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Evapotranspiration, Water Use Efficiency and Yield of Rainfed and Irrigated Tomato

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ABSTRACT

Field experiments were conducted to examine the variability in the pattern of water use (ET), water use efficiency and fruit yield of field grown rainfed and irrigated tomato during the late (post-rainy) sowing season in a humid zone of Nigeria. The annual pattern of rainfall and rainfed potential production of crops showed that the dry (post) rainy season is characterized by water adequacy index (Ao), which was calculated from rainfall and ETo ranging from 0.01 - 0.33 (Dec - March), The late sowing season falls within August-December (Ao < 0.34) ending in a terminal drought situation while the wet/rainy season falls season falls between March/April to July with an Ao ranging from 0.34 to 1.0. The mean seasonal values of SE, Tr, ETa were 37.6, 38.5, 73.8 and 25.1, 25.8, 53.2 mm for the respective rainfed and irrigated tomato. Mean seasonal soil water evaporation (SE) ranges from 37 and 11 mm. day^{-1} which constituted 5.6 and 14.4% of ETa for the respective rainfed and irrigated fields. Trends in the values of soil water evaporation for both rainfed and irrigated fields showed that greater SE was obtained under rainfed tomato, which also had lower crop transpiration. Evapotranspiration efficiencies (ET_E 0.35, 0.18 & 0.20, 0.12 kg water per kg dry matter) and crop water use efficiencies (WUE; 0.012, 0.20 & 0.013, 0.09 kg water per kg dry matter) for biomass and fruit yields in the respective rainfed and irrigated tomato. Transpiration efficiencies (TR_E) measured for biomass and fruit were 1.94 and 2.22; 1.91 and 2.17 kg water per kg dry matter. Relative water use (ETa/Eo) and drought index values for the respective rainfed and irrigated tomato were 1.08, 0.11 and 0.49, 0.11. Over rainfed tomato, plant biomass (root & shoot dry weights) and leaf area were enhanced by irrigation and the improved growth was accompanied by high fruit yield and WUE. © 2010 Friends Science Publishers

Key Words: Tropics; Rainfed; Irrigation; Drought; Water adequacy index; Evaporation; transpiration

INTRODUCTION

Tomato (*Lycopersicum esculentum*, Mill) is important as a dietary staple vegetable and cash earning plant in Nigeria. However, in the humid tropics, tomato cultivation is concentrated mainly in the wet rainy season, a period characterized by high incidence of pests and diseases, low fruit set and poor fruit quality (IAR & T, 1991). The high income potentials and the need for increased production to meet year-round food demand, prompts the cultivation of tomato in and out of season. Conceivably, the post-rainy season tomato could give higher yield and more remuneration but this period is occasioned by high soil temperatures and limiting soil moisture status, which have profound influence on growth and yield of crops (Agele *et al.*, 1999, 2004). Weather factors play important role in expression of crop yield however, there is inadequate information on weather-yield relationships especially in the weather dependent planting seasons of the humid tropics (Agele *et al.*, 1999). Approaches to maximize water use at periods of limited soil water availability should aim at realizing maximum yield for the same amount of available soil water and to closely match crop phenology and yield to periods and amount of soil moisture extraction.

Poor soil and water management practices (increased water demand for agriculture & over use by increased population etc.) will further exacerbate water availability problems. It is thus necessary to understand the crucial nature of good water management practices-making best usage of water for agriculture and adopt practices, which enhance water use efficiency in crop production. Since the sustainable exploitation of the water resources and agricultural potentials of the humid tropics may be affected by variable climate and extreme weather events, it is therefore imperative to put in place strategies for sustainable management of land and water resources. Improvements in soil and water management practices, advancement in technology and policy choices will enhance capacities and abilities to mitigate adverse effects of water shortages and limited water supplies.

In the tropics, agricultural crops are extensively cultivated under rainfed, however, increases in crop yields and water use efficiency are required. There are strong and growing needs to develop efficient strategies for

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environmental (weather & water) management for increased crop productivity particularly under rainfed agriculture of the humid and sub-humid tropics. In the tropics, the seasonality of sowing implies that crop production is rainfed and linked to seasonally available soil water (rainfed agriculture). Since water is the most important climatic factor in tropical agriculture, crops, which are seldom irrigated undergo severe water stress especially due to weather variations of the wet and dry season transition. It is necessary to quantify rainfed crop water use efficiency (WUE) so as to develop efficient strategies for environmental (weather & water) management for increased crop productivity. Crop water use models are valuable analytical tools to assess the performance of crops in relation to crop water extraction patterns under various soil moisture availability conditions and weather patterns in a season or location. Water balance models are useful for the quantification crop water use pattern of soil moisture availability and crop water use and the limits of extractable water by plant roots is important to the calculation of water use by crops, definition of growing season lengths and prediction of the onset of stress. However, in order to improve the efficiency of the use of water balance, the knowledge of crop water use in relation to weather events is required (Lansberg, 1988).

In addition, in plants, the onset of stress is related to the percentage of total available water in the root zone, water balance studies provide reasonable approximation of the onset of moisture stress. This limit is related to the percentage of total available water (c30%) in the root zone, and is also related to the point at which ratio of AET to PET is expected to be 0.6-0.7 (Kowal & Knabe, 1972; Lansberg, 1988). Hargreaves (1994) proposed a means for numerical evaluation of climatic potential for agricultural crop production, recommended that use of this methodology for agricultural development and planning and concluded that increased irrigation and well planned rainfed agriculture are needed to slow down erosion and deforestation, slash and burn agriculture and other forms of environmental quality degradation. It is imperative to develop strategies for environmentally sound irrigation and rainfed farming and reduction and elimination of incentives for practices that culminate in the degradation of soil and water resources of the humid and sub-humid tropics.

Worldwide, there has been a range of changes in climate overtime and such variability could constitute profound problems for agriculture (food supply & livelihoods) and water resources management. Global change is associated with variable seasonal and annual weather from its long-term average patterns. Climate change and global warming manifest among other things as heavier rains in the wet months and lower rainfall in dry months and delay in the onset of the rainy season and decreasing duration of cropping season length. The availability of water in both surface and underground resources depend on rainfall. Global warming accelerates the rate of land surface drying leaving less water moving in near-surface layers of soil. Increased rates of evaporation due to increased temperatures and low relative humidity will affect the amount of water available to recharge groundwater supplies and may lead to diminished potentials of water resources. Inter-annual and inter-seasonal variability in rainfall may be associated with increased regional susceptibility to soil erosion and runoff, declining soil moisture availability and agricultural productivity. The variability in climate and extreme weather events had been associated with declining water resources and hence depreciating availability of moisture for agriculture. These situation would have devastating consequences on agriculture, livelihoods and food security in the humid tropics. Such varaibility and its associated droughts and floods could elicit various responses in crops and may call for increased pressures and exploitation of water resources, increases in water stress situations (extremely high temperatures) and marginal growing environments.

It is necessary to improve information base of crop-climate relationships especially for rainfed and irrigated crops in sowing seasons characterized by terminal drought (drought prone sowing seasons) in the humid tropics. Data generated from such studies will help to identify the possibilities to modify technologies (soil water management methods & crop varieties) aimed at fitting expected soil moisture availability to patterns and magnitudes of crop water demand in order to improve crop productivity under specific soil moisture conditions. This would enable full exploitation of the soil and water resources and potentials of the late/dry sowing seasons characterized by terminal drought of the humid and sub-humid tropics. The study of growth responses to soil moisture reserve is basic to understanding crop adaptation and yield stability. The objective of this study therefore was to relate soil water use pattern to growth and yield of tomato in the wet and post-rainy season period (terminal drought situation) in a humid zone of Nigeria.

MATERIALS AND METHODS

Field experiments were conducted to examine the variability in crop consumptive water use (evapotranspiration–ET), water use efficiency (WUE) and fruit yield in field grown rainfed and irrigated tomato during the late (post-rainy) sowing seasons in a humid zone of Nigeria. Three weeks old seedlings of a variety of tomato (Akure local) transplanted into the field at a spacing of 90 x 30 cm for two wet season crops (sown in April 2004 & 2005) and two late season crops (sown in September 2004 & 2005) at the Teaching and Research Farm of the Federal University of Technology, Akure (7^o 5` N, $15^o$ 10` E), Nigeria. Soil moisture content was monitored with depth by the gravimetric method and drainage lysimeters were installed to monitor soil water evaporation and maximum evapotranspiration (ETM). Total evapotranspiration flux

(ET) and actual evaporanspiration (ETa) were determined in rainfed and irrigated late season tomato, while ET was partitioned into its components soil evaporation (SE) and plant transpiration (T).

The methods and equations of Hargreaves (1994) were used to numerically evaluate the climatic potentials for sustainable agricultural production in a humid zone of south western Nigeria. The climatic potential for rainfed agricultural production was determined from rainfall variables (water adequacy index, Ao). Water adequacy index (Ao) was calculated from rainfall and ETo was used to classify the year (seasons) for rainfed crop production. Potential (reference) crop evapotranspiration and rainfall were used in a crop yield function to evaluate the climatic agricultural potential of the humid rainforest belt of southern Nigeria. For the comparison comparing Ao with crop yield (rainfall yield functions), Hargreaves (1994) proposed a yield function (Y) for rainfed agriculture as:

$$Y = 0.8Ao+1.3Ao^2-1.1Ao^3 \text{--------------------------} 1$$

Ao was computed for a growing season length of 3 months and the yield function (Y) was used to estimate the relative potential yields for the early rainy and late (post) rainy growing seasons. Although Hargreaves (1994) proposed equation 1 for rainfed crops as however, for irrigated crop, (a state of adequacy of soil moisture) Y is assumed zero and Ao (X) as 1 for the amount of water required to produce maximum yield (assuming X is 0.7 (< 1), then Y is calculated as 1.593.

Actual evapotranspiration (ETa) was calculated by means of a water balance equation using measured values of soil moisture contents via the gravimetric method (Gardner, 1990). From the experimental field (under rainfed & irrigated tomato), ten points were sampled weekly starting from transplanting to crop physiological maturity. Five samples were taken within the row and five from the inter-row spaces in each field (rainfed & irrigated). Core samples were taken at incremental depths of 10 cm to 60 cm depth, while bulk density was determined for the samples taken at each soil depth and the values were used to convert gravimetric soil moisture content to volumetric ($cm^3.cm^{-3}$). From the water balance equation, Sw_1 and Sw_2 are initial and final moisture contents of soil. P is precipitation received and Ir (irrigation water applied). R is surface runoff, D is deep drainage, SE is soil surface evaporation and Tr (crop transpiration).

$$Sw1+P+Ir=Ro+D-AET(SE+T)+SW2 \ldots\ldots\ldots.2$$

AET is the residual term in the equation. Surface runoff R was assumed negligible because the soil surface was flat, slope less than 3%, precipitation intensity was low. Deep drainage D, was assumed zero due to the presence of gravely layer and low permeability clay in the sub soil horizon (50 – 60 cm depth) and to the low precipitation, only in few occasions did rainfall exceed soil retentive capacity (field capacity within the 60 cm depth was 16%). Declining rainfall amounts were received with increasing growth of tomato in the late cropping season (Agele *et al.*, 2002). Therefore measurements of soil moisture contents at the beginning and at the end of weekly cycle and rainfall allowed the estimation of total evapotranspiration (ETa - SE - Tr) as the residual term in equation 1. (after Dujimovich *et al.*, 1994). Soil evaporation (SE) was quantified by means of a 20 cm long by 15 cm diameter plastic cylindrical microlysimeters. Three microlysimeters were placed in each block and across the rows. Measurements began after crop leaf area index (LAI) was 3.5 and continued until physiological maturity. The weighing intervals were 2 to 3 times per week.

Drought index (Di) was calculated:

$$Droughtind\ ex(Di) = (1 - ETa / ETo) \ldots\ldots\ldots.3.$$

Crop transpiration efficiency (TrE) was estimated by the use of equation:

$$Tr = k/(e^o\text{-}e) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 4$$

(e^o-e) is atmospheric vapour pressure deficit for the day light period during which gas exchange occurs (Tanner & Sinclair, 1983) and k represents specie specific coefficient and a mean value of k = 0.08 was selected for tomato (Tanner & Sinclair, 1983).

Sinclair (1988) proposed the following relation for crop evapotranspiration water use efficiency:

$$WUE = Hk/(e^o\text{-}e)\ (1\text{-}SE/ETa) \ldots\ldots\ldots\ldots 5$$

Where WUE is evapotranspiration water use efficiency for crop yield. H is harvest index (ratio of marketable fruit yield to total biomass (e^o-e) is daily mean vapour pressure deficit measured during periods of crop transpiration The ratio of soil evaporation (SE) to crop transpiration (Tr) was obtained. Saturated vapour pressure deficit (svpd) was calculated using vapour pressure and relative humidity data recorded at the meteorological observatory, FUT, Akure, Nigeria. Average daily temperature was used to calculate thermal time (TT) for each day; TT (is daily temperature from emergence, E to date of first flowering, HV multiplied by the number of days from E to HV). Cardinal temperatures, namely base temperature (T_b 8 ^oC), optimum temperature (T_{opt} 32 ^oC), and maximum temperature (T_{max} 42 ^oC) (Agele *et al.*, 2002), were assumed in the calculation of heat unit accumulation measured as growing degree days (GDD) using the equation of McMaster and Wilhelm (1997).

$$GDD = \frac{T\max + T\min}{2} - \mathbf{T_{base}} \ldots\ldots\ldots\ldots 6.$$

Drip irrigation was applied using point source emitters, the emitters were selected with a coefficient of variation (CV) of 0.03 (CV for good emitter is < 0.05) The manufacturer's chart show 0.96 m as the pressure at which laterals would operate to ensure emitter discharge (deliver) of the specified amount or rate. Pressure variation in the lateral is kept within the range of emitter uniformity (En). For the drip system, En was\estimated as 0.94.

Peak evapotranspiration (ET_{peak}) rate for the crop under drip irrigation treatment was estimated after Schwab *et al.* (1993) as:

$$ET_{peak} = ETo*P/85 \qquad \ldots 7.$$

Where ET_{peak} is peak evapotranspiration rate for the month or period, ETo is the reference evapotranspiration, for the month/period (e.g., 5.1 mm/day), P is the total area covered by the crop leaf area (cm), which is assumed 80% (after Agele, 1999).

$$ET_{peak} = 5.1 *80/85 = 4.8 \text{ mm/day}.$$

The volume of water required per plant (irrigation requirement, I_R) was estimated as:

Irrigation requirement (I_R) = ET_{peak} * area/crop/En

$$(I_R) = ET_{peak} * \text{area/crop}/E_n \qquad \ldots 8$$
$$= 4.80 *0.18/0.94 = 0.92 \text{ (l/day)}.$$

Where area per crop is 0.18 m^2 (60 * 30 crop spacing).

Effective moisture content within 0-60 cm soil depth at incremental depths of 10 cm, is the sum of moisture contents (4.15 cm) in each layer 0-10, 10-20, 20-30, 30-40, 40-50, 50-60 cm) These gave soil moisture content of 0.80, 0.83, 0.88, 0.65 and 0.76% before irrigation. Moisture contents at site of experiment at field capacity (21 g/100 g soil) and permanent wilting point (PWP) (7.8 g/g soil) and the depth of root zone (RZd) for water extraction is within 0 - 60 cm for tomato (Agele, 1999).

Maximum allowable deficit (MAD) for tomato crop was 50%. Net water requirement (NWR) for irrigated tomato crop was calculated as:

$$NWR = (\text{Fc PWP}) * \text{Bd} * \text{RZd} * \text{MAD} \qquad \ldots 9$$

$$NWR = (21 – 7.8) * 1.26 * 60 * 0.5 \text{ (g/g*g/cm3*cm)}$$
$$= 498.96 = 49.9 \text{ mm} = 4.99 \text{ cm}.$$

Irrigation frequency/interval (Ir Interval) was calculated as net water requirement (NWR)/peak consumptive use rate (ET_{peak}) by the crop:

$$IrInterval = NWR / ETpeak \qquad \ldots 10$$
$$= NWR/ET_{peak}$$
$$= 4.99/4.8 = 1.$$

The calculated Ir Interval is once per day.

Consistent trends were obtained in the two experimental years of study and therefore, the obtained data were pooled and presented as means of two years for the wet and dry season tomato crops. The means of the pooled data collected from soil and plant parameters were subjected to analysis of variance (ANOVA) and treatment means were separated using Least Significance Test (LSD; $P < 0.05$) (Steel *et al*., 1997).

RESULTS

Both the rainfed and irrigated dry season tomato were grown in the same site and under similar weather events however, the agronomic practices (rainfed & irrigation) subjected the crop to variable soil hydrothermal regimes. Table I presents meteorological variables (2004 & 2005) at site of experiment during tomato growth. Under this prevailing weather conditions, there are high probabilities of exceeding crop specific high temperature thresholds and limiting soil water status during the dry season. The growing environmental conditions of the post rainy season is dominated by high available energy, atmospheric demand (vpd), supra-optimal air and soil temperatures and negligible rainfall, thus more marginal growing environments were experienced particularly during flowering and fruit filling stage of tomato. The post rainy season is also a terminal drought situation, despite the few (negligible) rains, this period is characterised by dry spells (of varying intensities & duration), which occurred between rainfall episodes. These environmental conditions strongly impacted growth duration, dry matter production, efficiencies of water use and fruit yield in tomato.

The dry (post) rainy season is characterized by Ao ranging from 0.01 - 0.33 (Dec -March), which means that the season is not suitable for rainfed cropping, while the late rainy season sowing falls within August-December (Ao < 0.34) and ends in a terminal drought situation and limited suitability of rainfed agriculture. However, supplementary irrigation will improve crop productivity in the late season cropping opportunity. The early (wet) rainy season falls between March/April to July with an Ao ranging from 0.34 to 1.0. The Ao values indicated that rainfed production is possible. Under rainfed agriculture, rainfall determines the growing season, then the average Ao during the growing season can be used as an index of potential crop production. Hargreaves (1994) recommended the use of this methodology for agricultural development and planning, and concluded that increased irrigation and well planned rainfed agriculture are needed to slow down erosion and deforestation, slash and burn agriculture and other forms of environmental quality degradation. The results of the annual pattern of rainfall and rainfed potential production of crops in the humid rainforest zone of Nigeria could be useful in the assessment of the climatological risks and the choice of agronomic or technological interventions to improve crop productivity in an area.

From the estimated and measured soil water evaporation (SE) (for tomato at LAI of 3.5), mean SE were 37 and 11 mm. day^{-1}, which constituted 5.6 and 14.4% of ETa for the respective rainfed and irrigated fields (Table IV). Under rainfed condition, seasonal rainfall amount represented 57% of ETa, while the remainder should be covered by SE and change in soil moisture reserve/storage. ETa is dependent on cumulative rainfall received during crop growth under rainfed condition. Greater SE was

Table I: Some meteorological variables at the site of the experiment during period of study (2004 & 2005)

Characters	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
					2004							
Total rainfall (mm)	0	5.6	39.8	109.7	189.3	257.8	288.4	239.3	200.7	156.6	13.5	4.7
Mean daily temp (°C)	32.4	32.7	32.8	29.3	28.9	29.4	30.2	28.4	29.2	31.8	32.1	33.0
Relative humidity (%)	31.7	47.1	55.4	69.7	74.3	79.4	81.3	78.0	69.0	62.0	43.0	27.0
Total sunshine (hours)	191.3	197.2	206.6	183.9	177.1	128.4	139.7	114.6	139.4	205.2	185.3	168.4
					2005							
Total rainfall (mm)	0	7.2	45.3	93.6	171.8	225.7	301.7	251.7	218.3	163.5	9.8	2.7
Mean daily temp (°C)	32.7	32.4	33.6	32.8	31.5	29.3	28.9	29.4	28.2	28.9	31.4	32.3
Relative humidity (%)	33.6	41.3	57.7	72.4	78.7	84.1	79.4	74.0	69.0	66.0	47.2	30.0
Total sunshine (hours)	197.1	219.4	211.0	191.8	169.7	134.2	129.9	118.3	143.2	209.2	178.7	171.9

Table II: Annual pattern of rainfall and rainfed potential production of crops in the humid rainforest zone of Nigeria

Criteria	Seasons (months) of the year	Productivity classification
Ao in the range of 0.01 – 0.33	Nov/Dec – March Dry season	Not suited for rainfed agriculture, irrigation is required
3 – 4 months with Ao of 0.34 or above	Aug – Dec. Late season	Terminal drought situation Limited suitability for rainfed agriculture, supplementary irrigation is required
Five or more months with Ao of 0.34 -1.0	Mar – July Rainy (wet) season	Rainfed production is possible Rainfall enhanced soil water availability is very adequate for rainfed

Table IIIa: Evapotranspiration components in rainfed and irrigated tomato

Month	P	S	R	D	ETa	ETo	Eo	ETa/Eo	SE	Transpiration	SE/ETa	P/ETo	Drought index
Sept	127	-14.6	3.1	0.2	131.6	122.5	121	1.14	60.9	80.7	4.3	9.0	0.10
Oct	97.1	-12.3	1.4	-0.1	109.8	131.3	142	0.76	53.6	55.7	4.9	8.9	0.16
Nov	51.0	-10.3	--	-0.1	78.5	157.2	151	0.41	42.4	36.1	5.4	6.5	0.50
Dec	1.3	-9.4	--	-0.1	30.7	143.8	160	1.90	18.4	12.3	6.0	4.2	0.79
Jan	0	-7.8	--	-0.1	15.7	118.3	133	1.18	11.6	7.4	7.3	--	0.87

Table IIIb: Evapotranspiration components in irrigated tomato

DAT	47	54	61	68	75	82	89	96	103	110	117
Mean soil water extraction	**6.8**	**8.0**	**10.5**	**12.0**	**13.0**	**14.0**	**14.4**	**15,7**	**16.5**	**16.2**	**16.0**
P	0	5.1	3.8	0	0	4.1	0	0	0	2.3	0
Ir ($l.d^{-1}$)	0.73	0.73	0.74	0.74	0.75	0.75	0.76	0.76	0.78	0.80	0.82
S	15	13.2	13.5	12.5	10..0	9.6	10.3	10.8	11.3	11.8	12.5
R	2.1	2.3	1.6	1.3	--	--	--	--	--	--	--
D	0.3	0.2	-0.1	-0.2	-0.1	-0.1	--	--	--	--	--
ETa	4.5	4.8	4.6	4.9	5.1	5.2	5.3	5.1	4.8	4.6	4.2
ETo	5.1	5.3	5.1	5.3	5.6	5.7	6.0	6.2	6.0	5.8	6.0
Eo	4.8	5.0	5.1	5.3	5.5	5.7	5.6	5.4	5.8	5.6	5.4
ETa/Eo	0.94	0.93	0.91	0.93	0.91	0.93	0.95	0.94	0.83	0.82	0.78
SE	2.1	2.3	2.2	2.6	2.4	2.2	2.1	2.2	2.1	2.5	2.6
Tr	2.4	2.3	2.4	2.5	2.6	2.9	3.1	3.2	3.0	2.4	2.2
SE/ETa	0.47	0.48	0.48	0.53	0.48	0.62	0.40	0.40	0.41	0.51	0.55
Tr/ETa	0.53	0.52	0.47	0.52	0.38	0.60	0.60	0.59	0.49	0.45	0.47
Drought index	0.16	0.09	0.10	0.08	0.11	0.16	0.13	0.15	0.16	0.22	0.25

Table IV: Calculated transpiration, evapotranspiration and crop water use efficiencies and rainfall (water) yield functions (Y)

Growing season	Biomass yield (g/m^2)	Fruit yield (g/m^2)	Transpiration efficiency (g/m^2.mm)		Evapotranspiration efficiency (g/m^2.mm)		Water use efficiency (g/m^2.mm)		Crop Yield function (Y)
			Biomass	Fruit	Biomass	Fruit	Biomass	Fruit	
Rainfed	134.2	75.4	1.94	1.91	0.35	0.20	0.012	0.202	0.35
Irrigated	152.6	103.7	2.22	2.17	0.18	0.12	0.013	0.093	1.59
LSD (0.05)	9.3	7.2	ns	ns	0.09	ns	ns	0.05	0.61

Y is rainfall crop yield function (Crop yield as a function of relative water adequacy) after Hargreaves (1994)

obtained under rainfed tomato, which also had lower crop transpiration. Trends in the values of soil water evaporation for both rainfed and irrigated fields would mean high moisture losses to the atmosphere, which was not used for crop production. The values of evapotranspiration efficiencies (ET_E; 0.35, 0.18 & 0.20, 0.12 kg water per kg dry matter) and crop water use efficiencies (WUE; 0.012, 0.20 & 0.013, 0.09 kg water per kg dry matter), for biomass

Table V: Growth and yield parameters taken on rainy season (rainfed) and late season (irrigated) crops

Season	Root length (m/m^2)	Root weight (g)	Shoot weight (g)	Leaf area (m2)	Ratio of root to max. leaf area	Growth duration (days)	Fruit Yield (t/ha)	Water Use efficiency (t/ha/mm)	Harvest index
					1999				
Irrigated	15.8	19.5	121.3	0,110	4.3	92	6.2	0.041	0.59
Rainfed	21.2	27.3	98.4	0.084	7.2	83	8.7	0.034	0.61
LSD (0.05)	0.66	0.64	0.91	0.021	0.6	3.8	0.34	0.14	0.21
					2000				
Irrigated	5.6	26.1	128.7	0.110	4.7	97	6.3	0.044	0.62
Rainfed	7.5	29.5	101.2	0.081	9.1	85	9.2	0.033	0.63
LSD (0.05)	0.25	1.01	0.040	0.7	0.8	2.9	0.38	0.005	0.21

Table VI: Correlation and regression relationships among components of evapotranspiration, water use efficiency, drought index and maximum temperature and vapour pressure deficit for rainfed and irrigated tomato

Parameters		Correlation coefficients:R^2(r)	Regression equation
	Rainfed	0.57(93)	y = 1.9056Ln(x) + 21.716
Eta vs tmax	Irrigated	0.25(- 43)	y = -4.8669x2 + 48.211x - 89.652
	Rainfed	0.61(83)	y = 2.6128Ln(x) + 20.492
SE vs Tmax	Irrigated	0.11(-27)	y = -10.91x2 + 52.877x - 34.491
Tr vs Tmax	Rainfed	0.48951)	y = 1.5662Ln(x) + 24.157
	Irrigated	0.28(- 41)	y = -8.8768x2 + 46.821x - 31.714
Drought index vs	Rainfed	0.57(- 66)	y = -3.5293x2 + 3.8033x + 2.2902
Tmax	Irrigated	0.49(51)	y = -21.189x + 32.427
ETa vs vpd	Rainfed	0.76(- 82)	y = -0.0058x + 3.3989
	Irrigated	0.50(- 63)	y = -0.7357x + 6.6395
Tr vs vpd	Rainfed	0.74(- 78)	y = -0.0095x + 3.3417
	Irrigated	0.71(73)	y = 2.1535Ln(x) + 0.8565
SE vs vpd	Rainfed	0.77(- 75)	y = -0.0137x + 3.4711
	Irrigated	0.10(25)	y = 3.5762x2 - 17.052x + 23.106
Drought index vs vpd	Rainfed	0.57(- 64)	y = -3.5293x2 + 3.8033x + 2.2902
	Irrigated	0.88(91)	y = 7.2378x + 1.6874
ETa vs Drought index	Rainfed	0.77(- 81)	y = -0.0002x2 + 0.0258x - 0.1726
	Irrigated	0.36(- 45)	y = -0.0901x + 0.5908
Tr vs Drought index	Rainfed	0.59(- 66)	y = -0.0004x2 + 0.0292x + 0.0867
	Irrigated	0.41(- 54)	y = -0.0302x + 0.2205
SE vs Drought index	Rainfed	0.73(- 77)	y = -0.0011x2 + 0.0797x - 0.6507
	Irrigated	0.72(- 80)	y = -0.2625x + 0.7928
	Across soil water management practices (rainfed/irrigation)		
Tr vs vpd		0.11(-24)	y = -1.316Ln(x) + 3.9146
SE vs vpd		0.35(- 44)	y = -30.873x2 + 16.07x + 1.0738
WUE vs vpd		0.69(- 70)	y = - 4.0151x + 3.3584
Tr vs Drought index		0.97(- 92)	y = -0.6492x + 1.5092
SE vs Drought index		0.91(- 95)	y = -0.0634x + 0.8473
WUE vs Drought index		0.87(- 90)	y = -4.0979x + 0.7753

*ETa (actual evapotranspiration; Se (soil water evaporation); WUE (water use efficiency) ;vpd (vapour pressure deficit)

and fruit in the respective rainfed and irrigated tomato are presented in (Table IV). Transpiration efficiencies TR_E, measured for biomass and fruit were 1.94 and 2.22; 1.91 and 2.17 kg water per kg dry matter (Table IVa). Tanner and Sinclair (1983) and Howell (1990) reported that transpiration ratios declined for crops grown under low atmospheric humidity (air dryness). Hulugalle and Lal (1986) and Agele *et al.* (2002) obtained seasonal ratios of relative water use (ETa/Eo) ranging from 0.77 and 0.80 for cowpea and maize intercrop towards the end of rainy season in south western Nigeria.

The effects of rainfed and irrigation were pronounced on crop growth duration, plant size (shoot biomass) and fruit yields of tomato. Over rainfed tomato, plant biomass (root & shoot dry weights) and leaf area were enhanced by irrigation and the improved growth was accompanied by high fruit yield and WUE (Table V). Under rainfed condition of the late season, high temperatures aggravate drought stress and declining dry matter accumulation and high temperature enhanced respiration rates, decreased canopy (leaf area) duration and dry matter accumulation and hastened leaf senescence, while high SVPD affects rates of plant growth and leaf expansion. Mean of the seasonal sum of ratio of soil evaporation to crop transpiration ranging from 0.56 to 0.11 was obtained (Table III). The time course of soil water balance and its components especially crop consumptive water use (ETa) show decreases in its values with increases in ETo and Eo (evaporative demand) under rainfed situation. The mean of the seasonal sum of relative water use (ETa/Eo: 1.08; 0.11) and drought index (0.49; 0.11) for the respective rainfed and irrigated tomato (Table III). The decreases in soil water storage appeared to be due to increases in climatic demand, relative water use (ETa/Eo) and drought index. Crop water use (ETa) values were not

Table VII: The patterns of water and energy utilization in rainfed and irrigated conditions at the phenophases of tomato

Characters	Planting to 50% flowering	50% flowering to physiological maturity	Total
	Total soil moisture storage ($cm^3.cm^2$) (within 0-60 cm depth)		
Rainfed crop	10.84	22.89	33.73
Irrigated crop	6.14	4.13	6.18
	Heat accumulation (GDD T_{b8} °C)		
Rainfed crop	1579	1332	2911
Irrigated crop	1474	1776	3250
	Cumulative ET per season (mm)		
Rainfed crop	261.4	339.5	600.9
Irrigated crop	333.1	393.5	726.6
	Total radiant energy (incident radiation; $MJ/m^2/day$)		
Rainfed crop	31.8	25.4	57.2
Irrigated crop	26.2	29.9	56.1
	Photothermal quotient (PTQ- MJ/m^2/degree day)		
Rainfed crop	0.020	0.019	--
Irrigated crop	0.018	0.017	--

stable and showed contrasting trend in the pre and post flowering phases of growth, while WUE was highly variable (Cv = 22 & 17%) especially after flowering in both rainfed and irrigated condition (Table IIIa & b).

The components of evapotarnspiartion (ETa, Se & Tr), WUE and drought index were examined in relation to some seasonal weather factors during tomato growth in the late/dry season (Table VI). Regression equations, which were fitted to quantify the effects of seasonal weather factors (maximum temperatures, svpd & drought index on ETa, Se & Tr WUE & drought index) on physiological processes showed variable degrees of associations, which at times were significant. The relationships yielded higher R^2 in rainfed crop, while irrigated crop had the least sensitivity to these weather factors. The sensitivity of tomato consumptive water use and water use efficiency to Tmax, vpd and drought index has implications for fruit yield in rainfed crop under the prevailing growing conditions of the dry season. Crop transpiration and soil water evaporation correlated negatively with drought index and vpd in rainfed tomato, while ETa, transpiration and soil water evaporation also correlated negatively with drought index in both rainfed and irrigated tomato. In both rainfed and irrigated tomato, negative correlations were obtained for Tr, Se and WUE and vpd and drought index. The effects of weather conditions on ET components and WUE can be incorporated into crop simulation models for the estimation of biomass and yield of late season crops in the humid tropics.

High degree of coupling between tomato plant and the atmosphere was obtained (Table VII). Seasonal crop water use (ET) differed between the rainfed and irrigated tomato; phenologically averaged values of ET accumulation were greater during reproductive growth in crops. The ratio of ET to radiation (Rn) varied during the phenophases, ET, which constitutes the main component, accounted for 82-86% of the available energy at the reproductive stages (i.e., 3.9 - 4.1 mm/day) when expressed as mass. The high ET during the post-flowering phase indicates that ET dissipates almost all the available energy under the high irradiance and evaporative demand of the late season (Agele, 2006). Crop water use (ET) was normalized by the LAI (ET/LAI) and differences in ET values in each crop (rainfed or irrigated) can be explained by trend of LAI during crop cycle. The sharp decline in the values of this parameter in rainfed crop, is attributable to exposure of soil surface by the sparse canopies (San Jose *et al.,* 2003). The pattern of water and energy use appeared to be important to the survival, crop functioning and hence its productivity in a given season of sowing. The underlying processes controlling water vapour and energy fluxes are important to understanding the responses of crop functioning to environmental conditions during its growth (San Jose *et al.,* 2003). This information could explain a crop's adaptation to the diverse growing environments of the rainy and late seasons.

The onset of the rainy season in addition to length and number of rain days and cessation date of rainfall affect soil water reserve and productivity of rainfed crops in the tropics (Omotosho *et al.*, 2000). It is therefore becoming more imperative to design soil and crop management systems to make productive use of seasonally available soil moisture and to reduce its adverse effects on crop productivity due to variable inter-and intra-seasonal rainfall and extreme weather factors. In the late season cropping opportunities, soil moisture deficit constitutes an important limitation to productivity of rainfed crops (Agele *et al.*, 2002). In this study, the use of irrigation buffered the edaphic (weather-soil) stress variables and improved the growth, development and yield performance of dry season tomato.

Our results may be useful inputs in modeling the effects of climate change on water supplies (rainfall) and crop water requirements and in the development of sustainable rainfed agriculture in the tropics. The results may also be useful for modeling the effects of variable growing season weather events on soil water supplies/availability, crop water use and efficiencies and yield. This study may contribute to expansion of methodologies of using climatic and soil data to provide a quantitative picture of crop available moisture under various seasonal weather conditions. In addition, it contributes to improved understanding of the bases of tomato adaptation to insufficient-moisture environment in the post rainy season.

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