Effects of regulated dry season irrigation on tree water use, root zone moisture dynamics and yield of cacao in a rainforest zone of Nigeria

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Abstract

A field trial was conducted to investigate the effects of regulated dry season irrigation on tree water use, root zone moisture dynamics and yield of cacao in a rainforest zone of Nigeria. Following cessation of rainfall in November, irrigation commenced from December 2017 to May 2018. Irrigation amount was computed based on crop evapotranspiration (ETo) and the reference evapotranspiration (ET0) ratio. Irrigation treatments were coded as IrT1, IrT2 and IrT3, consisting of water application using EPan *Pan coefficients (Kcp) of 1.0, 0.70 and 0.50 (9.6, 6.8 and 4.8 l/tree/day). Irrigation water applied at 5-days interval was discharged via point source emitters (2.8 l/h discharge rate) on drip lines laterally installed per row of trees. Irrigation requirements were on the average, 4.49, 3.14 and 2.44 mm, total water applied per irrigation events were 1009.88, 706.92 and 504.94 mm per plot (225 m²), total seasonal water applied were 33858, 23701 and 16929 mm, and soil moisture contents were 52, 45 and 28% for the respective IrT1, IrT2 and IrT3. Tree evapotranspiration (ETc) were 4.54, 3.19 and 2.32 mm/day while seasonal sums were 809, 566 and 404 mm while the ratio of ETC to EPan were 0.9, 0.69 and 0.53 for IrT1, IrT2 and IrT3. Tree water use efficiencies were 0.3 and 0.04 t/mm for Y/ETc and 0.16 to 0.19 kg/mm for Y/Irrigation respectively. Cacao pod and bean yields were 35.4, 22.1 and 10.3 t/ha and 2.29, 1.37 and 1.03 t/ha while yields decreased by 60 and 40% under IrT3 and IrT2 compared with IrT1. The study identified suitable Pan coefficients for scheduling irrigation during the dry season for cacao, full irrigation (EPan*1.0) applied at 9.6 l/tree/day will be needed to replenish soil water depletion to satisfy crop consumptive water use (transpiration and soil evaporation components). The low pressure gravity-drip irrigation system alleviated climate stress during the dry season and improved cacao performance in a tropical rainforest environment.

Introduction

Cocoa (Theobroma cacao L.) is an important perennial fruit tree with an estimated annual world production of 3.2 million tonnes (FAO, 2012). Within the cocoa-growing belt of West Africa, sale of cocoa beans is a major foreign exchange earner, the cocoa sector employs millions of smallholder farmers (small farm sizes ranging from 0.5 to 5.0 hectare (ha) and contributes about 70-100 % of their annual household incomes. In Nigeria, the main cocoa-producing areas are concentrated in the rainforest of the southern part of the country where an estimated 1.45 million hectares is cultivated. The productivity is 250 kg/ha, a yield level that is lower than those from Cote d'Ivoire and Indonesia (bean yields ranging from 600 to 1000 kg/ha respectively). In the smallholder cocoa farms of West Africa, farm sizes are small ranging from 0.5 to 5.0 hectare using low external inputs. The perennial fruit tree species of the rainforest of Nigeria: Cacao (Theobroma cacao), Coffee (Coffeea spp) and Kola (Kola spp.) are characterized by deciduous growth habit but are cultivated under rainfed conditions (Opeke, 2006, Charles et al., 2019)

Global warming and drought and other climate-related disasters are tied to the changing climate, extreme and variability of the weather (Ufccc, 2004, IPCC, 2014). The frequency and severity of drought event including (1.5 to 2 °C) warming are expected to increase in the near future as result of the decrease of regional precipitation and the increase in evapotranspiration driven by global warming (Sheffield et al., 2012, Trenberth et al., 2014,Tombesia et al., 2018). Among natural hazards, drought ranks first in terms of the number of people directly affected (Trenberth et al., 2014). The changing climatic events has implications for agriculture food security, economies, and welfare of the society and ecosystems (Graysons, 2013, Agele, 2021). Projections of climate change have pointed to an increase in mean temperature (c 2 °C by 2080) and potential evapotranspiration, decrease in precipitation and crop (actual) evapotranspiration under future scenarios and uncertainties (Trenberth et al., 2014, Tombesia et al., 2018). This implies future yield decreases which can be associated with enhanced heat and water stress under future climate conditions. Thus, climate Change (temperature and rainfall) scenarios for the rainforest of Nigeria which have been variously constructed using climate models have indicated variabilities in rainfall pattern (amount, distribution, onset and cessation dates) and elevated maximum and minimum temperatures. These projected climatic changes will exacerbate soil moisture and thermal stresses during the dry season with implications for crop performance (Trenberth et al., 2014, Tombesia et al., 2018, Agele, 2021).

Cocoa is cultivated as a rainfed crop, and it is highly sensitive to soil and weather conditions of low rainfall, soil and air moisture deficit and temperature stresses (Opeke, 2006, Zuidema et al., 2005, Charles et al., 2019). The changing growing environmental conditions (marginal soils and extreme weather events) impose constraints on cacao growth and productivity. In order to alleviate the constraints imposed by changing growing environmental conditions (marginal soils and extreme weather events) on cacao productivity, it is imperative to develop climatic-stress adaptive strategies for the fruit tree-based agroforestry systems of the rainforest tropics in the wake of changing climate/weather conditions (climate change and weather variabilities).

The FAO Penman-Monteith equation, is accepted worldwide as the standard method for estimating reference evapotranspiration (ETo). The reference evapotranspiration (ETo) is a measure of the evaporative demand of a given environment and thus crop consumptive water use which is the sum of evaporation from soil and plant transpiration from the field (Penman, 1948, Doorenbos and Pruitt, 1977, Ventura et al., 1999, Allen et al., 2005). The procedures to calculate ETo from radiation, wind, humidity and temperature data are presented in the FAO Paper No. 56. The standard procedure for estimating evapotranspiration is documented in the FAO I&D No. 56, where a list of Kc values for each crop and developmental stage is provided. This Kc approach has been used to obtain reference evapotranspiration (ETo) and crop consumptive water use (ETc) for arables, trees and vines (Allen et al., 1998, Ferreira, 2017). The ratio between ET and ETo, is defined as a crop coefficient (Kc). Thus, if Kc is known, the ETc is calculated as:

\[ \text{ETc} = \text{Kc} \times \text{ETo} \]

The FAO-56 dual crop coefficient approach (Allen et al., 1998, Allen and Pereira, 2009) also describes the relationship between crop evapotranspiration (ETc) and reference evapotranspiration (ETO) by separating the single Kc into the basal crop (Kcb) and soil water evaporation (Ke) coefficients. In the FAO-56 single crop coefficient approach, the effect of both crop transpiration and soil evaporation are integrated into a single crop coefficient (Kc). However, crop evapotranspiration (ETc) estimation is more accurate by dual crop coefficient approach than the single crop coefficient approach, the dual crop coefficient approach uses more parameters and take soil practices and crop characteristics into consideration (Monteith, 1973, Ventura et al., 1999, Zhang et al., 2013). In the dual approach a daily basal crop coefficient (Kcb), representing primarily the plant transpiration, and a daily soil evaporation coefficient (Ke) are considered separately according to the equation:

\[ \text{ETc} = \text{Kcb} \times \text{ETo} + \text{Ke} \times \text{ETo} \]
Experimental Site and Conditions

Materials And Methods

Experimental Site and Conditions
An experiment was conducted on the Research and Experiment Station of the Department of Crop, Soil and Pest Management, Federal University of Technology Akure, Nigeria. Akure is located in the rainforest zone of southwest Nigeria on latitude: 7° 18’ N, Longitude: 5° 8’ E and 350 m abs. Five to six years old fruiting cacao trees which had been previously irrigated during dry season from seedling establishment (April, 2013) till date were used.

The cocoa-growing rainforest belt of southern Nigeria, is characterized by wet and dry season transition, and the seasons have variable weather conditions. The annual rainfall range from 1500 to over 2000 mm distributed in a bimodal pattern within seven to eight months duration and 3 to 4 months of dry season. The dry season is a terminal drought situation characterized by inadequate rainfall, soil moisture, high vapour pressure deficit and temperature stresses and very clear sky (high intensity of solar radiation) (Famuwagun et al., 2017, Charles et al., 2019). In the rainforest cocoa growing belt of west Africa, fruit trees in plantations (cacao, kola, coffee, citrus species and oil palm) are seldom irrigated especially during the terminal drought situation of the dry season.

**Soil characteristics and moisture determination**

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 187 mm. The percent and volumetric soil water contents at field capacity and permanent wilting point are 21 and 10 % respectively. Mean bulk density was 1.25 g cm⁻³. The soil at the site of the experiments was Soil samples were taken and subjected to routine Laboratory analysis for physical (textural class, bulk density, water holding capacity) and chemical (organic matter, N, P, K, Ca, Mg, CEC, electrical conductivity) properties using standard procedures.

Soil samples were taken using soil Auger for water content measurement within the top soil layer (0 - 30 cm) by gravimetric method. Core samples were taken for bulk density and porosity measurement. Soil moisture content would attain field capacity in two days since the soil is sandy clay to silty clay loam (Agele et al., 2014). 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. Soil moisture depletion (SWD) was obtained from the differences in soil moisture contents (changes in soil moisture contents: DS) measured between two measurement period. Soil moisture contents were determined weekly at 20 cm depths from soil samples taken with augers and core samplers.

**Irrigation Strategies**

Cacao trees were drip-irrigated based on levels of cumulative pan evaporation. Irrigation treatments were based on the restoration of cumulative Pan evaporation (EPan) using variable Pan coefficients (Kcp) of 100, 70 and 50 % (Allen et al., 1998; Sezen et al., 2010; Agele et al., 2014). The Pan coefficients (100, 70 and 50 % Kcp; the relative water deficit of 0, 0.3 and 0.5) indicated zero, high and low water stress conditions respectively.

Irrigation amount was calculated using Pan evaporation and Pan coefficients (Kcp1: 1.0; Kcp2: 0.7, and Kcp3: 0.5) according to Doorenbos and Pruitt (1975) and Allen et al. (1998) as:

\[ \text{Ir} = A \times \text{EPan} \times \text{Kcp} \]

where Ir is the amount of applied irrigation water (mm), A is the plot area, EPan is the cumulative evaporation at irrigation interval (mm) and Kcp is the plant Pan coefficient.

Irrigation treatments were coded as EPan *100 Kcp (IrT1), EPan * 70 % Kcp (IrT2) and EPan *50 % Kcp (IrT3) while irrigation was fixed at 5 days-interval for the three irrigation treatments. Irrigation treatment IrT3 had the maximum water deficit which was used to determine stressed baseline while IrT1 suggest adequate irrigation to meet full crop water requirements (the non-crop water stress baseline). Irrigation water was applied using gravity-drip irrigation system at 4.8, 6.8 and 9.6 l/tree/day at each irrigation via point source emitters of 2l/h discharge rate which were installed on laterals per row of cacao tree spaced at 3 x 3 m. One drip lateral served each plant row and an inflow meter was installed at the control unit to measure total flow distributed to all replications in each treatment. Irrigation buckets were suspended on 3.5 m high tank stands to provide the required hydraulic heads (Agele et al., 2014, Charles et al., 2019).

Total amount (volume) of irrigation water applied per treatment was calculated using equation:

\[ V = P \times A \times \text{EPan} \times \text{Kcp} \]

where, \( V \) is the volume of irrigation water (L); \( P \) is wetting percentage (taken as 100 % for row crops); \( A \) is plot area (m²); \( \text{EPan} \) is the amount of cumulative evaporation for the irrigation interval (5-days) and \( \text{Kcp} \) Pan coefficients (1.0, 0.7 and 0.5). This corresponded to 7.14 mm (1.93 l/day), 10.7 mm (2.90 l/day), 14.28 mm (3.86 l/day) for the respective 0.5, 0.7 and 1.0 Kcp. 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, this replenished soil water in the 0.60 m profile depth to field capacity across treatments.

Following the pre-treatments of 4.82 l/day for 5 days, differential irrigation treatments commenced on 13th December, 2017 and was terminated May 9th, 2018. The amount of water applied per irrigation and seasonal irrigation amount varied from a maximum of 4.82 l/day and 127500 mm (DI level) to a minimum of 1.93 l/day and 20400 mm (DI₄ level). Irrigations continued until one week before the final harvest.

Actual crop evapotranspiration (ETc) of cacao under the irrigation amounts was calculated with the water balance equation (Equation 1) (Agele et al., 2014)

\[ \text{ET} + I + P + \Delta S - Dp - Rf \]

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where, ET, is actual crop evapotranspiration (mm); I, the amount of irrigation water applied (mm); P the precipitation (mm); ΔSW, 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 runoff were assumed to be negligible. Daily crop evapotranspiration was estimated using the pan evaporation data, pan factor and crop coefficient (Doorenbos and Pruitt, 1977, Agele et al., 2014). Data for Pan evaporation (EPan) used for the experiment were obtained from measurements with Class-A Pan (121 cm in diameter and 25.5 cm in depth) from the Meteorological Station, Department of Meteorology & Climate Science, FUTA located near the plots.

Deep percolation was considered as zero because there was no high underground water problem in the area. If available water in the root zone (0–90 cm) and total applied water amount by irrigation were above the field capacity, it would be assumed that water amount above field capacity leaked into the deeper soil zones and was called deep percolation (Dp: available total water amount at 0–90 cm soil depth before irrigation + applied irrigation water field capacity) (Doorenbos and Pruitt, 1977). Total water requirement (WR) was determined using the relation:

\[ WR = A \times B \times C \times D \times E \]  

where : WR = Water requirement (l per day /plant) A = Open Pan evaporation (mm/day) B = Pan factor (1.0, 0.7 and 0.5), C = Spacing of plant (m2 ), D = Crop factor (factor depends on plant growth, value for fully grown cacao = 1.13 but for cacao in the early fruiting stage, 0.83 was adopted). Water requirements (WR) were 9.63, 6.75 and 4.8 l/plant/day for the respective IrT1, IrT2 and IrT3 irrigation treatments.

Irrigation water requirement is determined using average season wise pan evaporation data for the area. The total water requirement (TWR) of the farm plot was obtained using the relation. Therefore, the total water requirement (TWR) of the farm plot is:

\[ TWR = WR \times \text{No. of Plants} \]

Maximum allowable deficit (MAD) for cacao (50% of available water storage capacity of the soil (AWC) Gross irrigation requirement (GIR) of an orchard or vineyard, the computed ETc, which is considered as the net irrigation requirement (NIR), should be divided by the application efficiency (AE).

\[ GIR = \frac{NWR}{AE} \]

Yield and crop water use were deployed to evaluate appropriate the efficiencies of irrigation management practices among the different irrigation strategies adopted.

**Orchard water use efficiencies**

Water productivity (irrigation water use efficiency (IWUE) and crop water use efficiency (WUE ) was determined based on the methods of Sezen et al. (2010) and Agele et al. (2014) as:

\[ IWUE = \frac{\text{Biomass weight (Y)}}{\text{total irrigation water applied (Ir)}} \]

\[ WUE (\text{crop}) = \frac{\text{Biomass weight (Y)}}{\text{Cumulative seasonal ETc}} \]

where IWUE is the irrigation water use efficiency (t.ha\(^{-1}\) mm), EY is the economical yield (t.ha\(^{-1}\)), Ir is the amount of applied irrigation water (mm).

Cacao water requirement was determined using FAO-56 single and dual crop coefficient models approach. The aim was to analyze the capacity of the FAO-56 single and dual crop coefficient models to assess cacao evapotranspiration and water requirements (estimating adequacy of irrigation amount for cacao).

The FAO-56 dual crop coefficient approach (Allen et al., 1998) describes the relationship between crop evapotranspiration (ETc) and reference evapotranspiration (ET0) by separating the single Kc into the basal crop (Kcb) and soil water evaporation (Kes) coefficients, while in the FAO-56 single crop coefficient approach, the effect of both crop transpiration and soil evaporation are integrated into a single crop coefficient (Kc). Cacao orchard irrigation was scheduled from transpiration and evaporation coefficients (Kcb, Kes). FAO I&D No. 56 publication offers opportunity for differentiating E from Tr by using a dual crop coefficient approach, according to the equation:

\[ ETc = (Kcb + Kes) \times ET0 \]

where Kcb is a transpiration coefficient and Kes is soil evaporation coefficient.

Kcb is basal crop coefficient (kcb = ETc/ET0)

\[ Kc = kcb + kes \]

and then,

\[ ETc = (kcb + kes) \times ET0 \]

**Size of cacao canopies**

Tree canopies may be characterized using two parameters: canopy volume (m\(^3\) of tree volume/m\(^2\) of ground surface) and leaf area density (m\(^2\) of leaf area/m\(^3\) of tree volume). Tree canopy can be measured with a measuring rod once the tree shape has been approximated as a sphere, an ellipsoid, or a truncated
inverted cone. As an alternative to the measurements or calculations of the radiation actually intercepted by the tree, a simple parameter that is easy to
determine is the degree of ground cover. The ground cover (normally expressed in percentage) is obtained by measuring the shaded area outlined from the
horizontal projection of the tree canopy

The ground cover (normally expressed in percentage) was obtained by measuring the shaded area outlined from the horizontal projection of the tree canopy

\[ A = \frac{d^2}{4} \text{ (m}^2) \] \ldots\ldots..17

\( d \) = diameter of shaded area by cacao canopy (2m), A is per cent ground cover by cacao canopy; Tree spacing is 3x3 m (9 m\(^2\)); d1 (areal canopy area), d2 (height bt d1 and d3); d3 (projection of canopy area on ground, d1 > d3).

Canopy volume = \( \frac{1}{3} \pi d^2 \left[ \frac{d_1^3}{4} + \frac{d_1 x d_3}{4} + d_1 d_3 \right] \) \ldots\ldots..18

**Soil surface evaporation as affected by irrigation**

Soil evaporation (non-wetted surface;\( E_{dz} \) Soil surface outside the emitter wetting) and surface evaporation from the soil wetted by the emitters (emitter wetted zone;\( E_{wz} \))

The equations derived from method of Orgaz et al. (2006) which was adapted for estimating the average monthly value of \( E_{wz} \) and \( W_{dz} \)

Evaporation (\( E_{dz} \)) from soil not wetted by emitters (\( E_{dz} \))

\[ E_{dz} = K_{s, e} E_{To} \text{ (mm/day)} \] \ldots\ldots..19

Where \( G \) is ground cover fraction of tree canopy, is monthly rainfall amount, \( w_z \) is fraction of soil surface wetted by drip emitters (\( E_{To} = \text{reference ET}. E_{wz} \) of 0.6\( E_{To} \) for dense crop cover/plant density; \( E_{wz} \) is the of soil surface kept wet by emitters, and Cover crop coefficient varies from 0.25 to 0.8

Evaporation (\( E_{dz} \)) from soil not wetted by emitters (\( E_{dz} \))

\[ E_{dz} = K_{s, e} E_{To} \text{ (mm/day)} \] \ldots\ldots..20

Where \( G \) is ground cover fraction of tree canopy, is monthly rainfall amount, \( w_z \) is fraction of soil surface wetted by drip emitters (\( E_{To} = \text{reference ET} \))

**Cover crops/weed cover transpiration (\( T_{cc} \)).**

Weed cover up to 2 m in a 3 m row spacing

**Transpiration (\( T_{r} \)) of cacao orchard**

Cacao is deciduous (partly evergreen in some cases), its crop coefficient (\( K_{c} \)) and \( T_{r} \) were determined using the methods of ......... (........) and Orgaz et al. (2006).

\[ K_{c}, T_{r} = (Q_{d}F_{1}) F_{2} \] \ldots\ldots..21

\[ Q_{d} = 1- e^{-k_{ext}V_{u}} \] \ldots\ldots..22

where \( K_{ext} \) is radiation extinction coefficient.

\[ K_{ext} = 0.52 + 0.00079dp - 0.76e^{-1.25DAF} \] \ldots\ldots..23

\[ DAF = 2 - 0.53(V_{u} - 0.5) \] \ldots\ldots..24

where DAF must be > 2; \( V_{u} = V_{o}(dp/10000), V_{o} = 1/6xD^2H \)

\( E \) (exponent = 2.718), \( H \) (height of canopy; m); \( D \) is average canopy diameter, m); \( V_{o} \) is canopy volume \( m^3/\text{tree} \); \( V_{u} \) is canopy volume as amount on ground cover \( m^3/m^2 \); \( DAF \) is leaf area density; \( dp \) is tree density; number/ha), \( F_{1} = 0.07 \) for tree density greater than 300 trees/ha), \( F_{2} \) is monthly coefficient of \( T_{r} \) which is about 0.7 to 1.0 from wet to dry seasons

\[ Q_{d} = 1 - e^{-k_{ext}V_{u}} \]

\[ K_{c}, T_{r} = (Q_{d}F_{1}) F_{2} \] \ldots\ldots..25
ETc = ETo Kc, Kc,t

Kc,t is empirical coefficient relating the ET of an orchard of incomplete cover to a mature orchard of full canopy cover. In addition, Kc,t relates to horizontal projection of tree shade/canopy (ground cover percent; Orgaz et al., 2006), and Kc,t is about 0 to 70% of G

Cacao orchard Transpiration (Tr) was determined as:

Tr = Kc, Tr ETo

where Kc, Tr is transpiration coefficient which varies bt 0.75 to 1.0 seasonally until leaf senescence onset for a fully wetted orchards (sufficient soil moisture situation) (Kc,Tr decrease at senescence and recovers at the onset of rainfall.

Results And Discussion

Weather conditions during period of study

The late (minor) rainy season (mid August to December) is characterized by high cloud overcast (overcast sky), low air temperatures and higher relative humidity compared with the major rainy season (April to mid August) and the dry season (Fig. 1). On the average, the rainy season had higher mean relative humidity averaged (71%) and lower air temperatures (32.8 °C) compared with the dry season (December to March). Also, higher air temperature and VPD and lower relative humidity were found for the unshaded open sun cacao compared with the shaded plants.

A low pressure gravity-drip system was deployed to deliver water to cacao rootzone which alleviated moisture stress during the dry season. Across sampling dates, different amounts of irrigation water were applied based on cumulative Pan evaporation (EPan)*Pan coefficients for the respective irrigation treatments IrT1 (EPan.kc:1.0), IrT2 (EPan.Kc:0.7) and IrT3 (EPan.Kc: 0.5). Irrigation amounts on monthly averages were 1009.88, 706.91 and 504.94 mm while seasonal totals were 2116.5, 8482.95 and 6059.25 mm for IrT1; IrT2 and IrT3 treatments. Well irrigated treatment (IrT1, EPan.kc:1.0) had highest amount delivered and lowest by IrT3 (EPan.kc:0.5) (Fig. 2). The deficit irrigations (IrT2 and IrT3) delivered 79 and 68% respectively water to cacao rootzone compared with the well irrigated condition. Peak and significantly higher values of irrigation amount were delivered at DOY 45, 60, 75 and 90, periods which coincided with highest EPan values (> 5 mm/day).

The irrigation treatments (IrT1, IrT2 and IrT3) affected soil moisture contents within cacao root zone. Soil moisture contents adequately reflected the irrigation water delivered across measurement dates (Fig. 3). Highest soil moisture contents were obtained for well irrigated (IrT1) and lowest for deficit irrigation (IrT3) treatment. For the respective deficit irrigation treatments (IrT2 and IrT3: 0.7 and 0.5 EPan coefficients), average soil moisture contents were 61, 48 and 42% for IrT1, IrT2 and IrT3 irrigation treatments (Fig. 3). Highest soil moisture contents and crop evapotranspiration (ETc) were obtained from well irrigated plots (IrT1: EPan*kcp (1.0 (9.6 l/tree/day)) followed by IrT2 (EPan*kapc (0.7) (6.8 l/tree/day) and lowest for IrT3 EPan*kcp (0.5) (4.8 l/tree/day). The deficit irrigation treatments (IrT2 and IrT3) had lower soil moisture contents (14.7 and 11.8%) which equated to 30 and 50% water savings.

Declines in soil moisture contents were obtained from DOY 345 to DOY 60, followed by increasing trends in soil moisture from DOY 75 till end of measurement (DOY 150). Declining trends in the values of soil moisture contents may be attributed to the increasing intensities in climatic demand (high vapour pressure deficits). Unfavourable weather of high temperatures and soil evaporation and low atmospheric humidity would enhance soil moisture depletion thus the low soil moisture status (Agele et al., 2011, Agele 2021). Increases in moisture were observed from DOY 75 till end of measurement (DOY 150) can be attributed to rainfall received following its commencement (Mid March). In general, the observed trends in the status of rootzone moisture is attributable to the prevailing weather conditions denoted by increasing intensities of climatic demand (vpd) and temperatures during periods (DOY 345 to 60) of experiment.

Cycle of soil water before and after irrigation

Soil water contents were measured using soil samples within the 0 - 20 cm soil profile depth before and one day after each irrigation. Soil moisture contents across measurement days ranged between wilting point (140 mm) before irrigation and field capacity (260 mm) after irrigation (data not shown). For the low and high water stress conditions (IrT2 and IrT3), soil moisture was often close to wilting point before each irrigation. For the deficit irrigation treatments (IrT2 and IrT3: 0.7 and 0.5 Pan coefficients), available water fell below 50% more often than not during the period of study. Because much more water was applied under high Pan coefficients (Kcp 1.0), soil moisture contents of well watered treatments (IrT1) was higher compared with deficit irrigation (IrT2 (0.7 Kcp: and IrT3 0.5 Kcp) treatments. The well watered treatment (IrT1), most times, maintained soil moisture within field capacity range.

In general, based on the values of soil moisture, the stored water within crop rootzone profile was used up between irrigation cycles. This is attributable to the intensities of climatic stress (high temperatures and vapour pressure deficits) which presumably enhanced soil evaporation and the rapid depletion of water stored in the soil profile. Soil moisture content immediately following irrigation gradually decreased towards next irrigation event, this situation confirms the inability of soil moisture reserve to satisfy cacao water demand during the dry season which was consistent with earlier reports of Famuwagun et al. (2017) and Charles et al. (2019).

Soil moisture depletions over two measurement days were deployed to determine cacao water use (ETc). Cacao water use (ETc) differed across measurement dates and irrigation treatments (Fig. 4a). Average cacao evapotranspiration (ETc) were 139, 97 and 63 mm/day for the respective IrT1 (IrT1 (Kc:1.0), IrT2 (Kc 0.7) and IrT3 (Kc 0.5). Cacao evapotranspiration (ETc) for the deficit irrigation treatments (IrT2: 0.7 and IrT3 0.5 EPan coefficients) were averagely 45 and 70% less compared to values to adequate irrigation (IrT1) treatment which signified soil moisture deficit stress. Peak ETc values were obtained at DOY 45, 60 and
75 possibly due to high EPan (> 5 mm/day), lowest for DOY 120 and 135 with increases afterwards. The increases in cacao water use (ETc) from DOY 135 afterwards are attributable the commencement of rainfall and associated replenishment of soil moisture, lowering of temperatures (air and soil) and high atmospheric humidity (declining atmospheric demand). The well watered treatment (IrT1) had highest ETc and the more deficit irrigation (IrT3) had least cacao water use (Fig. 4a). The mean ETc across measurement dates were 5.07, 3.55 and 2.63 mm/day for IrT1, IrT2 and IrT3 irrigation treatments for the period of experiment (December to May).

In addition to single crop coefficient (kc = 1.31), cacao water requirement (ETc) was also computed using the dual (kr: 1.04) crop coefficient (Fig. 4b). Means of cacao water use for dual crop coefficient across measurement dates were 5.2, 3.7 and 2.8 mm/day for IrT1, IrT2 and IrT3 irrigation treatments for the period of experiment (December to May). The time course of cacao water use estimated using both the single and dual crop coefficients are presented in Fig. 5a, b and c. Results showed similar trends in cacao ETc for both methods and irrigation treatments while values were higher for the dual coefficient compared with the single kc (Fig. 5a, b and c). The decreasing order of ETc for single kc and dual kc were IrT1 > IrT2 > IrT3. Crop evapotranspiration (ETc) increased with increases in the volume of irrigation water applied, this modified values of ETc obtained for both the single and dual kc approaches.

The magnitudes of cacao ETc (single and dual crop coefficients obtained from the respective irrigation treatments followed from the irrigation water delivered (Fig. 5a, b and c). The irrigation regimes affected soil moisture contents and thus, its availability to meet crop water use. The values of cacao water use obtained from the respective irrigation treatments would have followed from the irrigation water delivered. Irrigation under well watered treatment increased tree water use and soil moisture status compared with deficit irrigation treatments (IrT2 and IrT3) which is consistent with reports on citrus by Yang et al. (2002). The magnitude of cacao ETc obtained in this study are within the range of those reported in literatures (Carr, 2011). Cacao water use (ETc) values ranging from 3 to 5 mm/day during rains and less than 2 mm/day in the dry season has been reported under irrigation regime of 10 litre/tree/day (Penman, 1948), Kohler et al. (2010) obtained cacao ETc of 2 mm/day and Moser et al (2010) obtained 1.3 – 1.5 mm/day in Indonesia. Cacao transpiration average of 1.31 mm d⁻¹ (about 10 litres per tree per day) and ETc computed with a Penman potential ETo of 3 – 5 mm d⁻¹ have been reported (Moser et al., 2010). This value equates to crop factor (Kc) of about 0.3 (Penman, 1948, Moser et al., 2010). Field data (based on the sap flow method) suggest ETc rates of less than 2 mm/day for cocoa crop with a complete canopy, this appear to be low compared with potential ETo estimate of 3–5 mm d⁻¹ using Penman equation (Penman, 1948).

The ETc/EPan ratio denotes the proportion of climatic water demand satisfiable by crop water use (ETc). Among the irrigation treatments. The proportions of Pan evaporation (EPan) to cacao water use (ETc) denoted as ETc/EPan ratio, differed across measurement dates and irrigation treatments. The means of ETc/EPan ratios across measurement dates were 1.016, 0.714 and 0.492 for the respective IrT1, IrT2 and IrT3 treatments (Fig. 6a). ETc/EPan curves were similar but the ratios ranged from 1.16 to 0.50 which indicated that both climatic demand (EPan) and cacao water consumption (ETc) were high during the dry season at the site of study. Although a weak relationship, linear regression equation was fitted to the ETc/EPan trends as: Y = 0.011x+0.94, R² = 0.32. The ratio of water use (ETc) to irrigation water applied denotes the proportion of irrigation water applied used for crop evapotranspiration. Trends of ETc to irrigation were similar among irrigation treatments and measurement dates but values differed among irrigation treatments (Fig. 6b). The mean values were 1.016, 0.714 and 0.492 for the respective IrT1, IrT2 and IrT3 treatments (Fig. 6b). Generally, the ratios ranged from 1.13 to 0.27, 0.79 to 0.19 and 0.57 to 0.14 which indicated differences in the ability of irrigation water applied to satisfy climatic demand (EPan) driven trends of cacao water consumption (ETc). When soil water is readily available to a crop, the rate of water evaporation from an Evaporation Pan is proportional to the rate of crop water use (Doorenbos and Kassam, 1979, Allen et al., 1998). Doorenbos and Kassam (1979) found positive linear and significant logarithmic correlation (P < 0.01) between ETc and EPan while Smajstrla et al. (2000) obtained significant logarithmic correlation (P < 0.01) between ETc and EPan. These reports confirmed the established close relationship between plant water consumption and Pan evaporation.

**Soil evaporation from cacao orchard**

The ETc from an orchard is more complex. In addition to tree Tr, there could be Tr losses from cover crop or from weeds, and there are E losses from the soil. Under irrigation conditions, there are two E components that may differ in their rates: one is the E from the soil areas wetted by the emitters, and the other is the E from the rest of the soil surface which is only wetted by rainfall.

Soil evaporation was respectively estimated for the wetted zone (Edz) and the non-wetted zone (Ewz) during the period of experiment. The mean values for soil evaporation for the wetted (Edz) were 5.65, 2.82 and 0.19 mm/month for the respective IrT1, IrT2 and IrT3 treatments. The seasonal totals soil evaporation for the wetted (Edz) and the non-wetted (Ewz) zones were 234.29 and 33.94 mm respectively. Based on the cumulative seasonal totals, soil evaporation for the wetted zone (Edz) was averagely 7 times compared with the non-wetted zone(Ewz) (Fig. 7).

Irrigation replenished soil moisture depletion while cacao canopy produced cover to soil and a more favourable microclimate around the canopy spread. This is appear to explain the magnitudes of soil evaporation from the wetted (Edz) and the non-wetted (Ewz) zones within cacao field (Tombesia et al., 2018). Studies also indicated that the conditions at the soil surface due to (i) the percentage of soil surface wetted via irrigation, (ii) the irrigation intervals and (iii) the soil exposure to light determine the dynamics of Tr and Es in orchards (Bonachela, 2001, Tombesia et al., 2018). In this study, drip irrigation was deployed...
to replenish moisture depletion from cacao root zone. There were spatial variations in the degree of wetting within the orchard; some areas are frequently wetted by the emitters while the rest of the soil surface remains dry in the absence of rainfall. The drip lines were placed near the trees while the wetted areas are shaded by the cacao canopy. The effects of orchard canopy and drip irrigation appeared adequate to alleviate radiation-limited soil water evaporation (E). Measurements and models suggest that E from the soil surface in orchards, which are wetted frequently (every 1-2 days) by emitters is equivalent to about 60 percent of the ETo from the wet areas (Bonachela, 2001, Garcia-Tegera et al., 2017). As a first approximation, the quantification of E from the wetted spots in a drip-irrigated orchard can be made using a semi-empirical model of Bonachela (2001) of the relation:

\[ E_s = 0.6 \times E_{To} \]

Total pod and bean yields were highest for IrT1 (35.4 and 2.29 t/ha) followed by IrT2 (22.1 and 1.37 t/ha) and lowest (10.3 and 1.03 t ha\(^{-1}\)) for IrT3. Bean yields decreased by 60 and 40% under IrT3 and IrT2 compared with IrT1 (Table 1). Deficit irrigation however produced 30 and 50% water savings compared to well watered treatment (IrT1). Water productivity was affected by irrigation regimes. Water use efficiencies values ranged between 0.3 and 0.04 t/mm for Y/ETc and 0.16 to 0.19 kg/mm for V/Irrigation respectively (Table 1). The yields of pods and beans were significantly higher in IrT1 treatments compared with IrT2 while they were lowest significantly for IrT3. However, Carr (2011) and Charles et al. (2019) had reported that fruit yield does not only depend on irrigation amount but a function of other management practices adopted and soil properties such as infiltration rate, and water holding capacity. Irrigation effect was profound both on number and weight of pods and beans in cacao. Evaluation of irrigation amount and frequency should not only consider fruit yield and yield components, but also consider WUE (Garcia-Tejero et al., 2011, Charles et al., 2019). Other studies have reported irrigation effects on biomass, pod and bean yields of cacao. Dicbalis et al (2010) working in Australia examined effects of seasonal irrigation requirement of 470 mm and 200 l/tree for weekly irrigation and obtained resultant bean yields of 1.5 – 2.7 t/ha. Based on field trials by Diczbalis et al. (2010), the annual irrigation requirement was estimated as 470 mm, with peak weekly requirements of about 200 l/tree (1250 trees ha\(^{-1}\)) while bean yields of between 1.5 and 2.7 t ha\(^{-1}\) were obtained as achieved from young trees.

### Table 1
Summary of measured soil and cacao variables

| Irrigation | Seasonal irrigation | Som (%) | ETo (kc:1.13) | ETo (kr t: 1.04) | ETo/EPan ratio | Seasonal ETc | No. Pods/plant | Pod wgt (kg) | No. Beans/plant | Bean Wgt/Plant (g) | Bean wgt (kg/ha) | WUE (l/ha) | WUE (ETc) | EWz |
|------------|---------------------|---------|---------------|-----------------|----------------|---------------|----------------|-------------|----------------|-------------------|------------------|-----------|----------|------|
| IrT1       | 33858.2             | 21.4    | 5.07          | 5.2             | 0.92           | 139.1         | 15.4           | 4429        | 114            | 396.5             | 4.41             | 0.0117    | 0.032    | 5.65 |
| IrT2       | 32705.3             | 17.3    | 3.55          | 3.7             | 0.73           | 97.3          | 12.3           | 3125        | 102            | 334.3             | 3.72             | 0.0142    | 0.043    | 2.82 |
| IrT3       | 16929.4             | 14.4    | 2.63          | 2.8             | 0.56           | 62.7          | 9.8            | 2673        | 91             | 308.1             | 3.42             | 0.0182    | 0.055    | 0.19 |
| LSD (0.05) | 4.1                 | 1.8     | 0.21          | 1.6             | 0.21           | 17.3          | 2.7            | 134.5       | 5.4            | 23.8              | 0.25             | 0.003     | 0.005    | 1.33 |

Cocoa is cultivated as a rainfed crop but sensitive to weather extremes of low rainfall, soil moisture deficit and high temperature stresses had been variously reported in the literature (Opeke, 2006, Zuidema et al., 2005, Daymond and Hadley, 2004, Daymond et al., 2002, Charles et al., 2019). Global warming (including 1.5 to 2°C), drought and other climate-related disasters are tied to the changing climate, extreme and variability of the weather (IPCC, 2014, UFFCCC, 2004). These situations would drive decreases of regional precipitation and increase in evapotranspiration driven (Sheffield et al., 2012, Tombesia et al., 2018, Agele, 2021). These conditions may enhance yield decreases associated with enhanced heat and water stress under present and future climate conditions. The climate models of the rainforest of Nigeria have been variously constructed (Akinyeye et al., 2017). The results indicate that the projected climatic changes will exacerbate soil moisture and thermal stresses with implications for crop performance (Agele et al., 2021). As precipitation becomes more variable and unpredictable in addition to the expected increased warming due to changing climate, development of water-saving management practices for sustainable agriculture now and in the future is envisaged (Sheffield et al., 2012, Tombesia et al., 2018, Agele et al., 2021).

Establishing the optimal irrigation scheduling is important in the development of water-saving practices for sustainable cacao production and climate stress alleviation in the wake of the hydrothermal (extreme heat and water deficits) stresses envisage under future climate.

The site of study in the rainforest zone of Nigeria is characterized by bi-modal rainfall pattern and the wet-dry season transition. The rainfall distribution pattern is bi-modal from April to July and September to November. The dry season which span December of a year to April of the other, is a terminal drought situation characterized by inadequate rainfall, soil moisture deficit, high vapour pressure deficit and temperatures and very clear sky (high intensity of solar radiation (Agele et al., 2016, Famuwagun et al., 2017, Charles et al., 2019). Such unfavorable weather condition will enhance hydrothermal stresses, evapotranspiration, leaf senescence, branch and twig die-back and even tree mortality (Famuwagun et al., 2017, Charles et al., 2019). Accurate estimates of crop water requirements plays an important role in the improvement of crop productivity and irrigation performance. This issue is particularly relevant considering the need for intensification of irrigation agriculture and increased water scarcity in several regions of the world.

**Conclusions**
This study evaluated the dynamics of root zone moisture and cacao water use (ETc) under variable irrigation regimes using EPan and variable Pan coefficients (Kcp: 1, 0.7 and 0.5) using a low pressure gravity-drip irrigation system. Variable Pan coefficients were evaluated for irrigation scheduling for cacao in the rainforest zone of Nigeria. A secondary innovation, was the determination of cacao water and irrigation requirements. Results showed that full irrigation treatment (IrT1:EPan *Kcp = 1.0) produced highest replenishment of depleted moisture from root zone and maximum cacao water use, LAI, pod and bean yields. The lower soil moisture status and water use (ETc) under reduced irrigation treatments (IrT2 and IrT3) were associated with lower pod and bean yields. Although, full irrigation treatment (IrT1: EpAn*Kc 100) enhanced soil moisture storage, cacao ETc, pod and bean yields, the deficit irrigation treatments (IrT2: 0.7Kcp and IrT3: 0.5 Kcp) were accompanied by 30 and 50 water savings. Soil evaporation from the wetted (emitter zones: Ez) represented good fraction of seasonal orchard evapotranspiration (ET), values ranged from 15-31% which constituted 31% ground cover or fraction of soil surface wetted by the emitters. The deficit irrigation strategies imposed mild to severe water stress of cacao, the water saving advantage can be scaled up as irrigation strategy for dry season irrigation. The study established cacao water use, and irrigation requirement, cacao water use (ETc) and suitable Pan coefficients for scheduling irrigation for cacao. Full irrigation involving high Kc (EPan*1.0) applied at 9.6 l/tree/day will be needed to replenish soil water depletion to satisfy crop consumptive water use (ETc: transpiration and soil evaporation components) during the terminal drought situation of the dry season in the rainforest zone of Nigeria. Findings from this study would find use for irrigation decision making for cacao cultivation in the rainforest of the tropics, which is of relevance in the premise of growing environment conditions imposed by the changing climate, extreme and variability of weather. The low pressure gravity-drip irrigation system alleviated climate stress during the dry season and improved cacao performance in a tropical rainforest environment.

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Figures

![Figure 1](image.png)

**Figure 1**

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