Cacao water use,canopy characteristics and yield as affected by irrigation and shade in a rainforest zone of Nigeria

Abstract

The effects of shade and dry season irrigation were examined on tree water use, canopy characteristics and pod and bean yields of cacao (*Theobroma cacao* L.) . Treatments were 2 by 2 factorial combinations of irrigation intervals (5 and 10 days) and shade and no-shade (open sun) laid out in a split-plot scheme with 3 replications. Shade regimes constituted the main plots and irrigation intervals the sub-plot treatments.Irrigation water was delivered at 5-and 10-day intervals on emiiterlines using gravity drip system. Irrigation combinations affected cacao canopy characteristics (leaf area index) and light integrals (photosynthetic active radiation (PAR) and canopy light attenuation (extinction coefficient, k) within the cacao field. The unshaded-irrigation had higher proportion of incident radiation (I) transmitted (Io) through the canopy (I_O/I), PAR intensity, and canopy extinction coefficients (k) compared with the shaded plus irrigations at 5-and 10-day intervals. Cumulative seasonal irrigation (12119 and 8483 mm), soil moisture contents (19.6 to 13.7 %) and cacao water use (ETc: 3.8 and 3.2 mm/day) differed for the respective 5- and 10-day irrigation intervals. The unshaded plus 5- and 10-day irrigation intervals out-yielded the shaded-irrigation combinations for number and weights of pods and beans. Pod and bean yields were significantly different under irrigation treatments, the 5-day irrigation produced greater number and heavier pods and beans compared with the 10-day irrigation. For the shade-irrigation combinations the range of values were: weights of pods (78000 to 6000 kg/plant), beans (4.8 to 3.2 t/ha) and water productivities: Irrigation WUE: 0.45 to 0.33 mm/kg/ha) and ET WUE: 0.11 to 0.09 mm/kg/ha). The shade-irrigation strategy enhanced cacao leaf area index, water use and bean yields and ameliorated climate stress.

Keywords: Cacao, irrigation, shade, canopy, radiation, light extinction, wet-dry, die-back, climate stress, tropics

INTRODUCTION

Cocoa (*Theobroma cacao* L.) is an important perennial fruit tree with an estimate 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 over 1000,000 smallholder farm families and contributes about 70-100 % of framers' annual household incomes. Cocoa is a major cash crop which contribute immensely to the economy of Nigeria, it is the second largest foreign earner after crude oil and has provided job by engaging millions of people who are engaged along the cocoa value-chain (Famuwagun et al., 2017). In Nigeria, the main cocoa-producing areas are concentrated in rainforest of the southern part of Nigeria with an estimated total cultivation area of about 1.45 million hectares. Estimated productivity per hectare from cocoa fields in Nigeria is 250 kg, a yield level that is lower than those from Cote d'Ivoire and Indonesia, which have annual yield rates estimated at 600 kg and 1000 kg per hectare, respectively. In the small holder cocoa farms of West Africa, farm sizes are small ranging from 0.5 to 5.0 hectare (Charles et al., 2019)

The rainforest agroecologies of the humid tropics is characterized by wet and dry season transition. The rainforest belt of southern Nigeria has annual rainfall ranging 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 deficit, high vapour pressure deficit and temperatures and very clear sky (high intensity of solar radiation (Agele et al., 2016, Agele, 2021). Such unfavorable weather condition enhance massive leaf senescence, branch and twig die-back and even tree mortality (Ruf, 2011, Famuwagun et al., 2017). Cocoa is sensitive to weather extremes of low rainfall, soil and air moisture deficit and temperature stresses (Zuidema et al., 2005, Daymond and Hadley, 2008, Charles et al., 2019). Soil moisture deficit and high temperature stresses of the dry season have been reported as the cause of the massive seedling and fruiting tree mortality in the dry season (Opeke, 2006, Kohler et al., 2010, Famuwagun et al., 2017). Given the changing environment regimes (soil and weather/climate) and imposes constraints on crop productivity, it is imperative to develop climate-stress adaptive strategies and sustainable production practices for ameliorating effects of climate stresses (extreme weather conditions (hydrothermal stresses) on crop performance in the fruit tree-based agroforestry systems of the humid tropics.

Cacao is a shade tolerant specie, in which appropriate shading could lead to adequate photosynthetic rates, growth and seed yield (Daymond et al., 1992, Carr, 2011). Shading also helps to reduce effects of unfavourable ecological factors, such as low soil fertility, wind velocity and excessive evapotranspiration (Anim-Kwapong, 2003, Abdulai et al., 2017). The trees used for shade greatly contribute to the pool of soil organic matter, carbon sequestration and maintenance of biodiversity (Charles et al., 2019). Specifically in regions with low access to inorganic fertilizers, the multi-strata plantation that provided shade is used to maintain soil fertility with subsequent increase in nutrient availability for cacao (Beer et al., 1998, Koko et al., 2007). Trees for shading also reduce wind speed and evapotranspiration (Beer et al., 1998), consequently decrease humidity stresses during the dry season (Anim-Kwapong, 2003, Charles et al., 2019). This is essential for the survival and the establishment of cocoa seedlings in dry and seasonally humid environments since they are highly susceptible to dehydration (Ruf, 2011, Famuwagun et al., 2017).

Cocoa is intercropped around the world with other tree species of economic value (Almeida et al., 2002, Almeida and Valle, 2007). In Ghana and Ivory Cost for example, 50% of the total cacao farm area is under mild shade whilst an average of 10% in Ghana and 35% in Ivory Cost is managed under no shade (Ruf, 2011). Despite that, the authors inferred that the economic life of an unshaded Amelonado Cocoa farm in Ghana may not last for more than 15 years of intensive cropping. This means that cocoa can be produced without shade (open sun) with adequate management practices and water and nutrient replenishment (Padovan et al., 2005, Ruf, 2011). Many studies have provided new insights regarding the resilience of cocoa systems under marginal but severe climatic conditions that are projected to increase in future especially in the cocoa cultivation areas of West Africa. Hence, increasing research effort should be diverted to develop climate stress adaptation strategies to serve as proxy for projected future climatic conditions in the cocoa a cultivation areas of the humid tropics (Beer et al., 1998, Koko et al., 2007, Famuawagun et al., 2017, Abdulai et al., 2017). Ruf (2011) and Abdulai et al. (2017) evaluated the resilience of cocoa agroforestry (cocoa under shade) to sub-optimal and extreme climate compared with full sun cocoa. The authors obtained significantly higher combined transpiration of cocoa and shade trees than cocoa in full sun during wet and dry periods.

During wet period, transpiration rate of cocoa plants shaded trees was significantly lower than full sun cocoa. During the extreme drought year, cocoa plants under tree shade suffered high (70%) mortality and massive stress with significantly reduced sap flux density compared with cocoa in full sun which maintained higher sap flux density. Moreover, cocoa sap flux recovery after the extreme drought was significantly higher in full sun than under shade. Soil water content in full sun was higher than in shaded systems suggesting that cocoa mortality in the shaded systems was linked to strong competition for soil water (Kohlerlscher et al., 2010, Moser et al., 2010). Cocoa plants under shade trees suffered severe water stress resulting in massive mortality, but when soil water content was reaching critical limits, cocoa under full sun showed the highest drought resistance. The combined transpiration rate of the shade trees and cocoa plants resulted in higher water uptake with consequent reduction in soil water than under the full sun system. Cocoa plants under shade trees suffered severe water stress resulting in massive mortality, but when soil water content was reaching critical limits, cocoa under full sun showed the highest drought resistance (Abdulai et al., 2017, Charles et al., 2019).

Similar observations have been obtained for coffee systems where full sun system had higher soil water content during dry and extremely dry periods (beer et al., 1998, Padovan et al., 2015). Based on their findings, the authors opined that promotion of cocoa agroforestry systems such as use of shade trees for cocoa in West Africa and other regions where extended droughts are occurring or will likely occur under future climatic conditions has to be carefully reconsidered. In particular, shade tree species such as leguminous A. ferruginea constitute major risk to cocoa functioning under extended severe drought (Koko et al., 2007, Abdulai et al., 2017).

During the terminal drought condition of the dry season, fruit tree species are subjected to massive leaf senescence, shoot dieback in the crown (patchwork fashion of dieback), and death of twigs/ branches (Opeke, 2006, Charles et al., 2020). Such observations obtained for severe tree death under soil and air droughts (moisture deficits) and high soil and air temperatures had been attributed to water stress-induced hydraulic failure and hence cavitation events in the soil-canopy continuum (McDowell et al., 2008, Allen et al., 2015, Haeberle et al., 2016). Although, fruit trees in plantations (cacao, kola, coffee, citrus species and oil palm) are seldom grown under irrigation, the crops, they however grow under unfavourable weather conditions characterized by soil and air droughts (moisture deficits) and high soil and air temperatures stresses during the dry season (Adams et al., 2009, McDowell and Savento, 2010). In addition to leaf senescence, shoot dieback in the crown (patchwork fashion of dieback), and death of twigs/ branches and tree mortality the dry season during pod filling, the soil and weather conditions of the dry season also exert profound effects on flowering and pod production and reduced bean yields if it is sufficiently severe (Opeke, 2006, Allen et al., 2015, Charles et al., 2019).

Irrigation has been reported as tool to minimize seedling mortality during the establishment phase especially in the dry season characterized by little or no rainfall. Drip irrigation is economical and effective in water management as it increases soil moisture availability to meet crop demand for growth and yield can also be attained via drip irrigation as a means of applying water to crops. (Anim-Kwapong and Frimpong, 2005, Famuwagun et al., 2017, Charles et al., 2019). Water requirements (ETc) derived from estimates of potential evapotranspiration by a reference crop (ETo) require a crop factor (Kc = ETc/ETo). Allen et al. (1998) suggested a Kc value of 1.0–1.05 for a cocoa crop with a complete canopy. The Kc value is based on a theoretical understanding of the processes of transpiration and evaporation from a tall crop, and assumes full crop cover or frequent wetting of the soil surface. There is however inadequate published reports on the irrigation requirement and water use of cocoa in the field. Based on field trials, Diczbalis et al. (2010) reported the annual irrigation requirement of cacao as 470 mm, depending on the site, with peak weekly requirements of about 200 l tree−1 (1250 trees ha−1). Dry bean yields of between 1.5 and 2.7 t ha−1 have been achieved from young trees (Diczbalis et al., 2010). Penman (1948) reported potential ETo estimate of 3–5 mm d^{-1} MeasuredETc values in the range of 3-6 mm/day during rains and less than 2 mm/day in the dry season have been reported while other field data (based on the sap flow method) suggest ETc rates of less than 2 mm/day for a crop with a complete canopy, appear to be low (Allen et al., 1998, Diczbalis et al., 2010). Huan et al. (1986) examined the effects of supplementary irrigation (drip) applied daily to cocoa hybrid seedlings after a dry period (no rain for two weeks) Annual dry bean yields were increased by irrigation by about 45 % which was followed by increase in pod number (averaging +39%) and in bean weight (+7%). Hutcheon (1977) investigated the role of irrigation on the induction of Amelonado trees to flower throughout the dry season in order to produce pollen for use in manual pollination of a seed orchard in Ghana. When the cherelles were continuously removed, irrigated trees produced 30% more flowers than those that were unirrigated, although the flowering patterns were the same. There was no benefit from using over-tree sprinklers (to reduce internal water stress by raising the humidity) rather than micro-sprinklers under the trees. When cocoa is grown as a mixed crop with are coconut, irrigate once a week during November-December, once every six days during January-March and once in four to five days during April-May with 175 l water $tree^{-1}$. Maximum yields are obtained when cocoa is drip irrigated with 20 l day−1 tree−1.’ Assuming a planting density of 1600 trees ha−1 (2.5 m × 2.5 m) these figures equate to rates of water use equivalent to 5.6–7.0 mm d−1 or at 1100 trees ha−1 (3 m × 3 m) 3.9–4.8 mm d−1, and 2.2 or 3.2 mm d−1 for drip irrigation. No estimates of the yield benefits are given or of the total quantity of water to be applied over a season.

The characteristics of radiant energy (availability, transmission, interception/capture) and use efficiencies, leaf area index (LAI), transmitted radiation and canopy extinction coefficient (k) are affected by cultural practices adopted by farmers who are mostly small holders. Daymond et al. (1992) and Acheampong et al. (2013) reported that biomass accumulation and overall development in cacao depends on the intensity of PAR. However, is reported that cacao exhibited low light compensation point and that light was not a major limiting factor to assimilate production in young cacao in the nursery. Maximum photosynthesis occur in cacao at about 20% of the intensity of full sunlight (Hutcheon, 1977; Acheampong et al. 2013). The gradients of microclimate and canopy characteristics and radiant (light) energy characteristics (incident and transmission), capture and use efficiencies of PAR and dynamics of leaf area within cocoa were affected by shade regimes (Daymond et al., 1992, Agele et al., 2016). Differences in the densities of shade is reported to affects radiant energy availability (incidence), transmission and capture by cocoa tress for photosynthetic dry matter production (Agele et al., 2016, Charles et al., 2019). It is reported that light penetration through cacao canopy is a factor of leaf area index (LAI) which depend on variety, age, planting density, leaf size and whorled leaf arrangement which altered solar energy more into diffuse light and hence promotion of interception and transmitted components of incident radiation (Abdulai et al., 2017). In the rainforest of West Africa, cocoa small holder farmers provide shade for coca using shade tree species such as *A. ferruginea* including plantain, is reported to affect light integrals (transmitted light, PAR and photo activities of the canopy of the understory cacao) (Beer, 1987, Agele et al., 2016) In particular, shade significantly reduced the fraction of solar radiation transmission (visible components) through the canopy to the understorey cacao plants and the resultant reduced canopy formation (LAI) and pod/bean yields (Charles et al., 2019).

The cocoa sector is characterized by high socio-economic value hence the need for the development of adaptation strategies to mitigate impacts of climate change which is relevant for its future sustainability and competitiveness. Required are development of sustainable production guidelines and packages based on short- and long-term adaptation strategies. Agronomic interventions based on shade provision and irrigation to ameliorate the extreme weather conditions (hydrothermal stresses) of the dry season would alleviate climate stress effects on cacao performance. Although shade is commonly used to improve establishment and growth of crops (Beer, 1987, Beer et al., 1998, Abdulai et al., 2017, Famuwagun et al., 2017), there is inadequate knowledge about the combined effects of shade and irrigation on cacao in the rainforest of the humid tropics.

The environmental stresses constituted by the variability of the seasonal weather conditions (wet-dry transitions) would implicate adjustment in plant water relations and water use in order to maintain physiological integrity and productivity. Few studies had addressed these features in tropical trees and very little is known about cacao the responses of cacao to dry season irrigation and shading in the premise of unfavourable weather constituted by soil moisture deficit and high temperature stresses. Information is inadequate on effects of irrigation on cacao water use (evapotranspiration) especially, during the terminal drought situation of the dry season in the rainforest agroecology of Nigeria. Improvement of crop productivity and irrigation performance particularly relevant considering the need for intensification of irrigation agriculture and increased water scarcity in several regions of the world.

This study was designed to investigate the effects of regulated dry season irrigation on tree water use, root zone moisture dynamics and bean yield of cacao in a rainforest zone of Nigeria. A secondary innovation, is to determine cacao water requirements and rootzone mositure dynamics. Accurate estimation 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.

Materials& Methods

Experimental Site and Conditions

An experiment was conducted on the field using 5 years old cacao trees which had been previously irrigated since the first year of field establishment (2012).The study was carried out on the Research Station of the Department of Crop, Soil and Pest Management Federal University of Technology, Akure, Nigeria. Akure is geographically georeferenced on coordinate lines of 734393E (latitude) and 808614N (longitude) on the western flank of meridians and is located in the rainforest zone of south west Nigeria. The rainforest zone is characterized by bi-modal rainfall pattern and wet-dry seasonal transition. The rainy season span March to December while the modal episodes are March to July and September to early December with a short dry spell from July to August. The main dry season is from December to March.The dry season 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).

Treatments and experimental design

The treatments were 2 by 2 factorial combinations of shade regimes (Open sun and shaded) and irrigation intervals of 5- and 10-days which were arranged in split-plot design.

Preliminary studies based on variable irrigation amount and frequencies for cacao in a rainforest zone of Nigeria showed promising results (Agele personal communication, Charles et al., 2019). The present is a follow up study aimed at validating split-application of14.28 mm (3.86 $l.day^{-1}$) at 5- and 10-day interval for shaded and unshaded cacao field

The shade regime constituted the main plot while irrigation intervals were the sub-plot treatment. There was a shaded no-irrigation control. Twenty (20) cacao seedlings were selected randomly from the shaded, open sun and shaded no-irrigation control plots for sampling and measurements.Shade was provided by plantain (Musa spp.)including planting distance and conditions for cacao and Musa spp

Irrigation Strategies:

A drip irrigation system (drip irrigation) was laid out on the field including. This included a pumping machine, good water source, pipes, drip lines, overhead tank (with stand), and pressure control valves. The irrigation strategy consisted of water application at 5-day and 10-day intervals using gravity-drip irrigation system and water was discharged via point source emitters on the drip lines which were laterally installed per row of the plot.

Irrigation regimes consisted of water application using gravity-drip irrigation system via point source emitters which were installed on laterals per row of crop. The emitters were installed on laterals per row of crop and were spaced 3 x 3 m apart. Irrigation buckets were suspended on 5 m high tank stands to provide the required hydraulic heads (Agele et al., 2014). Irrigation was imposed using low-head (gravity) drip system which supplied water to plant roots via drippers using inline emitters with discharge rate of 2 $L. h^{-1}$ were spaced at 3 m intervals on the lateral. One drip lateral served each plant row. Single drip lateral line was laid for each plant row. An inflow meter was installed at the control unit to measure total flow distributed to all replications in each treatment.Irrigation was imposed based on the restoration of cumulative potential evapotranspiration (ETo) using values computed by the FAO method (Doorenbos and Pruitt, 1975; Allen et al., 1998) in the form:

$$\mathrm{ETa} = \mathrm{KcETo} \ldots\ldots\ldots\ldots\ldots\ldots 1$$

where ETo is potential evapotranspiration and Kc is the crop coefficient (Doorenbos and Pruitt, 1975; Allen et al., 1998). Crop coefficient (Kc) for cacao was adopted from Allen et al. (1998) coefficient depends on plant growth and it ranges from 1 – 1.15 for complete canopy closure cacao field (Allen et al., 1998). However, 0.83 was adopted as crop coefficient for cacao in the

early fruiting stage). Potential evapotranspiration (ETo) values for the months of Dec-May were computed by the Penman-Monteith combination equation (Doorenbos and Pruitt, 1975; Allen et al., 1998) using data obtained from the Meteorological Observatory, Department of Meteorology and Climate science, FUT, Akure, Nigeria. The crop coefficient (kc) ranged from 1 – 1.05 for complete canopy closure cacao field (Allen et al., 1998).
Water requirement (WR) was determined using the relation:

$WR = A * B * C * D * E$……… 2

where : WR = Water requirement (l $day^{-1}.plant^{-1}$) A = Open Pan evaporation (mm/day) B = Pan factor (1.0), C = Spacing of plant (m^2), D = Crop factor. Irrigation amount (volume of water applied) was calculated using equation:

$V = P * A * EPan * Kcp$ …………..3

where, V, is the volume of irrigation water (L); P, wetting percentage (taken as 100 % for row crops); A, is plot area (m^2); EPanis Panevaporation and Kcp Pan coefficients (1.0). This corresponded to 14.28mm (3.86 l/day) an amountthat was applied at 5- and 10-day intervals

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) was:

$TWR + WR * Number\ of\ plants$ ……………4

Maximum allowable deficit (MAD) for cacao was assumed as 50% of available water storage capacity of the soil (AWC)

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 two weeks, differential irrigation treatments commenced on 20th December , 2017 and was terminated May 20th, 2018. The actual evapotranspiration (ETc) of cacao trees under the irrigation intervals (5- and 10-days) was calculated with the water balance equation (Equation 1) (Agele et al., 2014)

$ET = I + P + dS - Dp - Rf$ …………5

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 run off were assumed to be negligible.

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).

Soil water measurements were taken throughout the growing season using the gravimetric method.
Maximum (management) allowable deficit (MAD) for cacao was set at 50 %.

Weather variables at site of experiment during the period of experiment (soil and air temperatures, vapour pressure deficit (vpd), solar radiation, wind speed were obtained from the Meteorological Observatory, Department of Meteorology and Climate science, FUT, Akure, Nigeria.

Cacao leaf area index (LAI) and canopy light integrals (incident, transmitted and absorbed radiation, the ratio of radiation measurements below and above the canopy and PAR) were measured using Canopy Analyzer (Delta T, UK). Incident solar radiation (RI) above the canopy was measured using a Pyranometer connected to the canopy analyzer system. The line sensor was attached to metal frame and lifted above the cacao canopy. The mean of three readings of incident radiation was recorded, these being above the centre of a tree and at opposite edges. To measure transmitted radiation (RT), the mean of ten readings below the same tree was recorded using the canopy analyzer system. The equipment was placed in positions across the canopy to reflect spatial variation. A large number of readings were taken below the canopy than above because the light environment was more heterogeneous. Photosynthetic Active Radiation (PAR) was measured in addition to solar radiation. Measurements were taken from ten marked trees (representing ten sampling areas within the canopy) from each of irrigation-shade treatment. For each tree, readings were taken simultaneously above and below the canopy using two sensors. The analyzer measures light transmitted by the ratio of radiative measurements below and above the canopy (Agele et al., 2016). The fraction of radiation intercepted (R_{fract},%) was calculated as:

$$Rfrcat = (R1 - RT/RI \text{ ………..6}$$

where I (incident radiation above canopy), T (transmitted radiation)

Canopy extinction coefficient

The Beer–Lambert Law describes absorption of light by plant pigments in solution. This function demonstrates that the absorption of light will be more or less exponential with increasing intercepting area down through the canopy. The light extinction coefficient (k), according to the Beer–Lambert Law is:

$$k = \left[\text{loge } \left(\frac{I}{Io}\right)\right] /\text{LAI …………7}$$

$$k = -\ln (\text{I} - \text{Io}) /\text{LAI …………….8}$$

where I and I_o are the irradiance values upon and under the canopy, respectively and LAI is the leaf area index of leaves causing the light attenuation, and k is the extinction coefficient or slope of the curve when the natural log (In) I/ I_o is plotted against LAI.

Light extinction coefficient k is calculated according to Dingkun et al., 1999 and Stroppiana et al. (2005) by inverting Lambert-Beer's law as:

$Kdf = -\ln(0.94\mathrm{PARtransmitted}/\mathrm{LAI}$ 9

Thus, representative values of k for cacao under the irrigation-shade treatments can be derived from the regression of ln (PAR$_{\text{transmitted}}$) against LAI (Dingkuhn et al., 1999).
Fractional radiation (I) interception was calculated according to the equation:

$I = (Ri - Rt)/Ri$ 10
where Ri is incident radiation and Rt is transmitted radiation

The proportion of transmitted (TR) from the incident radiation (Ra) is obtained by the formula:

$TR(\%) = \left(\frac{Rb}{Ra}\right) * 100$............11

RESULTS

The weather variables during period of study (345 to 150 Day of Year: DOY) is presented in Fig. 1.The period is characterized by variable open water evaporation (EPan), air temperature and vapour pressure deficits (VPD), relative humidity (RH) and rainfall. High values of EPan,, temperatures and VPD contrary to the lowest values of rainfall and RH were found at periods between 360 and 60 DOY followed by increases in rainfall and RH values from DOY 75 to 150 following the commencement of the rains. These weather conditions constitute unfavourable environment for cacao

Irrigation water application was based on cumulative ETo and thus, values varied across the period of experiment and between the 5- and 10-days irrigation intervals (Fig. 2).The 5-day irrigation delivered greater amount of irrigation water to cocoa root zone across sampling dates compared with 10-day interval.Shade and irrigation affect soil moisture status under cacao and its time dynamics (Fig. 3a, b and c). The irrigation treatments involving 5- and 10- day intervals imposed on the open sun and shaded cacao, produced differences in moisture contents within cacao root zone. Soil moisture contents adequately reflected the irrigation water delivered across measurement dates, higher soil moisture contents were obtained for the 5- day irrigation interval compared with the 10-day irrigation treatment. On the average, soil moisture contents were averagely 48 % for the 10-day irrigation combined with unshaded and shaded treatments (Fig. 3a) compared with 5-day irrigation and shade regime combinations. The 10-day irrigation interval had lower soil moisture contents.Compared with DOY 45 and 120 period when lowest soil moisture were obtained across irrigation-shade combinations, higher soil moisture contents were found between DOY 345and 75 and between DOY 120 and 150. The lowest soil moisture contents were obtained between DOY 45 and 120 across irrigation-shade combinations (Fig. 3a). In particular, lowest values of cacao LAI were obtained for DOY 45 to 105 for both shaded and unshaded as well as the 5- and 10-day irrigation intervals. There were significant differences ($P < 0.05$) in soil moisture between the 5- and 10-day irrigation intervals (Fig. 3b) as well as between the open sun and the shaded cacao (Fig. 3c). However, the 5-day intervals of irrigation delivered higher irrigation amount and enhanced soil moisture status compared with the 10-day intervals (Fig 3c).

The time course of the status of soil water before and after irrigation using moisture contents measurements from 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 (Fig.4). For the low and high water stress conditions (10-day interval), soil moisture very often was close to wilting point between irrigation events, under which available water fell below 50% more often than not during the period of study. The well-watered treatment (5-day irrigation) 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.

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.5). The mean cacao evapotranspiration (ETc) were 3.72 and 3.54, and 3.44 and 3.15 mm/day and seasonal totals of 48.2 and 38.3 for the respective5- and 10- day irrigation intervals plus unshaded and shaded treatments. The crop evapotranspiration (ETc) for the 10-day irrigation was averagely 45 % less compared to the 5-day interval of irrigation. The time course of cacao evapotranspiration (ETc) showed that cacao water use declined between DOY 345 to 45 while lowest values were found for DOY 45 to 105 for both shaded and unshaded as well as the 5- and 10-day irrigation intervals (Fig. 5).The ratio of cacao evapotranspiration (ETc) to reference evaporation (ETo) is depicted in Fig. 6. Highest values of ETc/ETo were obtained for DOY 45 to 105. ETc/ETo ratios were higher for 5-day irrigation and unshaded compared with 10-day intervals and shaded treatments. The lowest values of ETc/ETo (0.73 – 0.64) were obtained for DOY 60 to 90. These trends in values of ETc/ETo confirmed the ability of soil moisture to meet atmospheric demand for water vapour (ETo), hence the ETc/ETo ratios (Fig 6).

The effect of shading and irrigation on cacao leaf development as exemplified by the leaf area index (LAI) is presented in Fig. 6. The shade regimes combined with irrigation produced significant effects on leaf development (canopy extent measured as the leaf area index: LAI). Open sun combined with irrigation (5- and 10-day intervals) had significantly higher LAI and compared with the shaded-5- and 10-day irrigation intervals (Fig. 7). Cacao is deciduous in nature, aside from this, the intensity of atmospheric (climatic) demand seems to have driven the dynamics of cacao LAI. Similar to observations of cacaoETc trends, declines in LAI were observed from DOY 345 down to DOY 45 and 120 period when lowest ETc were obtained across treatment combinations (Fig. 6). In particular, lowest values of cacao LAI were obtained for DOY 45 to 105 for both shaded and unshaded as well as the 5- and 10-day irrigation intervals. Across sampling dates, cacao LAI were larger for open sun compared with the shaded for both intervals of irrigation. The effects shade and irrigation regimes of cacao canopy light extinction coefficient (light attenuation, k) is presented in Fig 8. Canopy light extinction declined as the intensities of unfavourable weather increased during the dry season. Following the observed pattern of LAI, canopy extinction coefficient (k) declines sharply from DOY 345 till termination of experiment at DOY 150. Across the shade regimes, lowest values of k were obtained from DOY 60 to 150 and across the shade regimes, the mean values of k were close

(0.8883 and 0.9012) (Fig 8b). the effects of irrigation interval on canopy light extinction coefficient was similar to those of shade (Fig. 7c). Over the period of observation, the 5-day irrigation produced higher k compared with the 10-day interval of irrigation.

The time course (yearly pattern) of flower and pod production is presented in Fig.9. The unshaded-irrigation combinations and the 5-day irrigation interval had higher number of trees bearing flowers and pods compared with the shaded and 10-day irrigation. However, cacao trees bear flowers and pods while peak flowering was observed between DOY 135 and 210 (Fig. 9) and lowest number of trees and flowers borne on them between DOY 285 and 75. These periods were characterizedby differences in rainfall amount and high temperatures. The commencement of the rains appears to drive pod production early in the year (about DOY 40) and peaked between DOY 165 and 225 flowering the increased trend in pod production, peak in production was observed between DOY 165 to 225 (Fig.9).

The summary of the measured soil and cacao parameters as affected by shade-irrigation combinations is presented in Table 1. The values of intercepted radiation, PAR, LAI and canopy extinction (k) were relatively higher for the unshaded cacao for both irrigation treatments. For both the unshaded-irrigation and the 5- and 10-day irrigation intervals, soil moisture status (20 and 14 %), cacao water use ETC: 3.8 to 3.2 mm/day) and ETc/ETo ratio of 0.9 to 0.7. irrigation enhanced cacao yield components as the number and weights of cacao pods and beans were (435 to 16-10 & 130-110) and 78000 to 6000 kg/plant and 435 to 290 beans/plant (4.8 to 3.2 t/ha) while water productivities for irrigation (WUE Ir: 0.45 to 0.33) and water use (WUE ETc: 11 to 9 %).Across harvest dates, open sun cacao produced significantly higher number and weights of pods and beans (Table 1). Pod and bean yields were significantly different under the intervals of irrigation, the 5-day irrigation produced larger number, and heavier pods and beans compared with the 10-day interval. The 5-day irrigation interval combined with unshaded (open sun) treatment out-yielded the shaded in terms of number and weights of pods and beans. Similarly, the 5-day irrigation combined with shade regimes (open sun and shaded) produced significantly higher number and weights of pods and beans compared with the 10-day irrigation interval (Table 1). Across the shade and non-shade treatments, 5- day irrigation interval had significant effect on pod and bean yields compared with the 10- days irrigation. The open sun cacao that was subjected to 5-day irrigation interval produced significantly higher number and heavier pods and beans and total bean weight over the 10-day irrigation combined with shade treatments. Across the shade and non-shade treatments, 5- day irrigation interval produced significantly higher number of pods compared with the 10- days irrigation.

DISCUSSION

The shade-irrigation strategy adopted affected soil moisture status, tree water use (cacao evapotranspiration), cacao canopy and radiant energy characteristics, pod and ben yield of cacao. Results showed that solar radiation integrals: (the ratio of transmitted to incident radiation, photosynthetic active radiation (PAR) and cacao canopy character (leaf area index) were higher for open sun compared with the shaded cacao. In addition, LAI and PAR were higher for the unshaded combined with 5- and 10-day irrigation intervals compared with the shaded-irrigation combinations except for light extinction coefficient (k) which was higher for shaded plots.Anim-Kwampong and Frimpong (2005) and Agele et al. (2016) reported that shade affected light characteristics within cacao field in particular, ratio of transmitted to incident radiation, PAR and

LAI. Open sun had advantage over the shaded trees because shading reduced the fraction of solar radiation transmission (visible components) through the canopy to the understorey cacao plants in addition to the resultant microclimate modification (Daymond et al., 1992, Charles et al., 2019). Such modification would have affected evapotranspiration and moisture loss from soil and leaf surface. Yapp and Hadley (1994) has suggested the optimal leaf area index of 4.0 for cacao, other reports had established lower optimum LAI for cocoa varieties characterized by high level of self- shading which suggest that such varieties would require more maintenance pruning. Practically, due to overlapping of leaves, a LA1 > 1 is required to cover the land surface (Anim-Kwampong and Frimpong, 2005) which ensures that leaves are able to intercept and transmit light within its canopy. However, at high LA1, mutual shading occurs and leaves at the bottom of the canopy receive very low light intensities while the uppermost leaves are exposed to light far above that required for maximum photosynthesis (light saturation). It has been reported that cacao exhibited low light compensation point and that light may not constitute a major limiting factor to assimilate production especially for young cacao. Maximum photosynthesis occurs in cacao at about 20% of the intensity of full sunlight (Hutcheon, 1976; Yapp and Hadley,1994; Abdulai, 2017). Open sun cocoa performed better in term of leaf development measured as leaf area index (LAI) and light interception but had low extinction coefficient (k). Irrigation interval affected cacao canopy extent during the period of observation. LAI was higher for 5-day compared with the 10-day intervals of irrigation. This observation is consistent with the reports of Beer et al (1998) that shaded crops in agroforestry systems would be disadvantaged in growth and yield characteristics in circumstances of low intensity of radiation. Alvim (1977) and Yapp and Hadley (1994) also found that shaded crops have a lower photosynthesis rate than exposed leaves due to lower transmitted PAR. The amount of light transmitted to cacao trees differed between open sun and shaded trees, the full sun system received the greatest amount..The observed effects of irrigation and shade on fractional light interception could be explained by variable canopy extent (leaf area index:LAI). This observation can be explained in part by canopy architecture (as reflected by differences in extinction coefficients) and the fact that the open sun maintains higher leaf area index than the shaded. The relationship between leaf area index and radiation interception for various crops has been reported (linear curve for Indian mustard(Kumaret al., 1997) and curvilinear for potato (Firman and Allen, 1980) and maize (Maddonni and Otegui, 1996). Alvim (1977) and Abdulai et al. (2017) stated that light penetration through cacao canopy is a factor of leaf area index (LAI) which alter solar energy more into diffuse light and hence promotion of interception and transmitted components of incident radiation. Optimum radiation transmission to maintain physiological functions of cacao trees is 400 μmol m^{-1} s^{-2}(Alvim, 1977, Yapp and Hadley, 1994). Radiation transmission within cacao trees affects tree growth and yieldin addition to shade effects on temperature, humidity and vapour pressure deficit which are related to good physiological performance and production of cacao (Daymond and Hadley, 2008; Charles et al., 2019).Canopy extinction coefficient (k) were higher for shaded cacao compared with open sun-irrigation combinations. Higher extinction coefficient for shaded cacao may be due to the lower transmitted light (diffuse radiation). Korner (2002) and Carr (2011) had stated that canopy light attenuation (canopy extinction coefficient) depends on the amount of transmitted light through canopies (diffuse radiation) as determined by plant LAI.Shade affects the attenuation of light and other radiation characteristics within the canopy, hence the differences in the magnitudes of canopy extinction coefficients (k) between shaded and non-shaded cacao. Goudriaanand Monteith (1990) affirmed that low extinction coefficient enhanced growth when plant canopy is fully developed and uniformly distributed.Differences in extinction coefficient around 0.61 to 0.96 among cacao genotypes has been reported from data collected from some Brazilian cacao varieties (Alvim, 1977; Yapp and Hadley,1994). The generally high values of the extinction coefficient observed for cocoa are a reflection of the fact that leaves of Theobroma cacao tend to be orientated towards the vertical (Alvim, 1977; Yapp and Hadley,1994). Higher intensity of solar radiation (transmitted through the cacao canopy) and photosynthetic active radiation (PAR)obtained for the unshaded compared with the shaded appeared to have translated to improved vigour of growth and canopy formation in the former treatment. Acheampong et al (2013) reported that biomass accumulation and overall development of cacao dependon the intensity of PAR received.The shade-irrigation combinations affected soil moisture and cacao water use while tree canopy characteristics influence the extent of radiation load reduction, evaporative demand and subsequent microclimate environment within cacao (Daymond et al. 1998, Charles et al., 2019).In particular, the shade-irrigation treatments ameliorated climatic stress conditions (possibly reduced thermal load within canopy and understorey cocoa). Shade conserves soil moisture and reduced soil temperatures and surface evaporation (Beer, 1987; de Almeida and Valle, 2007; Moseret et al, 2010). Agele et al. (2016) and Charles et al. (2019) reported that shading on cacao canopy plays major role in temperature regulation within cacao field and resultant magnitudes of evapotranspiration and moisture loss from the soil and plant surface. Irrigation improves soil moisture status with consequent increases in tree transpiration. The modified microclimate would enhance CO_2 assimilation by leaves. Abdulai et al. (2017) and Charles et al., 2019) had reported that large extent of tree canopy will increase vegetative growth and photosynthesis activity of leaves. The size of canopy influence radiation intensities and its transmission within canopy layers, therefore, tree canopy characteristics has been related to its effectiveness at reducing radiant energy load in vegetated community (Monteith and Unsworth 1990). The reduction of hydrothermal stress would have implications for cacao survival and productivity during the terminal drought situation of the dry season in the study area. Shading offered soil cover which aided moisture conservation (reduction in soil evaporation) in addition to reduced soil temperatures and surface evaporation (Beer, 1987; de Almeida and Valle, 2007; Kohler et al, 2010; Moseret et al, 2010, Acheampong et al., 2013).Vegetation canopy size determine surface roughness of landscapes, air movements and cooling effects by heat/thermal dissipation (Monteith and Unsworth 1990, Almeida et al., 2002, Koko et al., 2007). Canopy via the absorption of radiation enhances convective heat transfer and heat exchanges, little heat storage (low heat capacity/low sensible heat storage) (Monteith and Unsworth 1990). The properties of vegetation in terms of canopy extent and size also affect the ratio of sensible to latent heat of vaporization. Large canopy reduces soil water evaporation but enhances transpiration from plants (modified ET)and therefore, vapour release and cooling effects (Monteith and Unsworth 1990). The pattern of light transmission through leaves alters light interception efficiency. Erneholm (1948) and Alvim (1977) had proposed the cardinal temperature requirements for cacao as: monthly minimum of 15 °C and an absolute minimum of 10 °C respectively.Daymond and Hadley (2004) also established for cacao, base temperature for vegetative growth for genotypes ranging between 18.6 °C and 20.8 °C and 9 °C as the base temperature for pod development. Others are temperatures ranging from 7.5 °C to 12.9 °C and for pod production of cacao genotypes ((Alvim 1977, Monteith et al., 1981, Daymond and Hadley, 2008). Cacao pod and bean size also decline with increasing temperature, although this response appears to be genotype specific (End et al. 1988, Daymond and Hadley 2008).During the terminal drought condition of the dry season, fruit tree species are subjected to massive leaf senescence, shoot dieback in the crown (patchwork fashion of dieback), and death of twigs/ branches. These observations may be attributed to water stress-induced hydraulic failure and cavitation events along the soil-canopy continuum (Carr, 2011, McDowell et al., 2008, Allen et al., 2015, Haeberle et al., 2015). The environmental stresses of the wet-dry transitions would implicate adjustment in plant physiology in order to survive the dry season drought and high temperature stresses during this period (Agele et al., 2021).Few studies had addressed how vulnerable cacao and other fruit tree species are to drought and high temperature stresses of the dry season and implications of such on tree survival and productivity.Under the wet and dry season transition situations of the rainforest, improved knowledge/information about the cacaoirrigation requirements and water use (evapotranspiration) at the individual stand and watershed scales will be helpful to elucidate partitioning of water resources among co-occurring species and cacao orchard water balance. Physiological plasticities may obliterate negative effects of such stresses on species adaptation, (Haeberle et al., 2015). The plasticity of physiological functions may therefore enhance the resilience of cacao to impacts of variability and extremes of the weather now and in the future. Tree mortality events are expected to increase under the various climate change scenario projjections (now and in the future).Even in moist and wet tropical forests, tree mortality associated with drought occurs with consequences on biodiversity, ecological communities, and the terrestrial carbon cycle (Adams et al., 2009, McDowell and Savento, 20110).In circumstances of the terminal drought of the dry season, tropical tree crops are subjected to water stress-induced hydraulic constraints which would implicate adjustment in plant water relations, water use and photsyntehsis (McDowell, 2011, Haeberle et al., 2015). Improved insights into the suite of physiological traits which confer enhancement of survival and productivity of cacao during the dry season. Such may be useful for model development, and the design of water management practices for fruit trees and sustainable orchard/watershed water balance. Global change characterized by a range of shifts in climate over time and pronounced shifts in rainfall patterns, high temperatures and frequency and severity of droughts may imply increases in water stress situations (Schroth et al. 2016) and marginal growing environments (Agele, 2021). Physiological plasticities may obliterate negative effects of environmental stresses or increase species adaptation (Haeberle et al., 2015). The plasticity of physiological functions may therefore enhance the resilience of cacao to impacts of variability and extremes of the weather. In circumstances of the terminal drought of the dry season in the humid tropics, tree crops are subjected to water stress-induced hydraulic constraints which would implicate adjustment in plant water relations and water use (McDowell et al., 2008, McDowel and Savento 2010, Haeberle et al., 2015). Various studies have provided values of cacao irrigation requirements and tree water use: Penman (1948) compute 3 – 5mm/day as ETc and ETc of about 1.3mm (10 litre/tree/day),Kohlerlscher et al. (2010) reported 2 mm/day, Moset et al (2010) 1.3 – 1.5 mm/day. In Cote d'Ivoire , the depth of irrigation of 920 -1650 mm and EPancoefficients between 1.0 to 0.6 and 224 mm cumulative cacao water use during the dry season produced between 30 to 60 % cacao bean yield increases (Dicbalis et al., 2010). Dicbalis et al (2010) working in Australia reported seasonal irrigation requirement at 470 mm and 200 l/tree for weekly irrigation requirement with resultant bean yields of 1.5 – 2.7t/ha, Due to the differences in irrigation scheduling based on 5- and 10-day intervals, higher amount of water was applied under the 5- day (535 mm) which consequently enhanced soil moisture contents and cacao water use (ETc) compared to the 10-day intervals. In this study, the yields of cacao genotypePA 150 Series among the shade-irrigation combinations ranged between 7800 to 6000 kg pods/plant and 430 to 280 g beans per plant (4.8 to 3.2 t/ha).The more frequent irrigation out-yielded by 20 and 24 % for pod and beans respectively.The results of a field scale irrigation trial in Peninsular Malaysia, Huan et al. (1986) examine the effects of supplementary irrigation (drip) applied to mixed cacao hybrid seedlings. Annual dry bean yields were increased by irrigation from 1500 to 2400 kg ha^{-1} (+60%) in 1982 and from 1150 to 1450 kg ha−1 (+28%) in 1983. This followedincreases in pod number (averaging +39%) and in bean weight (+7%). Theyearly time course of flower and pod production showed that cacao bear flowers and pods with variable intensities during the year under the shade-irrigation combinations. . is presented in Fig. 9. The unshaded-irrigation combinations and the 5-day irrigation interval had higher number of trees bearing flowers and pods compared with the shaded and 10-day irrigation. However, cacao trees bear flowers and pods while the observed peak in flowering and pod production appear to be driven by rainfall, temperature and atmospheric dryness (vapour pressure deficits). Variability in climate between seasons and seasonal trends in weather events could regulate seasonal periodicity, water use, flowering and fruiting characteristics and hence productivity in fruit tree species (Carr, 2011, Daymond et al., 2013). Literature reports the influence of soil water deficits on flower induction and fruit production in fruit tree species, these reports indicate that water deficits induce a preparedness to flower, such that subsequent rains or watering cause extensive flowering (Alvim, 1977, Hutcheon, 1981). Low atmospheric humidity of the dry season has been suggested as a possible limiting factor to flowering and fruiting of tropical fruit tree species (Hutcheon, 1981, Carr, 2011). Hutcheon (1981) examined the ability of irrigation to induce Amelonado cacao trees to flower throughout the dry season and produce pollen for use in manual pollination of a Seed Orchard in Ghana. When the cherelles were continuously removed, irrigated trees produced 30% more flowers than those that were unirrigated, although the flowering patterns were the same.

Conclusions

The results of this study showed that shade and dry season irrigation affected tree water use, canopy characteristics and bean yield of cacao in a rainforest zone of south west Nigeria. The shade and irrigation treatments affected radiation properties (transmission through cacao canopy, photosynthetic active radiation (PAR), canopy leaf area (LAI) and leaf light attenuation (extinction coefficient, k). Irrigation and shade affected soil moisture status canopy and solar radiation integrals (fractional light interception, extinction coefficient, photosynthetic active radiation: PAR) appeared to resulted in differences in canopy development, flowering and pod and bean production in cacao. The unshaded (open sun) cacao combined with 5-day irrigation had enhanced soil moisture status, cacao water use (ETc), pod and bean yields of cacaocompared with the shade-10-day irrigation. The shade and irrigation combinations affected pod and bean yields of cacao, and open sun cacao combined with 5-day irrigations produced significantly higher number and weights of pods and beans. Pod and bean yields were significantly different under the intervals of irrigation, the 5-day irrigation produced larger number, and heavier pods and beans compared with the 10-day interval. The 5-day irrigation interval combined with unshaded (open sun) treatment out-yielded the shaded in terms of number and weights of pods and beans compared with the shaded-irrigation combination.The shade-drip irrigation strategy adopted ameliorated dry season terminal drought (hydrothermal stresses) effects on cacao performance. Thus, drip irrigation appears a veritable tool for water management decisions, alleviation of dry season terminal drought (hydrothermal) and optimizing water productivity of cacao in the rainforest zone of Nigeria.

This option can be scaled up for enhancing growth, survival, establishment and flower/pod production for cacao in the rainforest of the tropics, and as input modelling cacao water requirements, irrigation scheduling and performance under sub-optimal soil and climate. Findings will serve as usefulinput modelling cacao water requirements, irrigation scheduling and performance under sub-optimal soil and climate conditions

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Table 1. Summary of measured soil and cacao parameters as affected by shade-irrigation combinations

Irrigation-Shade treatments	Seasonal irrigation	Scm (%)	ETc	Seasonal ETc	ETc/ ETo	No.Pods/ plant	Pod wgt /plant (kg)	No. Beans/ plant	Bean Wgt/ Plant (g)	Bean wgt (t/ha)	WUE (Bean) (Irr)	WUE (Bean) (ETc)	I/Io	PAR	LAI	K
Unshaded + 5-day	3090.2	19.6	3.76	45.4	0.87	15.7	7817.3	127.3	435.2	4.84	0.044	0.107	0.31	643.7	3.57	0.64
Shaded + 5-day	21813.6	17.4	3.63	42.3	0.81	12.3	7138.7	119.5	381.4	4.33	0.041	0.102	0.29	612.4	3.45	0.56
Unshaded+10-day	3090.2	15.1	3.44	40.2	0.78	11.4	6148.6	113.2	327.5	3.64	0.038	0.091	0.27	585.8	3.38	0.58
Shaded +10-day	21813.6	13.7	3.15	36.5	0.73	9.2	5935.4	109.4	289.3	3.22	0.033	0.088	0.23	529,7	3.19	0.52
Shade (Shd)		2.4	1.2	1.4	0.18	0.57	1.3	147.3	144.7	1.19	0.013	0.003	0.044	75.6	0.52	0.05
Irrigation Ir		1.9	0.81	1.14	0.13	0.8	0.94	131.5	115.4	1.06	0.007	0.003	0.05	61.3	0.31	0.03
Shd* Ir		ns	Ns	ns	ns	*	*	*	*	*	*	*	*	*	ns	*

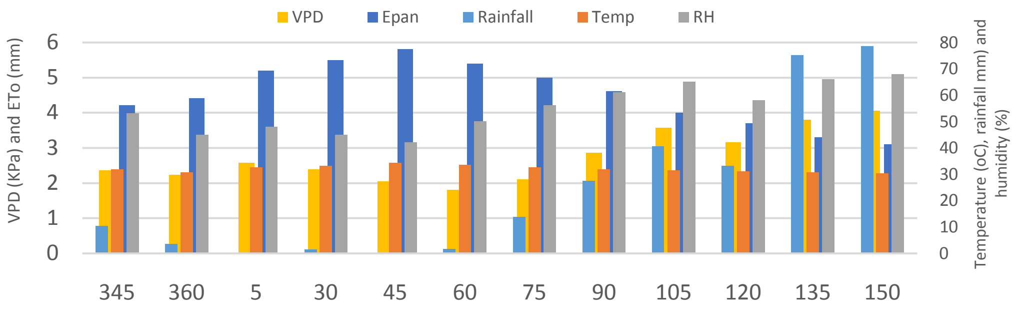

Fig. 1. Weather variables during period of experiment (December to May): VPD (vapour pressure deficit (kPa), EPan (Open water evaporation (mm), (Temp (mean tempetrature; °C), and RH (Relative humidity,; %)

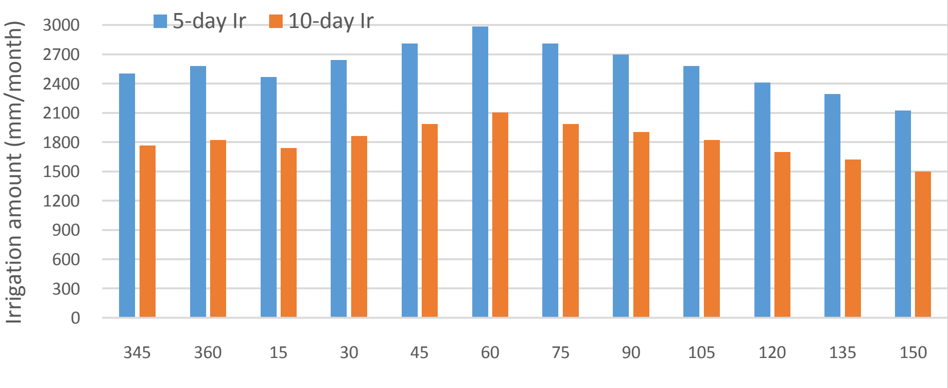

Fig. 2 Seasonal irrigation water applied (5- and 10-day irrigation intervals)

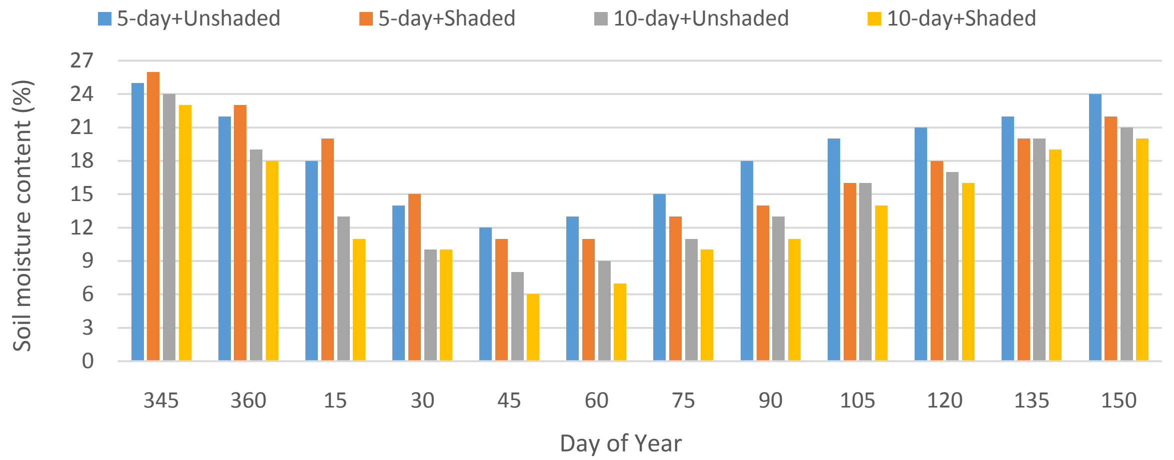

Fig. 3a .Shade and irrigation effects on soil moisture status

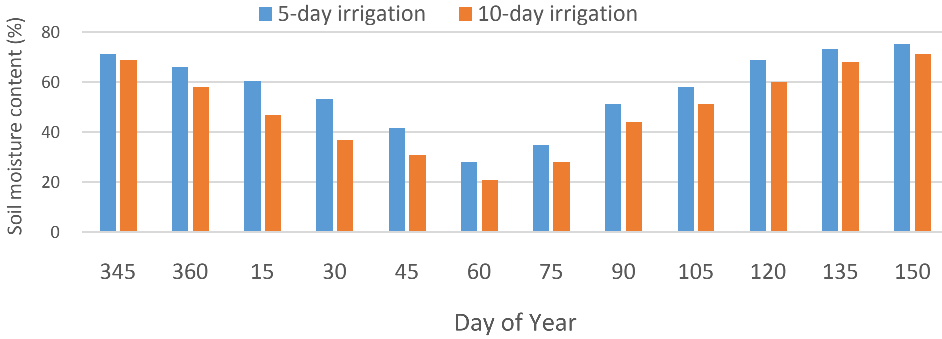

Fig. 3b. Irrigation effect on soil moisture status

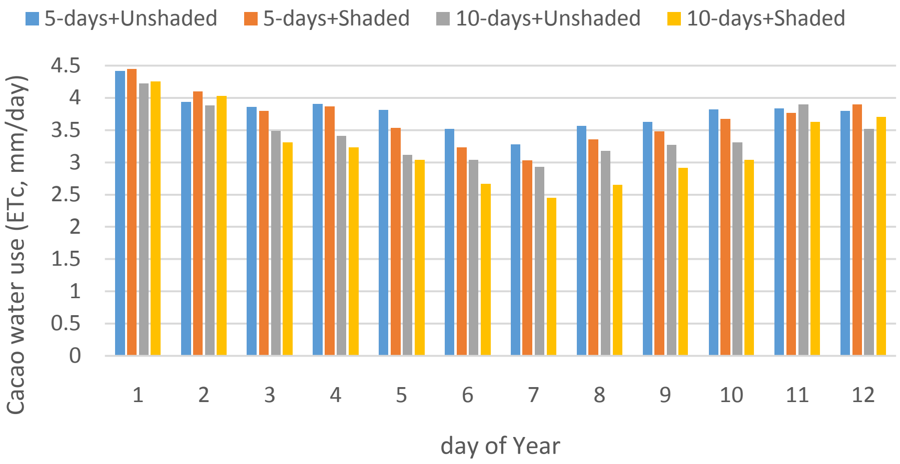

Fig. 5a. Shade and irrigation effects on cacao water use (ETc)

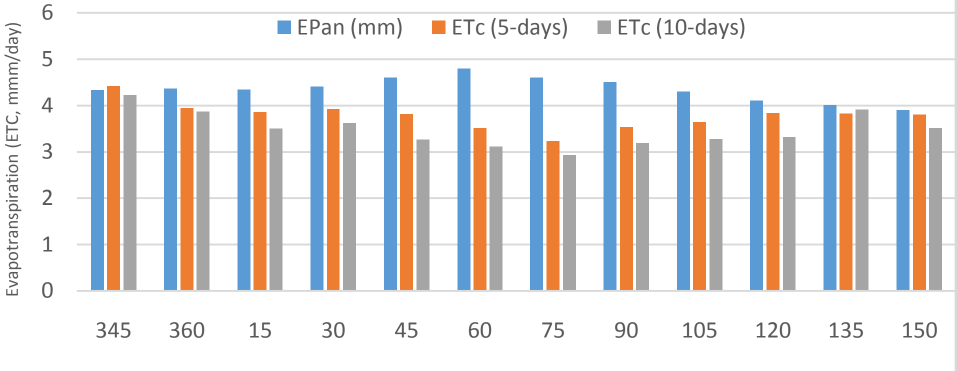

Fig. 5b. Cacao evapotranspiration (ETc) as affected by irrigation intervals

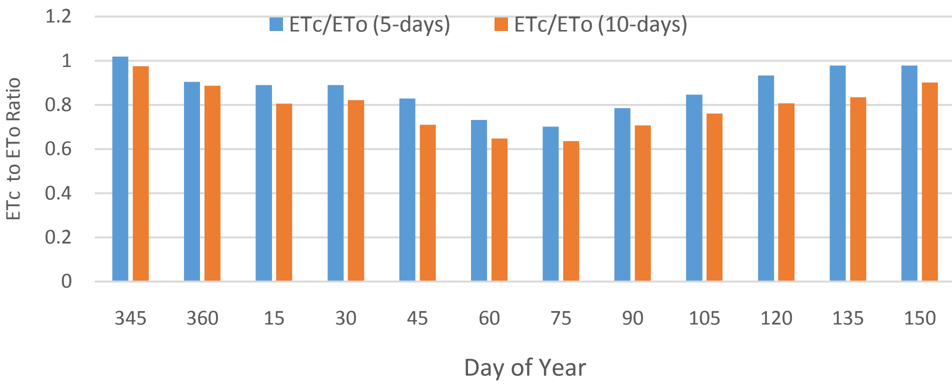

Fig. 6. Ratio of ETc to ETo as affected by irrigation intervals

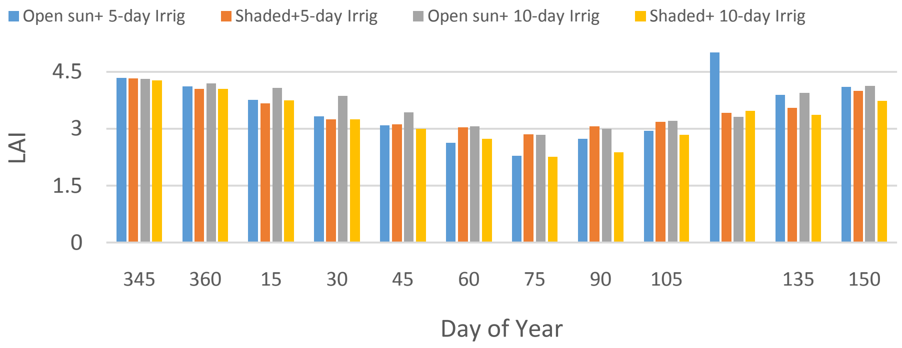

Fig. 7. Effect of shade and irrigation on cacao LAI

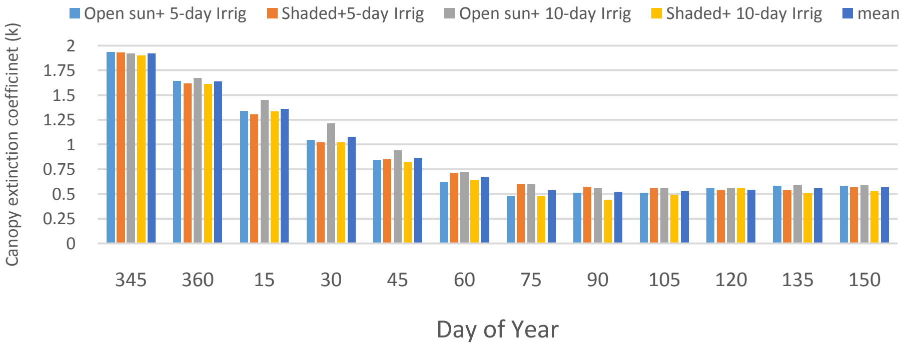

Fig. 8a. Shade-irrigation effect on canopy extinction coefficienct

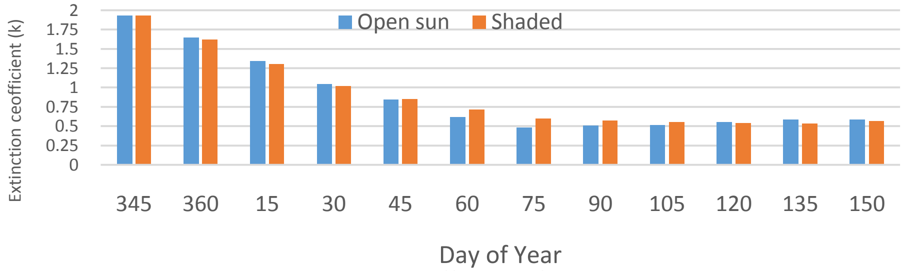

Fig. 8b. Canopy extinction coefficient of shaded and unshaded cacao