

# 1 **Dry season irrigation regime effects on water use, root zone moisture and yield** 2 **of cacao in a rainforest zone of Nigeria**

## 3 **Abstract**

4 *The humid tropics is characterized by wet-dry seasonal transitions, irrigation has the potential*  
5 *for building adaptation and resilience to climate stress for enhancing crop performance. A field*  
6 *trial was conducted to investigate the effects of dry season irrigation regimes on water use, root*  
7 *zone moisture dynamics and yield of cacao in a rainforest zone of Nigeria. Irrigation amounts*  
8 *computed as  $EPan \times Pan$  coefficients were based on cumulative class A Pan evaporation.*  
9 *Irrigation treatments were coded as IrT1 ( $EPan \times 1.0$ ), IrT2 ( $EPan \times 0.7$ ) and IrT3 ( $EPan \times 0.5$ ).*  
10 *Irrigation water was applied 5-days interval and discharged via point source emitters (2.8 l/h*  
11 *discharge rate ) on drip lines laterally installed per row of trees. Mean irrigation requirements*  
12 *were 4.49 mm (9.81:9.6 l/tree/day), 3.14 mm (7.06:6.8 l/tree/day) and 2.44 mm (5.49: 4.8*  
13 *l/tree/day) while total seasonal water applied were 121.19, 84.83 and 60.59 l/tree for IrT1, IrT2*  
14 *and IrT3 respectively. Mean soil moisture contents and cacao evapotranspiration ( $ET_c$ ) were 52,*  
15 *45 and 28 % and 4.54, 3.19 and 2.32 mm/day while evaporation from soil area wetted by*  
16 *emitters ( $EW_z$ ) were 5.65, 2.82 and 0.19 mm/day for respective IrT1, IrT2 and IrT3. The deficit*  
17 *irrigation strategies (IrT2 and 31 IrT3) imposed soil moisture deficit stress on cacao and*  
18 *produced lower pod and bean yields, it however enhanced water use efficiencies (25 and 44 %)*  
19 *and 30 and 50 % water savings. The study established suitable Pan coefficients for scheduling*  
20 *irrigation for cacao yield enhancement and drought (climate stress) amelioration.*

21 **Keywords:** *Cacao, Pan evaporation, crop coefficient, water use, seasonal transition, climate stress.*

22

## 23 **Introduction**

24 *Cacao (*Theobroma cacao* L.) is an important perennial fruit tree with an estimated annual world*  
25 *production of 3.2 million tonnes (FAO, 2012). Within the cocoa-growing belt of West Africa,*  
26 *sale of cocoa beans is a major foreign exchange earner, the cocoa sector employs millions of*  
27 *smallholder farmers (small farm sizes ranging from 0.5 to 5.0 hectare (ha) and contributes about*  
28 *70-100 % of their annual household incomes. In Nigeria, the main cocoa-producing areas are*  
29 *concentrated in the rainforest of the southern part of the country where an estimated 1.45 million*  
30 *hectares is cultivated. The productivity is 250 kg/ha, a yield level that is lower than those from*  
31 *Cote d'Ivoire and Indonesia (bean yields ranging from 600 to 1000 kg/ha respectively). In the*  
32 *smallholder cocoa farms of West Africa, farm sizes are small ranging from 0.5 to 5.0 hectare*  
33 *using low external inputs. The perennial fruit tree species of the rainforest of Nigeria: Cacao*  
34 *(*Theobroma cacao*), Coffee (*Coffea* spp) and Kola (*Kola* spp.) are characterized by deciduous*  
35 *growth habit but are cultivated under rainfed conditions (Opeke, 2006, Charles et al., 2019)*

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

54 Cocoa is cultivated as a rainfed crop, and it is highly sensitive to soil and weather conditions of  
55 low rainfall, soil and air moisture deficit and temperature stresses (Opeke, 2006, Zuidema et al.,  
56 2005, Charles et al., 2019). The changing growing environmental conditions (marginal soils and  
57 extreme weather events) impose constraints on cacao growth and productivity. In order to  
58 alleviate the constraints imposed by changing growing environmental conditions (marginal soils  
59 and extreme weather events) on cacao productivity, it is imperative to develop climatic-stress  
60 adaptive strategies for the fruit tree-based agroforestry systems of the rainforest tropics in the  
61 wake of changing climate/weather conditions (climate change and weather variabilities).

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

73  $ET_c = K_c ET_o \dots\dots\dots 1$

74 The FAO-56 dual crop coefficient approach (Allen et al., 1998, Allen and Pereira, 2009) also  
75 describes the relationship between crop evapotranspiration (ET<sub>c</sub>) and reference  
76 evapotranspiration (ET<sub>o</sub>) by separating the single K<sub>c</sub> into the basal crop (K<sub>cb</sub>) and soil water  
77 evaporation (K<sub>e</sub>) coefficients. In the FAO-56 single crop coefficient approach, the effect of both  
78 crop transpiration and soil evaporation are integrated into a single crop coefficient (K<sub>c</sub>).

79 However, crop evapotranspiration (ETc) estimation is more accurate by dual crop coefficient  
80 approach than the single crop coefficient approach, the dual crop coefficient approach uses more  
81 parameters and take soil practices and crop characteristics into consideration (Monteith, 1973,  
82 Ventura et al., 1999, Zhang et al., 2013). In the dual approach a daily basal crop coefficient  
83 (Kcb), representing primarily the plant transpiration, and a daily soil evaporation coefficient (Ke)  
84 are considered separately according to the equation:

85  $Kc = Kcb + Ke$  .....2

86  $ETc = (Kcb + Ke) ETo$  .....3

87 Kcb is a transpiration coefficient and Ke is an evaporation coefficient. The Kcb and Ke are the  
88 basal crop and the soil evaporation coefficients. For the dual Kc method, Ks applies only to  
89 transpiration (Tr) and provides actual transpiration (Ta). The values of Ks are obtained using its  
90 relationship with measured water stress indicators. The FAO procedure for estimating crop  
91 consumptive use requirements provides a list of Kc values for each crop and developmental  
92 stage. In the Kc approach both crop transpiration and soil evaporation are timely averaged into a  
93 single coefficient (Kc) commonly used to obtain the ETc for various crops. The FAO No. 56  
94 Publication offers the option of differentiating E from Tr by using a dual crop coefficient  
95 approach. The estimates of crop water requirements (ETc) are derivable from the product of  
96 potential evapotranspiration of a reference crop (ETo) using a crop factor (kc). Based on these  
97 relations:

98  $ETc = ETo * kc$  .....4

99 The crop coefficient kc is estimated as:

100  $kc = ETo/ETc$  .....5

101 The crop coefficient (Kc) is based on a theoretical understanding of the processes of transpiration  
102 and evaporation from a tall crop, and assumes full crop cover or frequent wetting of the soil  
103 surface. Allen et al. (1998) suggested a Kc value of 1.0–1.05 for a cocoa crop with a complete  
104 canopy.

105 Information is inadequate on the actual water use (ETc) of cocoa on the field (Carr, 2011).  
106 Estimated values of ETc ranging from 3 to 6 mm/day during rains and less than 2 mm/day in the  
107 dry season have been reported for cocoa (Penman, 1948). Field data (based on the sap flow  
108 method) suggest ETc rates of less than 2 mm/day for cocoa crop with a complete canopy, this  
109 appear to be low compared with potential ETo estimate of 3–5 mm d<sup>-1</sup> using Penman equation  
110 (Penman, 1948). In a simulated El Niño drought experiment reported by Moser et al. (2010) in  
111 Indonesia, there were no significant differences in cocoa leaf, stem and branch wood, or fine root  
112 biomass production between the rainfed control treatment and the one in which rain through-fall  
113 was reduced by 70–80% (for dry soil profile to permanent wilting point during the year). The  
114 combined average rate of water use by both cocoa and *Gliricidia sepium* (measured using heat  
115 dissipation sap flux sensors) was 1.3 mm. d<sup>-1</sup> in the protected plots reduced rain through-fall  
116 (rainfall reduction between 70–80 %) and 1.5 mm d<sup>-1</sup> in the control (70% of which was from the

117 cocoa trees). These crop water use values were described as low (Kohler et al., 2010). Over a  
118 consecutive 18-day period, transpiration average was equivalent to  $1.31 \text{ mm d}^{-1}$ , (about 10 litres  
119 per tree per day) compared with a Penman potential  $E_{To}$  estimate of  $3\text{--}5 \text{ mm d}^{-1}$  which equates  
120 to a crop factor ( $K_c$ ) of about 0.3 (Penman, 1948, Moser et al., 2010). The reports of cocoa water  
121 use and yield production when grown as mixed crop with coconut and once a week irrigation  
122 during November-December, once every six days during January-March and once in four to five  
123 days during April-May with  $175 \text{ l water tree}^{-1}$ . Maximum yields were obtained when cocoa was  
124 drip irrigated with  $20 \text{ l tree}^{-1} \text{ day}^{-1}$  and the total irrigation amount was  $175 \text{ l per tree}$ .  
125 Assuming a planting density of  $1600 \text{ trees ha}^{-1}$  ( $2.5 \text{ m} \times 2.5 \text{ m}$ ) these figures equate to water use  
126 values of  $5.6\text{--}7.0 \text{ mm d}^{-1}$  or  $3.9\text{--}4.8 \text{ mm d}^{-1}$ , and  $2.2$  or  $3.2 \text{ mm d}^{-1}$  at  $1100 \text{ trees ha}^{-1}$  ( $3 \text{ m} \times 3$   
127  $\text{m}$ ) under drip irrigation. No estimates of the yield benefits are given or the total quantity of water  
128 to be applied over a season. Based on field trials by Diczbalis et al. (2010), the annual irrigation  
129 requirement was estimated as  $470 \text{ mm}$ , with peak weekly requirements of about  $200 \text{ l tree}^{-1}$   
130 ( $1250 \text{ trees ha}^{-1}$ ) while dry bean yields of between  $1.5$  and  $2.7 \text{ t ha}^{-1}$  was achieved from young  
131 trees.

132 The annual total rainfall in the cocoa growing regions of Nigeria is about  $1500 \text{ mm}$  (less than  
133  $2000 \text{ mm}$ ). The rainfall distribution pattern is bi-modal from April to July and September to  
134 November. There is a short dry period from July to August during which the relative humidity is  
135 still high with over cast weather conditions. There is a main dry season from November to  
136 February-March. The four to six months of dry weather results in soil water deficit and since  
137 irrigation is not part of the farming system, causing seedling mortality (Famuwagun et al., 2017).  
138 In bearing plants, the existence of the short dry season during main crop pod filling can affect  
139 bean size if it is sufficiently severe. In adult plantings, water deficits result in lower yields and an  
140 increase in the level of mirid (capsid) damage. In the rainforest cocoa growing belt of west  
141 Africa, fruit trees in plantations (cacao, kola, coffee, citrus species and oil palm) are seldom  
142 irrigated especially during the terminal drought situation of the dry season. Few studies had  
143 addressed the responses of cacao to dry season irrigation especially, the effects of irrigation on  
144 root zone moisture dynamics, tree water use, growth and yield in the premise of unfavourable  
145 weather constituted by soil moisture deficit and high temperature stresses of the dry season.

146 Given the changing environment regimes (soil and weather/climate) and increasing worldwide  
147 demand for cocoa, it is important to develop sustainable production systems based on sound  
148 agronomic practices such as irrigation to ameliorate the extreme weather conditions  
149 (hydrothermal stresses), improve its productivity and extend frontiers of its production to  
150 marginal weather and soil conditions. Few studies had addressed these features in tropical trees  
151 and very little is known about cacao the responses of cacao to dry season irrigation in the  
152 premise of unfavourable weather constituted by soil moisture deficit and high temperature  
153 stresses. In addition, information is inadequate on water use of cocoa and dynamics of soil  
154 moisture extraction as affected by irrigation regimes. Experiments were designed to examine the  
155 effects of regulated dry season irrigation on root zone moisture dynamics tree water use, and  
156 bean yield of cacao in a rainforest zone of Nigeria.

## 157 **Materials and Methods**

158 *Experimental Site and Conditions*

159 An experiment was conducted on the Research and Experiment Station of the Department of  
160 Crop, Soil and Pest Management, Federal University of Technology Akure, Nigeria. Akure is  
161 located in the rainforest zone of south west Nigeria on latitude: 7° 18<sup>1</sup> N, Longitude: 5° 8<sup>1</sup> E and  
162 350 m abs. Five to six years old fruiting cacao trees which had been previously irrigated during  
163 dry season from seedling establishment (April, 2013) till date were used.

164 The cocoa-growing rainforest belt of southern Nigeria, is characterized by wet and dry season  
165 transition, and the seasons have variable weather conditions. The annual rainfall range from  
166 1500 to over 2000 mm distributed in a bimodal pattern within seven to eight months duration  
167 and 3 to 4 months of dry season. The dry season is a terminal drought situation characterized by  
168 inadequate rainfall,, soil moisture, high vapour pressure deficit and temperatures stresses and  
169 very clear sky (high intensity of solar radiation) (Famuwagun et al., 2017, Charles et al., 2019).In  
170 the rainforest cocoa growing belt of west Africa, fruit trees in plantations (cacao, kola, coffee,  
171 citrus species and oil palm) are seldom irrigated especially during the terminal drought situation  
172 of the dry season

173 *Soil characteristics and moisture determination*

174 The soil of the site of experiment is sandy-clay-loam with relatively high water holding capacity.  
175 Available soil water in the upper 0.60 m of the soil depth is 187 mm. the percent and volumetric  
176 soil water contents at field capacity and permanent wilting point are 21 and 10 % respectively.  
177 Mean bulk density was 1.25 g cm<sup>-3</sup>.

178 Soil samples were taken using soil Auger for water content measurement within the top soil layer  
179 (0 - 30 cm) by gravimetric method. Core samples were taken for bulk density and porosity  
180 measurement. Soil moisture content would attain field capacity in two days since the soil is  
181 sandy clay to silty clay loam (Agele et al., 2014). The samples were taken two days after and just  
182 before the next irrigation. The difference in moisture content between the two sampling periods  
183 was taken to be the moisture used. That is, the evapotranspiration by the crop for that period.  
184 Since it was assumed that drainage was negligible (no drainage), the moisture change was  
185 principally attributed to evapotranspiration. Soil moisture depletion (SWD) was obtained from  
186 the differences in soil moisture contents (changes in soil moisture contents:( $\Delta S$ ) measured  
187 between two measurement period. Soil moisture contents were determined weekly at 20 cm  
188 depths from soil samples taken with augers and core samplers.

189 **Irrigation Strategies**

190 Cacao trees were drip-irrigated based on levels of cumulative pan evaporation. Irrigation  
191 treatments were based on the restoration of cumulative Pan evaporation (EPan) using variable  
192 Pan coefficients (Kcp) of 100, 70 and 50 % (Allen et al., 1998; Sezen et al., 2010; Agele et al.,  
193 2014). The Pan coefficients (100, 70 and 50 % Kcp; the relative water deficit of 0, 0.3 and 0.5)  
194 indicated zero, high and low water stress conditions and respectively. Irrigation amount was  
195 calculated using Pan evaporation and Pan coefficients (Kcp1: 1.0; Kcp2: 0.7, and Kcp3: 0.5)  
196 according to Doorenbos and Pruitt (1975) and Allen et al. (1998) as:

197  $Ir = A * EPan * Kcp$ .....6

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

200 Irrigation treatments were coded as EPan \*100 Kcp (IrT1), EPan \* 70 % Kcp (IrT2) and EPan  
201 \*50 % Kcp ( IrT3) while irrigation was fixed at 5 days-interval for the three irrigation treatments.  
202 Irrigation treatment IrT3 had the maximum water deficit which was used to determine stressed  
203 baseline while IrT1 suggest adequate irrigation to meet full crop water requirements (the non-  
204 crop water stress baseline). Irrigation water was applied using gravity-drip irrigation system at  
205 4.8, 6.8 and 9.6 l/tree/day at each irrigation via point source emitters of 2l/h discharge rate which  
206 were installed on laterals per row of cacao tree spaced at 3 x 3 m. One drip lateral served each  
207 plant row and an inflow meter was installed at the control unit to measure total flow distributed  
208 to all replications in each treatment. Irrigation buckets were suspended on 3.5 m high tank  
209 stands to provide the required hydraulic heads (Agele et al., 2014, Charles et al., 2019).

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

211  $V = P * A * EPan * Kcp$  .....7

212 where, V, is the volume of irrigation water (L); P, wetting percentage (taken as 100 % for row  
213 crops); A, is plot area (m<sup>2</sup>); EPan is the amount of cumulative evaporation for the irrigation  
214 interval (5-days) and Kcp Pan coefficients (1.0, 0.7 and 0.5). This corresponded to 7.14 mm  
215 (1.93 l/day), 10.7 mm (2.90 l/day), 14.28mm (3.86 l/day) for the respective 0.5, 0.7 and 1.0 Kcp.  
216 In order to attain good plant stand, a pre-treatment total of 135 mm of irrigation water was  
217 applied equally to all treatment plots in several applications, this replenished soil water in the  
218 0.60 m profile depth to field capacity across treatments. Following the pre-treatments of 4.82  
219 l/day for 5 days, differential irrigation treatments commenced on 13<sup>th</sup> December , 2017 and was  
220 terminated May 9<sup>th</sup>, 2018. The amount of water applied per irrigation and seasonal irrigation  
221 amount varied from a maximum of 4.82 l/day and 127500 mm (DI<sub>1</sub> level) to a minimum of 1.93  
222 l/day and 20400 mm (DI<sub>4</sub> level). Irrigations continued until one week before the final harvest.  
223 Actual crop evapotranspiration (ETc) of cacao under the irrigation amounts was calculated with  
224 the water balance equation (Equation 1) (Agele et al., 2014)

225  $ET + I + P + \Delta S - Dp - Rf$  .....8

226 where, ET, is actual crop evapotranspiration (mm); I, the amount of irrigation water applied  
227 (mm); P the precipitation (mm);  $\Delta SW$ , changes in the soil water content (mm); Dp, the deep  
228 percolation (mm); Rf, amount of runoff (mm). Since the amount of irrigation water was  
229 controlled, deep percolation and run off were assumed to be negligible. Daily crop  
230 evapotranspiration was estimated using the pan evaporation data, pan factor and crop coefficient  
231 (Doorenbos and Pruitt, 1977, Agele et al., 2014). Data for Pan evaporation (EPan) used for the  
232 experiment were obtained from measurements with Class-A Pan (121 cm in diameter and 25.5  
233 cm in depth) from the Meteorological Station, Department of Meteorology & Climate Science,  
234 FUTA) located near the plots.

235 Deep percolation was considered as zero because there was no high underground water problem  
236 in the area. If available water in the root zone (0–90 cm) and total applied water amount by  
237 irrigation were above the field capacity, it would be assumed that water amount above field  
238 capacity leaked into the deeper soil zones and was called deep percolation (Dp: available total

239 water amount at 0–90 cm soil depth before irrigation + applied irrigation water field capacity)  
240 (Doorenbos and Pruitt, 1977). Total water requirement (WR) was determined using the relation:

241  $WR = A \times B \times C \times D \times E$  .....9

242 where : WR = Water requirement (l per day /plant) A = Open Pan evaporation (mm/day) B = Pan  
243 factor (1.0, 0.7 and 0.5), C = Spacing of plant (m<sup>2</sup> ), D = Crop factor (factor depends on plant  
244 growth, value for fully grown cacao = 1.13 but for cacao in the early fruiting stage, 0.83 was  
245 adopted). Water requirements (WR) were 9.63, 6.75 and 4.8 l/plant/day for the respective IrT1,  
246 IrT2 and IrT3 irrigation treatments.

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

250  
251  $TWR = WR \times \text{No. of Plants}$ .....10

252 Maximum allowable deficit (MAD) for cacao (50% of available water storage capacity of the  
253 soil (AWC) Gross irrigation requirement (GIR) of an orchard or vineyard, the computed ET<sub>c</sub>,  
254 which is considered as the net irrigation requirement (NIR), should be divided by the application  
255 efficiency (AE).

256  $GIR = NWR/AE$  .....11

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

### 259 *Orchard water use efficiencies*

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

262  $IWUE = \text{Biomass weight (Y)}/\text{total irrigation water applied (Ir)}$ .....12

263  $WUE (\text{crop}) = \text{Biomass weight (Y)}/\text{Cumulative seasonal ET}_c$ .....13

264 where IWUE is the irrigation water use efficiency (t.ha<sup>-1</sup> mm), EY is the economical yield (t.ha<sup>-1</sup>  
265 ), Ir is the amount of applied irrigation water (mm).

266  
267 Cacao water requirement was determined using FAO-56 single and dual crop coefficient models  
268 approach. The aim was to analyze the capacity of the FAO-56 single and dual crop coefficient  
269 models to assess cacao evapotranspiration and water requirements (estimating adequacy of  
270 irrigation amount for cacao) . The FAO-56 dual crop coefficient approach (Allen et al., 1998)  
271 describes the relationship between crop evapotranspiration (ET<sub>c</sub>) and reference  
272 evapotranspiration (ET<sub>0</sub>) by separating the single K<sub>c</sub> into the basal crop ( K<sub>cb</sub>) and soil water  
273 evaporation (K<sub>e</sub>) coefficients, while in the FAO-56 single crop coefficient approach, the effect of  
274 both crop transpiration and soil evaporation are integrated into a single crop coefficient  
275 (K<sub>c</sub>).Cacao orchard irrigation was scheduled from transpiration and evaporation coefficients  
276 (K<sub>cb</sub>, K<sub>e</sub>). FAO I&D No. 56 publication offers opportunity for differentiating E from Tr by  
277 using a dual crop coefficient approach, according to the equation:

278  $ET_c = (K_{cb} + K_e) ET_0$  .....14

279

280 where Kcb is a transpiration coefficient and Ke is soil evaporation coefficient.

281 Kcb is basal crop coefficient ( $k_{cb} = ET_c/ET_o$ )

282

283  $K_c = k_{cb} + k_e$ .....15,

284 and then,

285  $ET_c = (k_{cb} + k_e) ET_o$ .....16

286

### 287 **Size of cacao canopies**

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

295

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

298

299  $A = \frac{\pi d^2}{4} (m^2)$ .....17

300  $d$ = diameter of shaded area by cacao canopy ( 2m),  $A$  is per cent ground cover by cacao  
301 canopy; Tree spacing is 3x3 m ( $9 m^2$ );  $d_1$  (areal canopy area),  $d_2$  (height bt  $d_1$  and  $d_3$ );  $d_3$   
302 (projection of canopy area on ground,  $d_1 > d_3$ ).

303 Canopy volume =  $\frac{1}{3} \pi d_2 [ \frac{d_1^2}{4} + \frac{d_3^2}{4} + d_1 d_3 ]$ .....18

304

### 305 **Soil surface evaporation as affected by irrigation**

306 Soil evaporation from surface not wetted by emitters ( $E_{dz}$ : the rest of the soil surface outside the  
307 emitter wetting pattern ) and surface evaporation from the soil wetted by the emitters (emitter  
308 wetted zone ( $E_{Wz}$ ) were estimated.

309 The equations derived from the study on olive orchard ET by Orgaz et al. (2006) was adapted for  
310 estimating values of  $E_{Wz}$  and  $W_{dz}$

311 Evaporation ( $E_{Dz}$ ) from soil not wetted by emitters ( $E_{Dz}$ )

312  $E_{dz} = K_s \cdot e \cdot ET_o$  (mm/day).....19

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

317 Evaporation ( $E_{Dz}$ ) from soil not wetted by emitters ( $E_{Dz}$ )

318  $E_{dz} = K_s \cdot e \cdot ET_o$  (mm/day).....20

319 Where  $G$  is ground cover fraction of tree canopy, is monthly rainfall amount,  $w_z$  is fraction of  
320 soil surface wetted by drip emitters ( $ET_o$  = reference ET)

321 Cover crops/weed cover transpiration ( $Tr_{cc}$ ).

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

323

### 324 **Transpiration (Tr) of cacao orchard**

325 Cacao is deciduous (partly evergreen in some cases), its crop coefficient ( $K_c$ ) and  $Tr$  were  
 326 determined using the methods of Orgaz et al. (2006).

327  $K_c, Tr = (Q_d F_1) F_2 \dots \dots \dots 21$

328  
 329  $Q_d = 1 - e^{-k_{ext} V_u} \dots \dots \dots 22$

330 where  $K_{ext}$  is radiation extinction coefficient.

331  
 332  $K_{ext} = 0.52 + 0.00079 dp - 0.76 e^{-1.25 DAF} \dots \dots \dots 23$

333  
 334  $DAF = 2 - 0.53(V_u - 0.5) \dots \dots \dots 24$

335 where  $DAF$  must be  $> 2$ ;  $V_u = V_o(dp/10000)$ ,  $V_o = 1/6 \times D^2 H$

336  
 337  $E$  (exponent = 2.718),  $H$  (height of canopy; m);  $D$  is average canopy diameter, m);  $V_o$  is canopy  
 338 volume ;  $m^3/tree$ );  $V_u$  is canopy volume as amount on ground cover;  $m^3/m^2$ );  $DAF$  is leaf area  
 339 density;  $dp$  is tree density; number/ha),  $F_i = 0.07$  for tree density greater than 300 trees/ha),  $F_2$  is  
 340 monthly coefficient of  $Tr$  which is about 0.7 to 1.0 from wet to dry seasons

341  $Q_d = 1 - e^{-k_{ext} V_u}$

342  
 343  $K_c, Tr = (Q_d F_1) F_2 \dots \dots \dots 25$

344  
 345  $ET_c = ET_o K_c K_{r,t} \dots \dots \dots 26$

346  $K_{c,t}$  is empirical coefficient relating the  $ET$  of an orchard of incomplete cover to a mature  
 347 orchard of full canopy cover. In addition,  $K_{r,t}$  relates to horizontal projection of tree  
 348 shade/canopy (ground cover per cent; Orgaz et al., 2006), and  $K_{r,t}$  is about 0 to 70% of  $G$

349

350 **Cacao orchard Transpiration ( $Tr$ ) was determined as:**

351  $Tr = K_c, Tr ETO \dots \dots \dots 27$

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

355 **Results and Discussion**

356 **Weather conditions during period of study**

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

363 A low pressure gravity-drip system was deployed to deliver water to cacao rootzone which  
 364 alleviated moisture stress during the dry season. Across sampling dates, different amounts of  
 365 irrigation water were applied based on cumulative Pan evaporation ( $E_{Pan}$ )\*Pan coefficients for  
 366 the respective irrigation treatments IrT1 ( $E_{Pan.kc}:1.0$ ), IrT2 ( $E_{Pan.Kc}:0.7$ ) and IrT3 ( $E_{Pan.Kc}:$   
 367 0.5). Irrigation amounts on monthly averages were 1009.88, 706.91 and 504.94 mm while  
 368 seasonal totals were 2116.5, 8482.95 and 6059.25 mm for IrT1; IrT2 and IrT3 treatments. Well  
 369 irrigated treatment (IrT1,  $E_{Pan.kc}:1.0$ ) had highest amount delivered and lowest by IrT3

370 (EPan.kc:0.5) (Fig. 2). The deficit irrigations (IrT2 and IrT3) delivered 79 and 68 % respectively  
371 water to cacao rootzone compared with the well irrigated condition. Peak and significantly  
372 higher values of irrigation amount were delivered at DOY 45, 60, 75 and 90, periods which  
373 coincided with highest EPan values ( > 5 mm/day). The irrigation treatments (IrT1, IrT2 and  
374 IrT3) affected soil moisture contents within cacao root zone. Soil moisture contents adequately  
375 reflected the irrigation water delivered across measurement dates (Fig. 3). Highest soil moisture  
376 contents were obtained for well irrigated (IrT1) and lowest for deficit irrigation (IrT3) treatment.  
377 For the respective deficit irrigation treatments (IrT2 and IrT3: 0.7 and 0.5 EPan coefficients),  
378 average soil moisture contents were 61, 48 and 42 % for IrT1, IrT2 and IrT3 irrigation  
379 treatments (Fig.3). Highest soil moisture contents and crop evapotranspiration (ETc) were  
380 obtained from well irrigated plots (IrT1: EPan\*kcp (1.0 (9.6 l/tree/day) followed by IrT2  
381 (EPan\*kcp (0.7) (6.8 l/tree/day) and lowest for IrT3 EPan\*kcp (0.5) (4.8 l/tree/day). The deficit  
382 irrigation treatments (IrT2 and IrT3) had lower soil moisture contents (14.7 and 11.8 % ) which  
383 equated to 30 and 50 % water savings.

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

#### 395 ***Cycle of soil water before and after irrigation***

396 Soil water contents were measured using soil samples within the 0 - 20 cm soil profile depth  
397 before and one day after each irrigation. Soil moisture contents across measurement days ranged  
398 between wilting point (140 mm) before irrigation and field capacity (260 mm) after irrigation  
399 (data not shown). For the low and high water stress conditions (IrT2 and IrT3), soil moisture was  
400 often close to wilting point before each irrigation. For the deficit irrigation treatments (IrT2 and  
401 IrT3: 0.7 and 0.5 Pan coefficients), available water fell below 50% more often than not during  
402 the period of study. Because much more water was applied under high Pan coefficients (Kcp  
403 1.0), soil moisture contents of well watered treatments (IrT1) was higher compared with deficit  
404 irrigation (IrT2 (0.7 Kcp: and IrT3 0.5 Kcp) treatments. The well watered treatment (IrT1), most  
405 times, maintained soil moisture within field capacity range.

406 In general, based on the values of soil moisture, the stored water within crop rootzone profile  
407 was used up between irrigation cycles. This is attributable to the intensities of climatic stress  
408 (high temperatures and vapour pressure deficits) which presumably enhanced soil evaporation

409 and the rapid depletion of water stored in the soil profile. Soil moisture content immediately  
410 following irrigation gradually decreased towards next irrigation event, this situation confirms the  
411 inability of soil moisture reserve to satisfy cacao water demand during the dry season which was  
412 consistent with earlier reports of Famuwagun et al. (2017) and Charles et al. (2019).

413 Soil moisture depletions over two measurement days were deployed to determine cacao water  
414 use (ETc). Cacao water use (ETc) differed across measurement dates and irrigation treatments  
415 (Fig. 4a). Average cacao evapotranspiration (ETc) were 139, 97 and 63 mm/day for the respective  
416 IrT1 (Kc:1.0), IrT2 (Kc 0.7) and IrT3 (Kc 0.5). Cacao evapotranspiration (ETc) for the  
417 deficit irrigation treatments (IrT2: 0.7 and IrT3:0.5 EPan coefficients) were about 45 and 70 %  
418 less than values for adequate irrigation (IrT1) treatment. Peak ETc values were obtained at DOY  
419 45, 60 and 75 possibly due to high EPan (> 5 mm/day), lowest for DOY 120 and 135 with  
420 increases afterwards. The increases in cacao water use (ETc) from DOY 135 afterwards are  
421 attributable the commencement of rainfall and associated replenishment of soil moisture,  
422 lowering of temperatures (air and soil) and high atmospheric humidity (declining atmospheric  
423 demand). The well watered treatment (IrT1) had highest ETc and the more deficit irrigation  
424 (IrT3) had least cacao water use (Fig. 4a). The mean ETc across measurement dates were 5.07,  
425 3.55 and 2.63 mm/day for IrT1, IrT2 and IrT3 irrigation treatments for the period of experiment  
426 (December to May).

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

437 The FAO-56 dual crop coefficient approach (Allen et al., 1998) which describes the relationship  
438 between crop evapotranspiration (ETc) and reference evapotranspiration (ETo), separates the  
439 crop coefficient (Kc) into the basal crop (Kcb) and soil water evaporation (Ke) coefficients. In  
440 the single crop coefficient approach, the effect of both crop transpiration and soil evaporation are  
441 integrated into a single crop coefficient (Kc) while in the dual coefficient approach, a daily basal  
442 crop coefficient (representing plant transpiration: Kcb) and daily soil evaporation coefficient  
443 (Ke) in the form of  $K_c = K_{cb} + K_e$ . However, crop evapotranspiration (ETc) estimation is more  
444 accurate by dual crop coefficient approach than the single crop coefficient approach, the dual  
445 crop coefficient approach uses more parameters and take soil management practices and crop  
446 characteristics into consideration (Allen et al., 1998).

447 The magnitudes of cacao ETc (single and dual crop coefficients obtained from the respective  
448 irrigation treatments followed from the irrigation water delivered (Fig. 5a, b and c). The  
449 irrigation regimes affected soil moisture contents and thus, its availability to meet crop water use.  
450 The values of cacao water use obtained from the respective irrigation treatments would have  
451 followed from the irrigation water delivered. Irrigation under well watered treatment increased  
452 tree water use and soil moisture status compared with deficit irrigation treatments (IrT2 and

453 IRT3) which is consistent with reports on citrus by Yang et al. (2018). The magnitude of cacao  
454 ETc obtained in this study are within the range of those reported in literatures (Carr, 2011).  
455 Cacao water use (ETc) values ranging from 3 to 5 mm/day during rains and less than 2 mm/day  
456 in the dry season has been reported under irrigation regime of 10 litre/tree/day (Penman, 1948),  
457 Kohler et al. (2010) obtained cacao ETc of 2 mm/day and Moser et al (2010) obtained 1.3 – 1.5  
458 mm/day in Indonesia. Cacao transpiration average of 1.31 mm d<sup>-1</sup> (about 10 litres per tree per  
459 day) and ETc computed with a Penman potential ETo of 3 – 5 mm d<sup>-1</sup> have been reported  
460 (Moser et al., 2010). This value equates to crop factor (Kc) of about 0.3 (Penman, 1948, Moser et  
461 al., 2010). Field data (based on the sap flow method) suggest ETc rates of less than 2 mm/day  
462 for cocoa crop with a complete canopy, this appear to be low compared with potential ETo  
463 estimate of 3–5 mm d<sup>-1</sup> using Penman equation (Penman, 1948).

464 The ETc/EPan ratio denotes the proportion of climatic water demand satisfiable by crop water  
465 use (ETc). Among the irrigation treatments. The proportions of Pan evaporation (EPan) to cacao  
466 water use (ETc) denoted as ETc/EPan ratio, differed across measurement dates and irrigation  
467 treatments. The means of ETc/EPan ratios across measurement dates were 1.016, 0.714 and  
468 0.492 for the respective IrT1, IrT2 and IrT3 treatments (Fig.6a). ETc/EPan curves were similar  
469 but the ratios ranged from 1.16 to 0.50 which indicated that both climatic demand (EPan) and  
470 cacao water consumption (ETc) were high during the dry season at the site of study. Although a  
471 weak relationship, linear regression equation was fitted to the ETc/EPan trends as:  $Y =$   
472  $0.011x+0.94$ ,  $R^2 = 0.32$ ). The ratio of water use (ETc) to irrigation water applied denotes the  
473 proportion of irrigation water applied used for crop evapotranspiration. Trends of ETc to  
474 irrigation were similar among irrigation treatments and measurement dates but values differed  
475 among irrigation treatments (Fig. 6b). The mean values were 1.016, 0.714 and 0.492 for the  
476 respective IrT1, IrT2 and IrT3 treatments (Fig.6b). Generally, the ratios ranged from 1.13 to  
477 0.27, 0.79 to 0.19 and 0.57 to 0.14 which indicated differences in the ability of irrigation water  
478 applied to satisfy climatic demand (EPan) driven trends of cacao water consumption (ETc).  
479 When soil water is readily available to a crop, the rate of water evaporation from an Evaporation  
480 Pan is proportional to the rate of crop water use (Doorenbos and Kassam, 1979, Allen et al.,  
481 1998). Doorenbos and Kassam (1979) found positive linear and significant logarithmic  
482 correlation ( $P < 0.01$ ) between ETc and EPan while Smajstrla et al. (2000) obtained significant  
483 logarithmic correlation ( $P < 0.01$ ) between ETc and EPan. These reports confirmed the  
484 established close relationship between plant water consumption and Pan evaporation.

#### 485 **Soil evaporation from cacao orchard**

486 The ETc from an orchard is more complex. In addition to tree Tr, there could be Tr losses from  
487 cover crop or from weeds, and there are E losses from the soil. Under irrigation conditions, there  
488 are two E components that may differ in their rates: one is the E from the soil areas wetted by the  
489 emitters, and the other is the E from the rest of the soil surface which is only wetted by  
490 rainfall. Soil evaporation was respectively estimated for the wetted zone (Edz) and the non-  
491 wetted zone (Ewz) during the period of experiment. The mean values for soil evaporation for the  
492 wetted (Edz) were 5.65, 2.82 and 0.19 mm/month for the respective IrT1, IrT2 and IrT3  
493 treatments. The seasonal totals soil evaporation for the wetted (Edz) and the non-wetted (Ewz)  
494 zones were 234.29 and 33.94 mm respectively. Based on the cumulative seasonal totals, soil  
495 evaporation for the wetted zone (Edz) was averagely 7 times compared with the non-wetted  
496 zone (Ewz) (Fig. 7). Irrigation replenished soil moisture depletion while cacao canopy produced

497 cover to soil and a more favourable microclimate around the canopy spread. This is appear to  
498 explain the magnitudes of soil evaporation from the wetted (Edz) and the non-wetted (Ewz)  
499 zones within cacao field (Tombesia et al., 2018). Studies also indicated that the conditions at the  
500 soil surface due to (i) the percentage of soil surface wetted via irrigation, (ii) the irrigation  
501 intervals and (iii) the soil exposure to light determine the dynamics of Tr and Es in orchards  
502 (Bonachela, 2001, Tombesia et al., 2018).

503 In this study, drip irrigation was deployed to replenish moisture depletion from cacao root zone.  
504 There were spatial variations in the degree of wetting within the orchard; some areas are  
505 frequently wetted by the emitters while the rest of the soil surface remains dry in the absence of  
506 rainfall. The drip lines were placed near the trees while the wetted areas are shaded by the cacao  
507 canopy. The effects of orchard canopy and drip irrigation appeared adequate to alleviate  
508 radiation-limited soil water evaporation (E). Measurements and models suggest that E from the  
509 soil surface in orchards, which are wetted frequently (every 1-2 days) by emitters is equivalent  
510 to about 60 percent of the ETo from the wet areas (Bonachela, 2001, Garcia-Tegera et al., 2017).  
511 As a first approximation, the quantification of E from the wetted spots in a drip-irrigated orchard  
512 can be made using a semi-empirical model of Bonachela (2001) of the relation:

513  
514  $Es = 0.6 ETo$ .....28

515  
516 Total pod and bean yields were highest for IrT1 (35.4 and 2.29 t.ha<sup>-1</sup>) followed by IrT2 (22.1  
517 and 1.37 t.ha<sup>-1</sup>) and lowest (10.3 and 1.03 t ha<sup>-1</sup>) for IrT3. Bean yields decreased by 60 and 40  
518 % under IrT3 and IrT2 compared with IrT1 (Table 1). Deficit irrigations however produced 30  
519 and 50 % water savings compared to well watered treatment (IrT1). Water productivity was  
520 affected by irrigation regimes. Water use efficiencies values ranged between 0.3 and 0.04 t/mm  
521 for the ratio of yield to evapotranspiration (Y/ETc) and 0.16 to 0.19 kg/mm for ratio of yield to  
522 irrigation amount (Y/Irrig) respectively (Table 1).

523 The yields of pods and beans were significantly higher in IrT1 treatments compared with IrT2  
524 while they were lowest significantly for IrT3. However, Carr (2011) and Charles et al. (2019)  
525 had reported that fruit yield does not only depend on irrigation amount but a function of other  
526 management practices adopted and soil properties such as infiltration rate, and water holding  
527 capacity.

528 Irrigation effect was significant both on number and weight of pods and beans in cacao.  
529 Evaluation of irrigation amount and frequency should not only consider fruit yield and yield  
530 components, but also consider WUE (García-Tejero et al., 2011, Charles et al., 2019). Other  
531 studies have reported irrigation effects on biomass, pod and bean yields of cacao. Dicbalis et al  
532 (2010) working in Australia examined effects of seasonal irrigation requirement of 470 mm and  
533 200 l/tree for weekly irrigation and obtained resultant bean yields of 1.5 – 2.7t/ha. Based on  
534 field trials by Diczbalis et al. (2010), the annual irrigation requirement was estimated as 470  
535 mm, with peak weekly requirements of about 200 l tree<sup>-1</sup> (1250 trees ha<sup>-1</sup>) while bean yields of  
536 between 1.5 and 2.7 t ha<sup>-1</sup> were obtained as achieved from young trees.

537

538 Cocoa is cultivated as a rainfed crop but sensitive to weather extremes of low rainfall, soil  
539 moisture deficit and high temperature stresses had been variously reported in the literature  
540 (Opeke, 2006, Zuidema et al., 2005, Daymond and Hadley, 2004, Daymond et al., 2002, Charles  
541 et al., 2019). Global warming (including 1.5 to 2 °C ), drought and other climate-related  
542 disasters are tied to the changing climate, extreme and variability of the weather (IPCC, 2014,  
543 UFCCC, 2004). These situations would drive decreases of regional precipitation and increase in  
544 evapotranspiration driven (Sheffield et al., 2012, Tombesia et al., 2018, Agele, 2021). These  
545 conditions may enhance yield decreases associated with enhanced heat and water stress under  
546 present and future climate conditions. The climate models of the rainforest of Nigeria have been  
547 variously constructed (Akinseye et al., 2017). The results indicate that the projected climatic  
548 changes will exacerbate soil moisture and thermal stresses with implications for crop  
549 performance (Agele et al., 2021). As precipitation becomes more variable and unpredictable in  
550 addition to the expected increased warming due to changing climate, development of water-  
551 saving management practices for sustainable agriculture now and in the future is envisaged  
552 (Sheffield et al., 2012, Tombesia et al., 2018, Agele et al., 2021). Establishing the optimal  
553 irrigation scheduling is important in the development of water-saving practices for sustainable  
554 cacao production and climate stress alleviation in the wake of the hydrothermal (extreme heat  
555 and water deficits) stresses envisaged under future climate.

556 The site of study in the rainforest zone of Nigeria is characterized by bi-modal rainfall pattern  
557 and the wet-dry season transition. The rainfall distribution pattern is bi-modal from April to July  
558 and September to November. The dry season which span December of a year to April of the  
559 other, is a terminal drought situation characterized by inadequate rainfall, soil moisture deficit,  
560 high vapour pressure deficit and temperatures and very clear sky (high intensity of solar radiation  
561 (Agele et al., 2016, Famuwagun et al., 2017, Charles et al., 2019). Such unfavorable weather  
562 condition will enhance hydrothermal stresses, evapotranspiration, leaf senescence, branch and  
563 twig die-back and even tree mortality (Famuwagun et al., 2017, Charles et al., 2019).

## 564 *Conclusions*

565 The variable irrigation based on variable Pan coefficients (1.0, 0.7 and 0.5) affected dynamics of  
566 root zone moisture, cacao water use (ETc) and yields. Study established suitable Pan coefficients  
567 for scheduling irrigation during the terminal drought situation of the dry season in a rainforest  
568 zone of Nigeria. Relative to adequate irrigation (IrT1), deficit irrigations (IrT2 and IrT3)  
569 produced lower soil moisture, water use (ETc) pod and bean yields which were however  
570 accompanied by 25 to 44 % increases in water use efficiencies and 30 and 50 % water savings.  
571 The water saving advantage of deficit irrigation strategies can be scaled up for adoption. The  
572 low pressure gravitydrip irrigation system alleviated climate stress during the dry season and  
573 improved cacao performance. Findings will be of relevance to adaptation strategy in the premise  
574 of the changing climate, extreme and variability of weather while measured cacao water use  
575 (ETc) will find use for improving irrigation models for fruit trees.  
576

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582 any other journal]

583

## 584 **Highlights**

585 • *Irrigation based on variable Pan coefficients (1.0, 0.7 and 0.5) affected rootzone moisture, cacao water use*  
586 *(ETc) and yields.*

587 • *Deficit irrigations (IrT2:EPan \*0.7 and IrT3: EPan \* 0.5) produced lower water use (ETc), pod and bean yields*  
588 *of cacao, but enhanced water use efficiencies ( 25 to 44 %) and water savings (30 and 50 %).*

589 • *Low pressure gravity-drip irrigation alleviated climate stress and is of relevance as adaptation strategy in the*  
590 *era of climate change*

591

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710 Table 1. Summary of measured soil and cacao variables as affected by irrigation regimes. Irrigation  
 711 treatments were: IrT1: Epan\*1.0 kcp, IrT2: Epan \*0.7 kcp and IrT3: Epan \* 0.5 kcp.

Irrigation	Seasonal irrigation	Scm (%)	ETc Single (kc:1.13)	ETc Dual (kr t: 1.04)	ETc/EPan ratio	Seasonal ETc	No.Pod s/ plant	Pod wgt /plant (kg)	No. Beans / plant	Bean Wgt/ Plant (g)	Bean wgt (kg/ha)	WUE (Irr)	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	1.6	0.21	17.3	2.7	112.3	5.4	23.8	0.25	0.003	0.005	1.33

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713 Abbreviations: ETc::crop water use/evapotranspiration), ETc (single): ETc using single coefficient, ETc  
 714 (dual): ETc using dual coefficient, WUE: water use efficiency, EWUE(Irrig): WUE computed as ratio of  
 715 bean yield to irrigation amount(t/mm/ha), WUE (ETc): WUE computed as the ratio of bean yield to crop  
 716 water use (t/mm/ha), EWz (surface evaporation from soil area wetted by emitters (emitter wetted zone).  
 717 Following data analysis, the statistical significance of irrigation treatment on the measured variables was  
 718 indicated by the LSD while the significance of differences between treatment means were explored at P <  
 719 0.05. Irrigation requirement was based on cumulative class A Pan evaporation and Pan coefficients (kcp)

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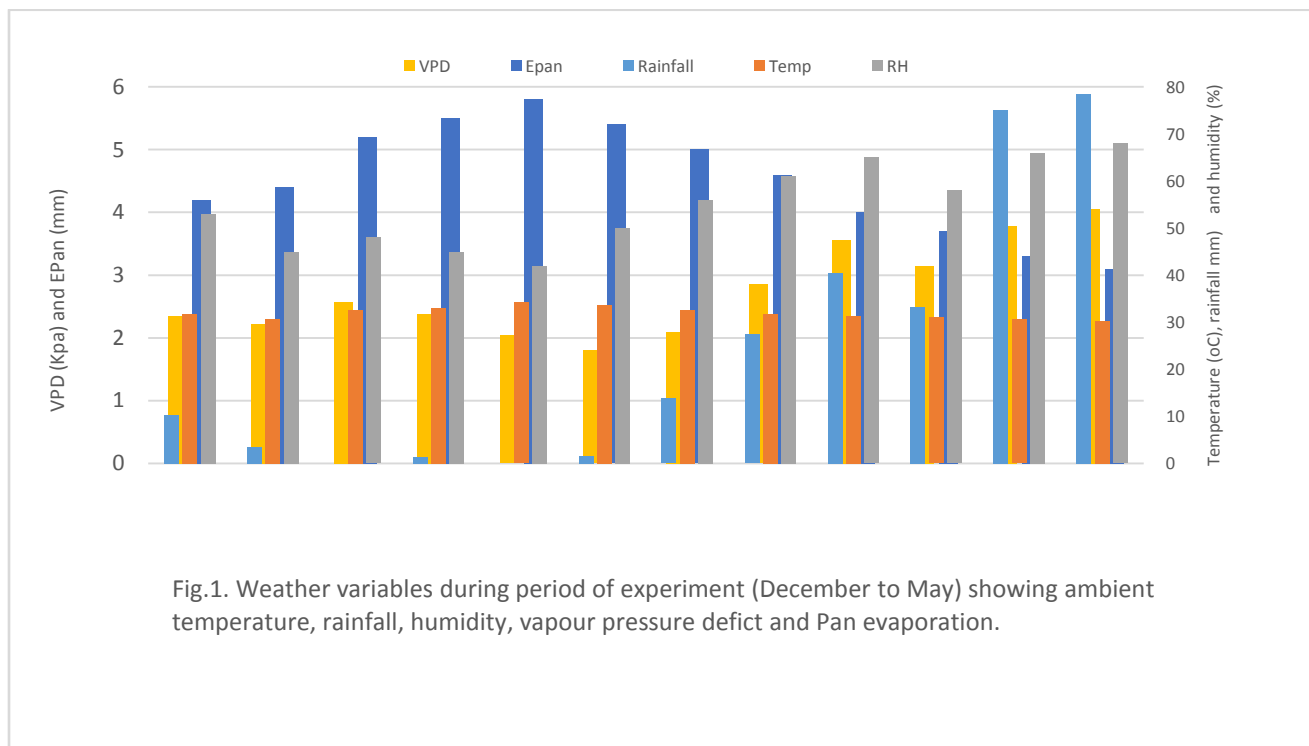
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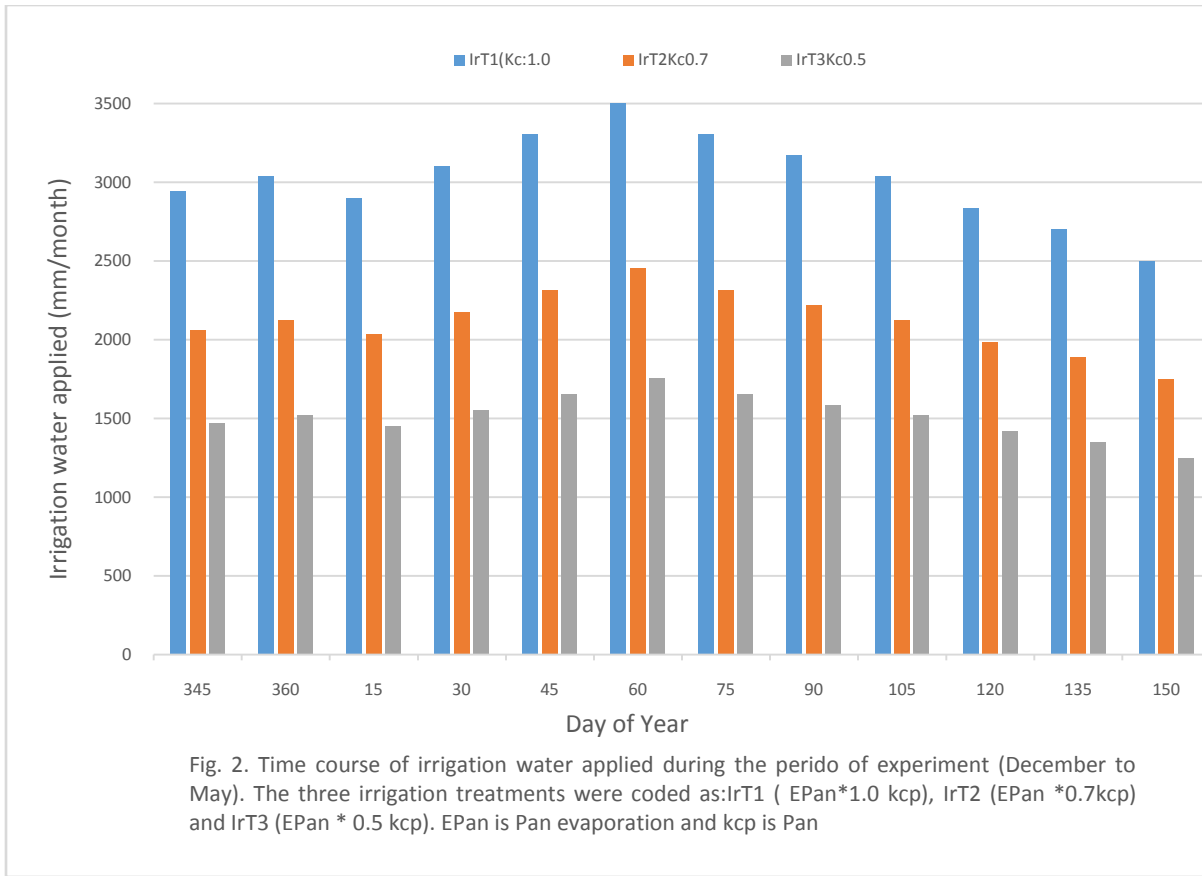
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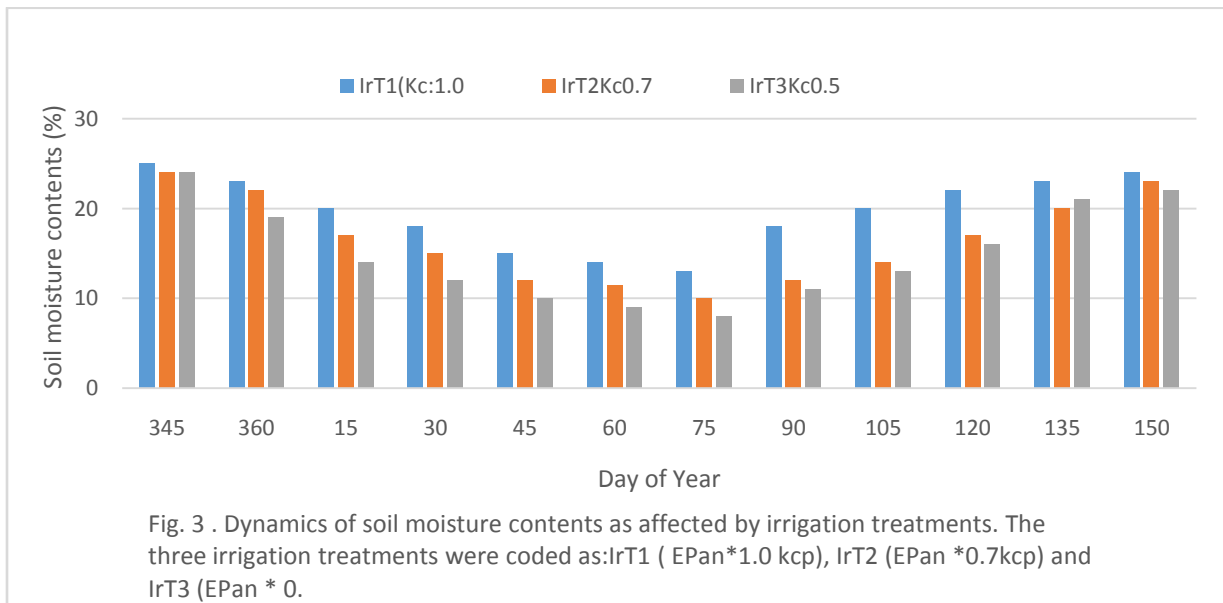
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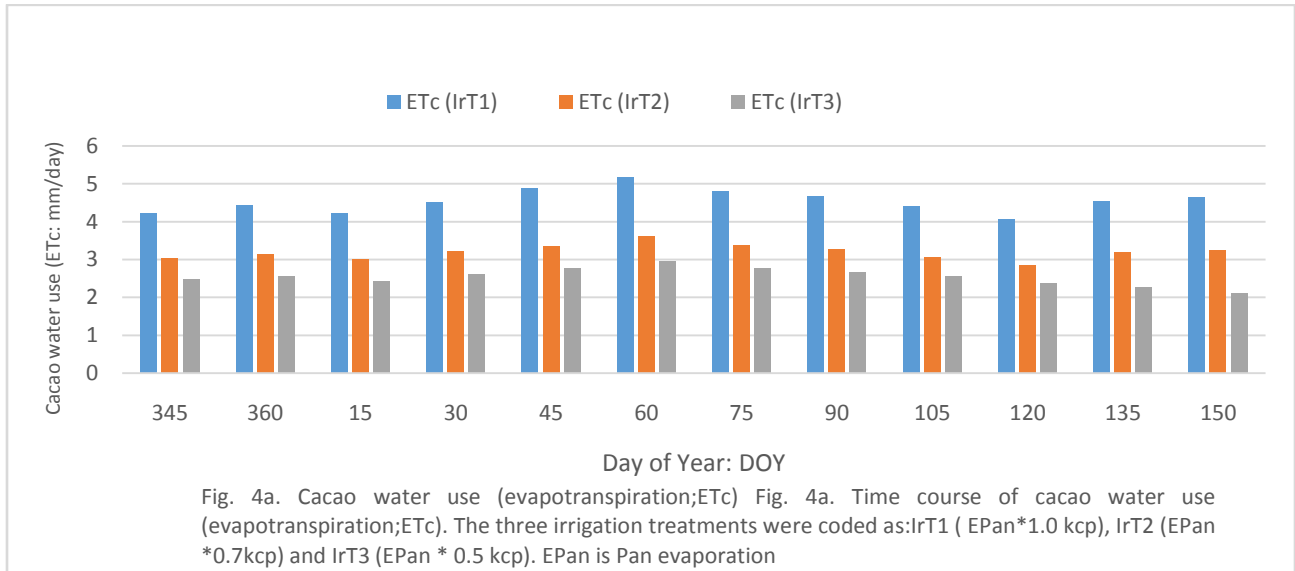
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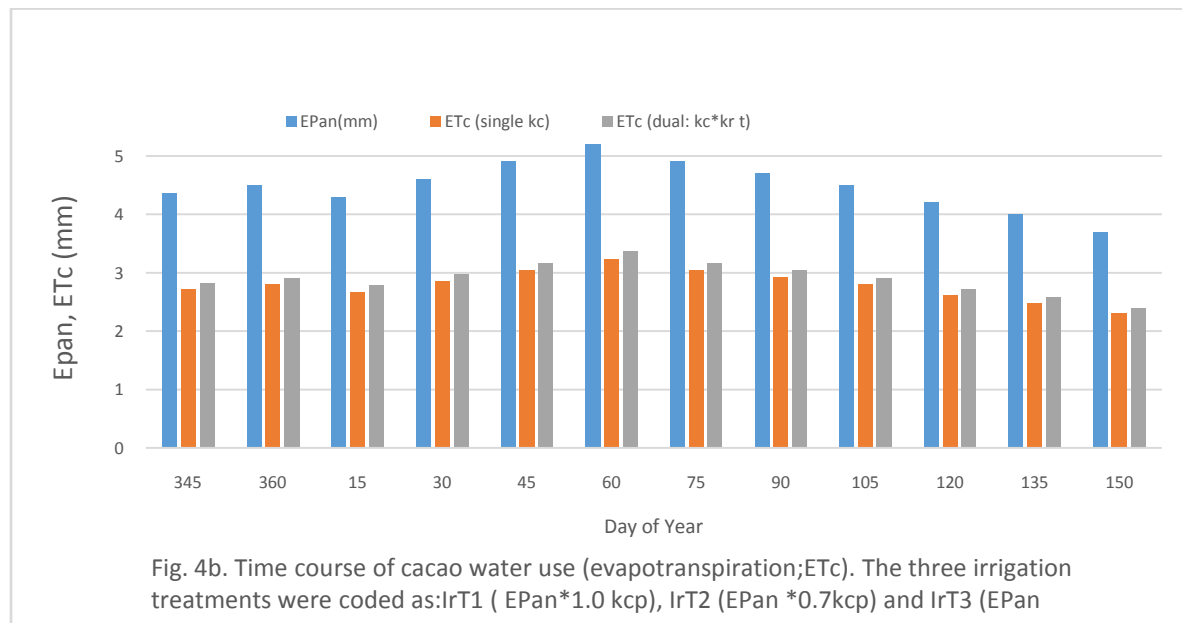
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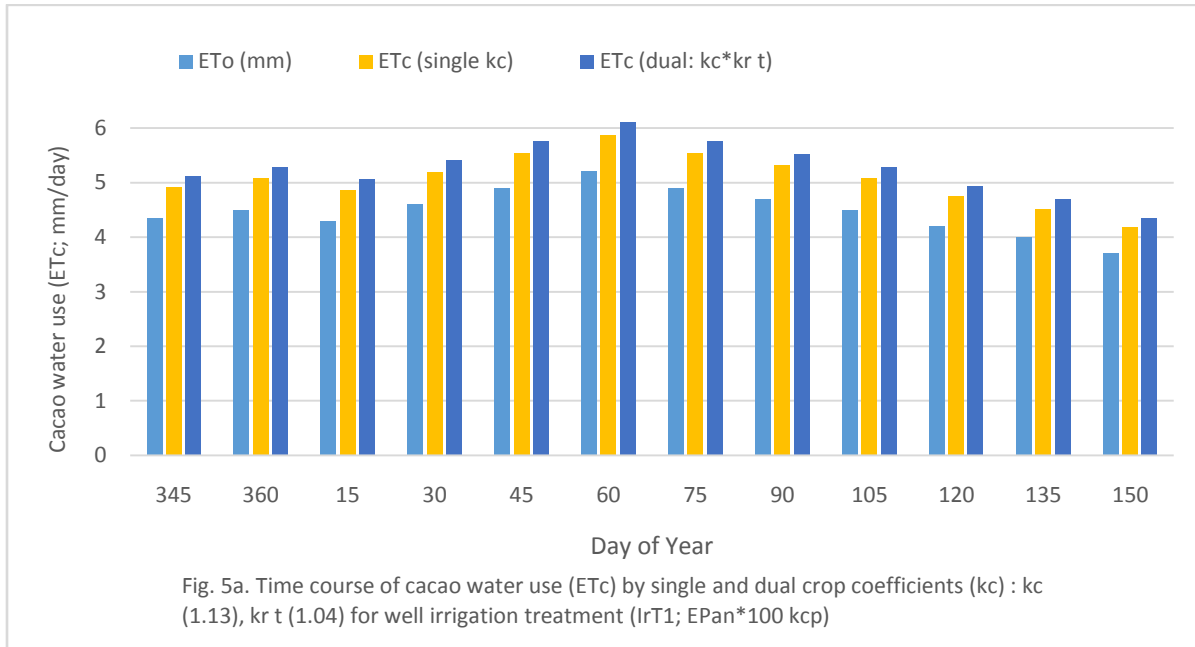
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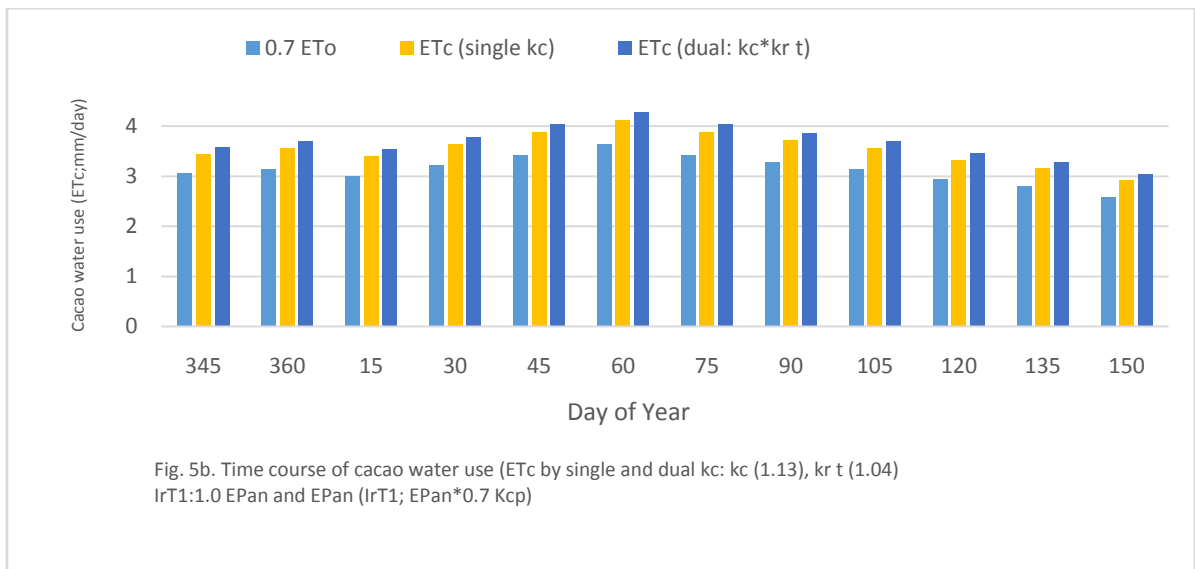
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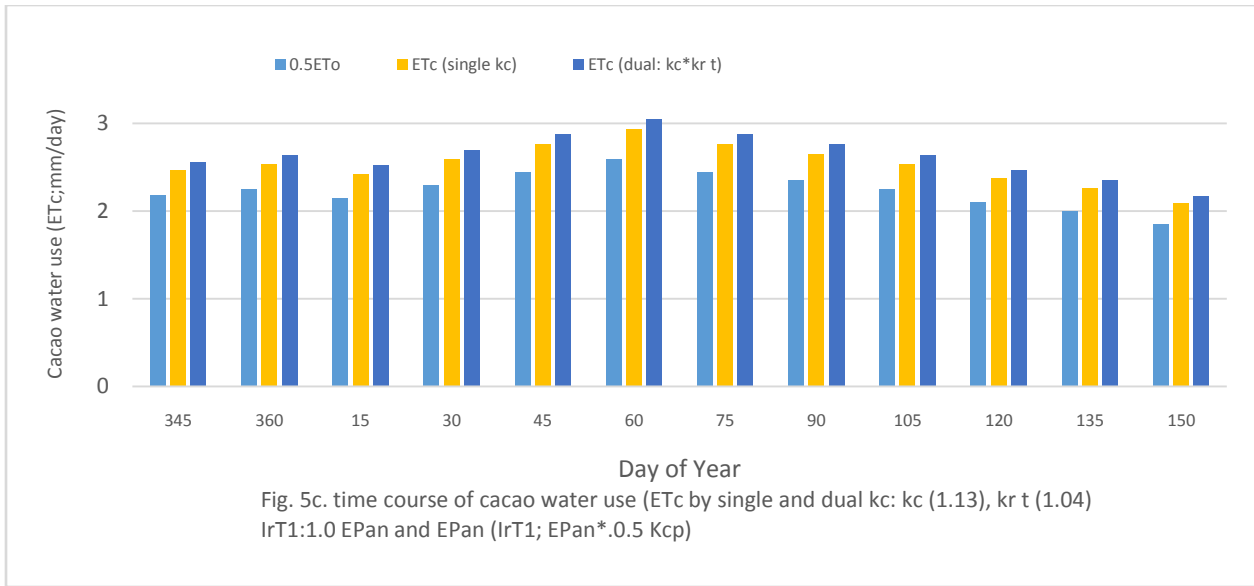
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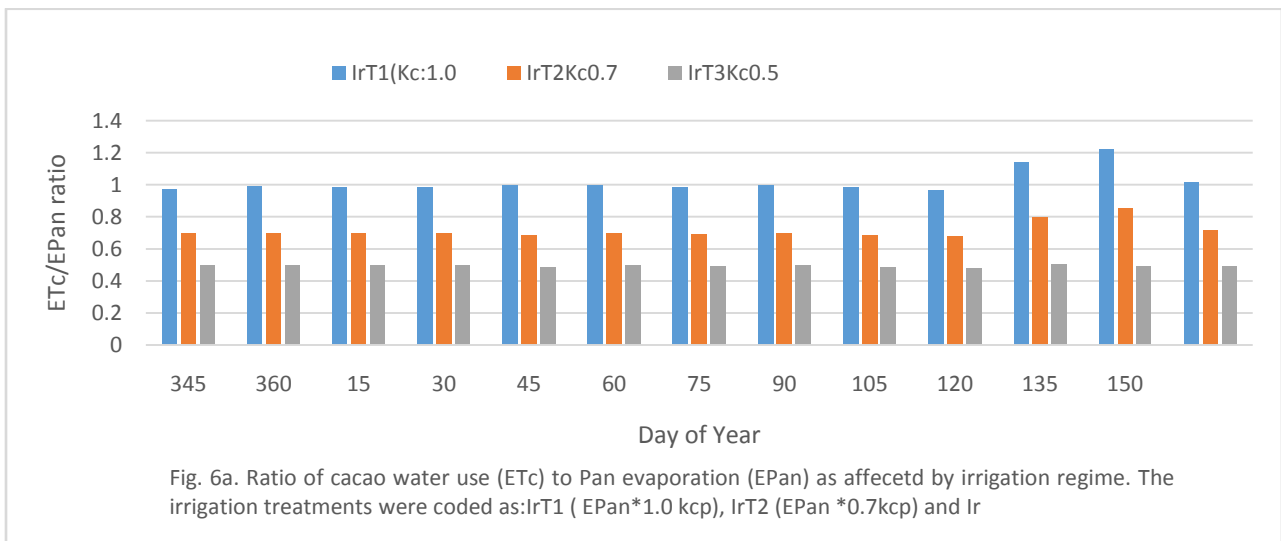
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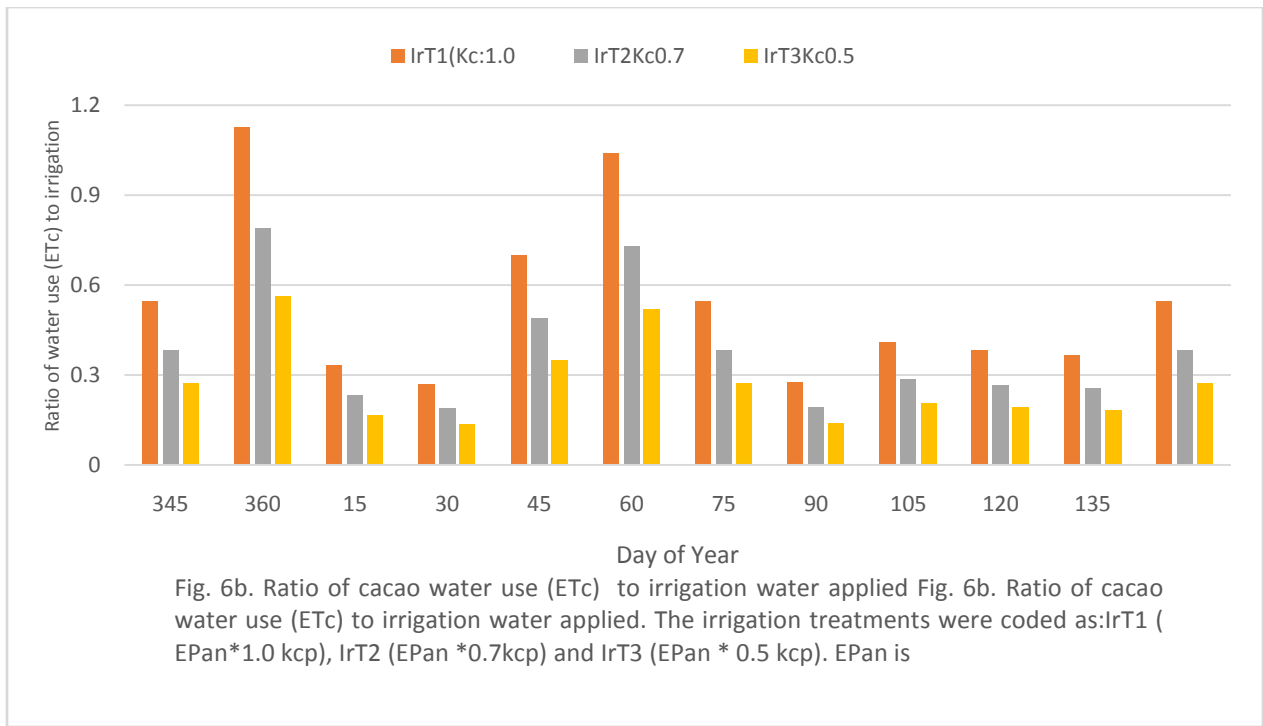
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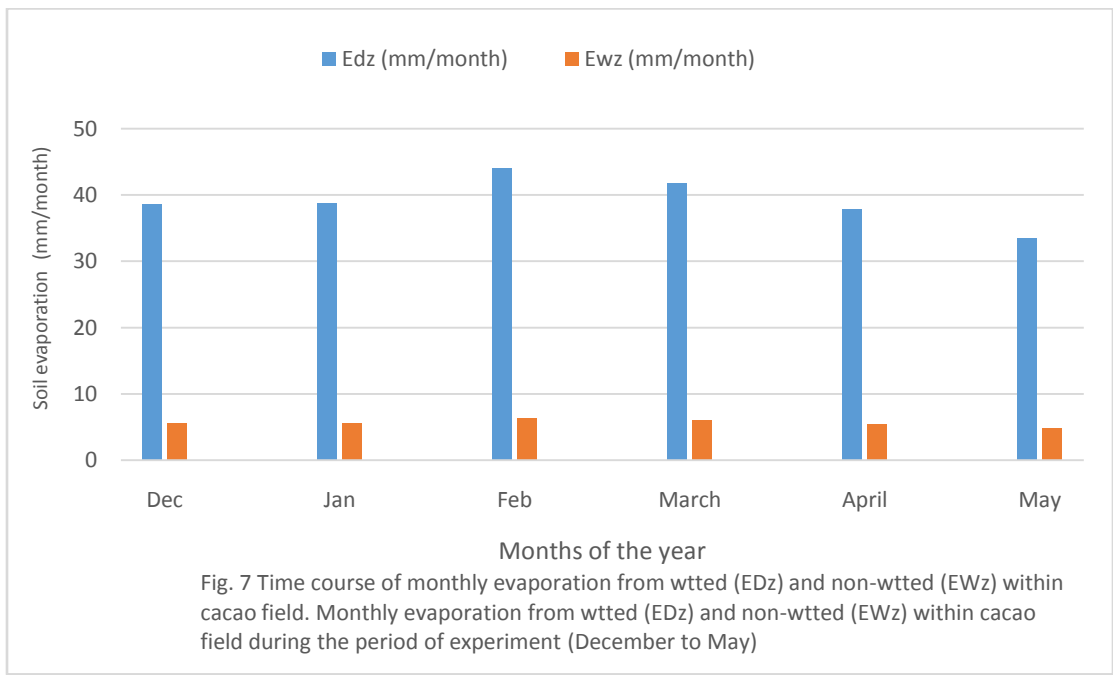


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