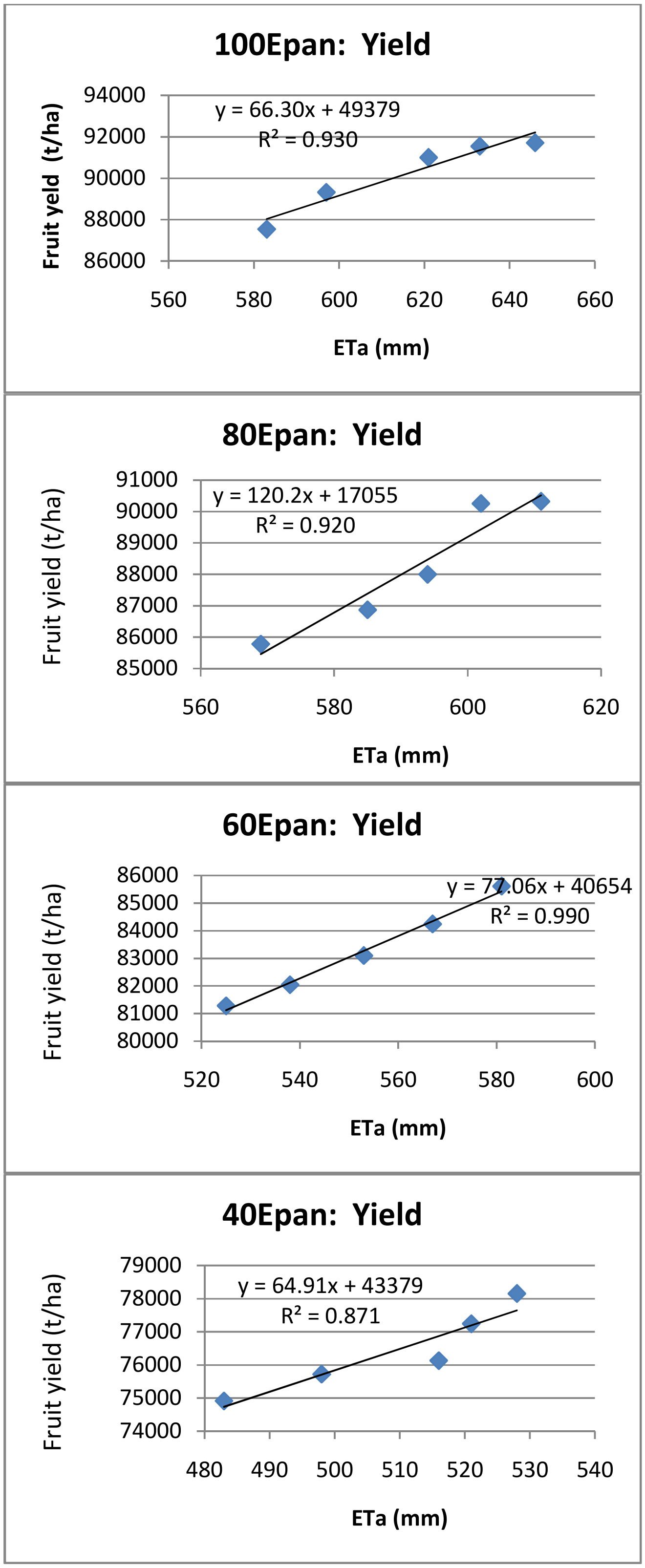

Fig. 5. Relationships between seasonal crop water use (ETa) and yield of pepper

The maximum fruit yield (Ym) is usually associated with the scheduling treatment that satisfies maximum evapotranspiration rate which also accumulates the maximum seasonal evapotranspiration (ETm) [2,1,25].

4. CONCLUSION

This study was conducted as part of a wide research programme to assess the effects of differential irrigation on the productivity of pepper in a humid tropical environment. The results showed that differential irrigation affected growth, water - yield functions and stress development of dry season pepper grown in an inland swamp (inland floodplain). The amount of irrigation at each event and seasonal sum of irrigation amount were 4.82 l/day; 127500 mm and 1.93 l/day; 20400 mm for the respective well irrigated control (DI_1) and the most stressfull (DI_4) treatment. Seasonal crop evapotranspiration (ETc) (including the contribution from soil water storage) were 612 and 516 mm for the respective reference treatment (well irrigated control; DI_1) and the highest water stress treatment (limited irrigation; DI_4). Fruit yields of pepper plants declined with increasing soil moisture deficits. Highest fruit yields were obtained under the well watered control (DI_1; 11.2 $t.ha^{-1}$) and lowest under the highest deficit irrigation (DI_4; 7.6 $t.ha^{-1}$). Maximum water use efficiencies (IWUE and WUE) were observed in DI_1 (0.72 and 1.34 kg m^{-3}) and minimum in DI_4 treatments (2.73 and 1.37 kg m^{-3}) crop water sensitivity indices (ky) were 1.79 and 2.30 for the respective DI_2 and DI_4 treatments. The values of irrigation and crop water use (evapotranspiration) efficiencies were (IWUE; 0.72, 0.1.08, 1.81 and 2.73; WUE (ET_E;); 1.34, 1.54, 1.56 and 1.61 mm of water per ton dry matter respectively. The effect of differential irrigation on pepper yield was quantified via the moisture stress sensitivity indices (drought response factor, K_y) from the relative yield (Ya/Ym) and the relative evapotranspiration (ETa/ETm) and relative yield (Ya/Ym) and soil moisture deficit (SAWa/SAWm) relationships of the water production models. The stress sensitivity factor (ky) for each model was obtained by using multiple linear regression technique. The mean values of water production function (ky) were 0.92 and 2.25 for the respective (a:1 – (Ya/Ym) = ky (1 – (ETa/ETm) and (b: 1 – (Ya/Ym) = ky 1 – SAWa/SAWm) models. The results indicated that the adopted models (a and b) are valid to be used to predict pepper yield under different irrigation applications. Regression equations were worked out between yield of pepper and seasonal evapotranspiration, and between irrigation and the efficiencies of crop water (WUE) and irrigation use (IWUE). The crop water stress sensitivity index that was developed is useful in fruit yield monitoring and can thus be used as tool for enhancing the precision of irrigation scheduling and for integration into agricultural water use models.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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