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Effect of water stress on crop coefficient of irrigated Soybeans (*Glycine max L merr.)* under sub-humid conditions

Omotayo B. ADEBOYE[1*], Bart SCHULTZ[2], Kenneth O. ADEKALU[1] and Krishna C. PRASAD[3]

[1]*Department of Agricultural and Environmental Engineering, Obafemi Awolowo University, Ile-Ife, Nigeria*
[2]*Land and Water Development IHE Delft, Delft, the Netherlands*
[3]*Freelance Irrigation and Water Resources Management Consultant, Lalitpur, Nepal*

**Corresponding author: adeboyeob@oauife.edu.ng*

ORCID: 0000-0002-2428-4226

Abstract

In order to manage irrigation systems effectively and sustainably for food production, it is important to estimate crop evapotranspiration with high precision and understand the relationship between functional parameters in the soil-water-plant-atmosphere system. Soybean was drip irrigated for two seasons in Ile-Ife, Nigeria. The experimental factor was the timing of irrigation. The treatments consisted of full irrigation (T_{1111}); skipping of irrigation every other week during flowering (T_{0111}); pod initiation (T_{1011}); seed filling (T_{1101}) and maturity (T_{1110}). The treatments were arranged in a randomized complete block design with three replicates. Leaf area index (*LAI*), canopy cover (*CC*) and crop coefficient (k_c) were measured and the single crop coefficient approach was used to determine evapotranspiration (ET_c). The *crop coefficient* (k_c) during flowering and maturity ranged from 1.14-1.29 and 0.49-1.19 respectively, while during pod initiation and seed filling, it was 1.29 in the seasons. The actual crop coefficient (k_{ci}) when irrigation was skipped during flowering, pod initiation, seed filling and maturity ranged from 1.04-1.46; 1.30-1.48; 0.82-1.48 and 0.77-1.17 respectively in the seasons. The k_{ci} when irrigation was skipped during flowering, pod initiation, seed filling and maturity reduced by 13.4, 11; 26 and 17% respectively compared with the fully irrigated soybeans. Exponential equations described excellently the relationship between k_{ci} and green leaf area index (*LAI)* ($0.87 \leq r^2 \leq 0.97$; $p < 0.0001$). There was strong linear correlation between k_{ci} *and* daily actual evapotranspiration (ET_c) ($0.73 \leq r^2 \leq 0.84$; $p < 0.0001$) in the seasons. The k_{ci} and canopy cover (CC) are highly and significantly linearly related ($0.89 \leq r^2 \leq 0.97$; $p < 0.0001$) and intercept very close to zero. Skipping of irrigation during the reproductive stages of soybeans reduced the crop coefficient and evapotranspiration.

Keywords: Drip irrigation, soybeans, crop coefficient, full and deficit irrigation

Research article
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INTRODUCTION

The crop coefficient plays a key role in many agricultural practices and it has been widely used to estimate actual evapotranspiration in irrigation scheduling (Pereira *et al.*, 1999). Crop coefficients are properties of plants used in predicting evapotranspiration (ET). Characteristics that distinguish a cropped surface from the reference surface are integrated into the crop coefficient when computing crop evapotranspiration.

The crop coefficient depends on the type of crop, stage of crop growth, soil moisture, health, and height of the plants, canopy cover and orientation in space (Allen *et al.*, 1998). Two major approaches are used in estimating the crop coefficient and these are the single and dual crop coefficient approaches. In the single crop coefficient method, the difference in evapotranspiration between reference grass and cropped field is combined into a coefficient. Evapotranspiration from a reference surface is also called reference evapotranspiration (ET_o) and is determined from weather data such as air temperature, humidity, solar radiation and wind speed at a location. The crop coefficient is computed from the ratio of crop water use to the ET_o. This method has been widely used in the planning and design of less frequent irrigation systems such as drip irrigation (Kang *et al.*, 2003; Hanson and May, 2006; Marin *et al.*, 2016). However, in the dual crop coefficient method, the crop coefficient is sectioned into evaporation (k_e) and transpiration (basal crop coefficient, k_{cb}) between the crop and the reference surface (Allen *et al.*, 1998). The crop coefficient curve is a description of the pattern of seasonal distribution of k_c. It can be related to time, thermal unit called growing degree-days or other agronomic parameters. The k_c for most of the agricultural crops increases from the lowest values at emergence or transplantation depending on canopy development until it reaches the peak value at maximum canopy cover. The k_c reduces shortly after reaching the maximum canopy cover in a cropping season. Growth characteristics and irrigation management influence the degree of declination of K_c during the late season (Kamble and Irmak, 2008). Crop coefficients depend largely on roughness of canopy, age of leaf and wetness of the surface (Justice and Townshend, 2002). As a crop canopy develops the ratio of transpiration to evapotranspiration increases, until transpiration constitutes a larger proportion of evapotranspiration compared to evaporation of water from soil. During this stage, plant canopy intercepts most of the radiant energy before a very small proportion reaches the soil surface. This occurs because the interception of radiant energy by the foliage increases until most light is intercepted before it reaches the soil. Researches show that the crop coefficient is highly correlated with the area of leafs (Williams *et al.*, 2003), leaf area index (*LAI*) of vegetables (Pereira *et al.*, 2011), canopy cover (de Medeiros *et al.*, 2001); and the fraction of light intercepted by the crop canopy (Williams and Ayars, 2005; Marsal *et al.*, 2014). However, the degree of correlation has not yet been generated for all tropical crops. There is variability in k_c in space and in time. This is due to variability in varieties, date of emergence, land use pattern, density of vegetation, rainfall and environmental conditions, such as air temperature, wind speed and vapour pressure deficit. For instance, k_c of soybeans varied from 0.54 to 1.11, 0.80 to 1.04 and 0.41 to 1.09 in 2002, 2003 and 2005 respectively (Payero and Irmak, 2013). They found that differences in weather conditions affected the crop coefficient of soybeans and cumulative growing degree-days. In addition, they found that the frequency of the wetting event affected the crop coefficient of soybeans. Doorenbos and Pruitt (1977) presented k_c for a large number of crops under varying climatic conditions, which could be used in places where local data is not available. The k_c was updated by Allen et al., (1998).

There have been criticisms on the applications of empirical crop coefficients because their values vary according to the conditions of climate and crop stages. Suyker and Verma (2009) found that the midseason k_c for irrigated soybeans was 0.98±0.02. The k_c for irrigated soybeans during early season, mid-season and later season were 0.27±0.17, 0.98±0.02, and 0.32±0.12 respectively (Suyker and Verma, 2009). The k_c found in literatures are for surface or sprinkler irrigation. The crop coefficients under localised irrigation systems are very scarce. Drip irrigation systems have been proven very efficient in saving water and improving water productivity. These systems are gaining acceptance even among the smallholders and commercial farmers in sub-Saharan Africa (Rai et al., 2017).

Therefore, in order to increase accuracy of evapotranspiration for an area or region, there is a need to compute and study the trend and dynamics of k_c under irrigated conditions in order to schedule water allocation accurately, calibrate crop yield models for local, regional, and global applications (Kashyap and Panda, 2001).

The development of simple techniques for estimating the crop coefficient at each stage of crop growth using a fraction of intercepted light by plant canopy would be very useful for computation of crop evapotranspiration and water management for crop production in the tropics and temperate regions.

The cost of operating other irrigation methods such as sprinkler irrigation is very high coupled with non-availability of energy for continuous use. In the recent times, interest in drip irrigation is increasing because of fluctuations in rainfall, limited water supply and the cost of pumping water for crop production. Drip irrigation can double or triple water productivity and thereby boosting crop per drop (Rai et al., 2017). The area under drip and other 'micro' irrigation methods has risen by more than 1000%, from 1.03 million ha in 1986 to more than 11 million ha at present over the last 30 years (Reinders and Niekerk, 2018).

Drip irrigation is highly efficient water application system because water is applied to the immediate vicinity of plant and therefore, less water is lost due to evaporation. Virtually all the water that is diverted under drip irrigation is consumptively used (Richter, 2014). The main challenge of adopting drip irrigation is its capital cost, which is up to US$ 2470 ha^{-1} (Hanson and May, 2006) and US$ 5700-6010 ha^{-1} (Adeboye *et al.*, 2015). The objectives of the study are to determine the effects of skipping irrigation every other week during vegetative and reproductive stages of growth on crop coefficients of drip-irrigated soybeans and to generate dynamic regression models between parameters that could be used to predict development of crops under application of full and deficit irrigation.

MATERIAL and METHOD

Study area

The fieldwork was carried at the teaching and research farms of Obafemi Awolowo University, Ile-Ife, Nigeria during the dry seasons of 2013 and 2014. The experimental field is located at latitude 7°28′0″N and longitude 4°34′0″E, 271 m+MSL (mean sea level). It is in the sub-humid area of Nigeria. The dry season extends from November to March, and the climate is conducive for the cultivation of grains and legumes under total and supplementary irrigation. In the recent times, there is variability in monthly distribution of rainfall, and time of occurrence.

These fluctuations in the daily rainfall often make it risky to grow crops during the rainy season or difficult to make a precise prediction of rainfall contributions to crop water use during the dry season. The first season was warmer than the second was. The upper 50 cm was sandy loam while the lower 50 cm contained more clay. The upper 50 cm was richer in organic matter than the lower 50 cm. The pH, phosphorus, and iron were higher in the upper 50 cm than in the lower 50 cm of the soil profile. However, the average total nitrogen, sodium, and potassium in the upper and lower 50 cm of the soil profile were uniform (Table 1).

The experimental factor was the timing of the irrigation. The treatments were arranged in a randomised complete block design (Table 2).

Table 1. Physical and chemical properties of the soil at the experimental field in the growing seasons

Soil depth (cm)	**00 - 20**	**20 - 40**	**40 - 60**	**60 -80**	**80 - 100**
Sand (%)	75	71	59	57	63
Clay (%)	15	19	21	30	18
Silt (%)	10	10	20	13	19
Texture class*	Sandy loam	Sandy loam	Sandy clay loam	Sandy clay loam	Sandy loam
BD (g cm^{-3})	1.49	1.56	1.58	1.57	1.62
OM (%)	1.28	0.74	0.61	0.44	0.34
FC (m^3 m^{-3})	0.18	0.27	0.2	0.31	0.29
PWP (m^3 m^{-3})	0.08	0.13	0.09	0.21	0.19
TAW (m^3 m^{-3})	0.10	0.10	0.12	0.10	0.10
K_{sat} (mm day^{-1})	880	570	415	350	580

BD, Bulk density; FC, Field capacity; PWP, permanent wilting point; TAW, Total available water; OM, Organic matter; *USDA Classification

Table 2. Experimental treatments and their descriptions in the seasons

Experimental label	**Description**
TT_{1111}	Irrigation was maintained weekly without stopping at any of the reproductive growth stage: flowering (R1 and R2 growth stages), pod initiation (R3 and R4 growth stages), seed filling (R5 and R6 growth stages) and maturity stage (R7 and R8 stages) (FI treatment);
TT_{0111}	Irrigation was skipped every other week during flowering
TT_{1011}	Irrigation was skipped every other week during pod initiation
TT_{1101}	Irrigation was skipped every other week during seed filling
TT_{1110}	Irrigation was skipped every other week during maturity

Field layout, cultivation, and measurement

At the commencement of the fieldwork in both seasons, the experimental field was harrowed and the stumps were removed manually. Perennial and spear grasses were controlled by using Force up^{TM}, Isopropylamine salt at 3 litres ha^{-1}. The field was pre-irrigated to a depth of 20 mm in order to initiate germination of the seeds. An indeterminate variety "TGX 1448 2^{E}", was planted on the 2nd of February (DOY 33) (day of the year) in 2013 (first season) and 8th of November 2013 (DOY 312), second season. The year 2012 was a wet year in the study area and much rainfall was recorded at the end of the year and early parts of 2013. The researchers experienced delay in the procurement of irrigation equipment in the first season coupled with logistic challenges. These were responsible for the late commencement of the experiment in the stated time. Three seeds were sown 4 cm below the soil surface and the plant spacing was 0.6 by 0.3 m, resulting in 166,668 plants ha^{-1}. Each plot occupied 12 m^2 and an alleyway of 1 m was used in separating the plots from one another.

The area of the experimental field was 19 by 15 m (285 m^2). After sowing of the seeds, defoliating beetles and aphids on the field were controlled by using Magic Force^{TM} (Lambda-Cyhalothrin 15 g/L+Dimethoate 300 g/LEC) (Jubaili Agro Chemicals, Ibadan, Nigeria) at 1.5 litre ha^{-1} at intervals of two weeks. After physiological maturity of the crop on 25th May, 2013 (DOY 145) in 112 DAP (days after planting) and 25th February, 2014 (DOY 56), 110 DAP an area of 5.37 m^2 (central rows) was harvested from each plot and the grain yields per ha were estimated.

Design of drip irrigation system

The daily crop water use was estimated using the Penman-Monteith approach described in Allen *et al.,* (1998). The estimated peak evapotranspiration during the initial, and development stages was 1.13 and 6.53 mm day^{-1} respectively while at mid and late stages, it was 6.69 and 3.83 mm day^{-1} respectively. The pressure compensating inline-drip line (Dripworks, Inc., USA), 2.2 l h^{-1} and pressure of 1 bar was used to apply water to the crop throughout the growing seasons. The length of each lateral was 5 m and contained 17 point in-line emitters, which were pre-spaced at intervals of 0.3 m. The pressure compensating mechanism ensured even distribution of pressure along the laterals even in hilly and undulating areas. At the beginning of the experiments, the coefficient of variation of the discharges from the emitters was 0.03, which was described as excellent for a point source emitter (Michael, 2008). The statistical uniformity indicator U_s, a measure of the uniformity achieved by each emitter was 95%. Emission uniformity of the inline-drip system was 90.7% based on the approach in Ghinassi (2008). Volume of water required per plant per day at the initial stage was determined from the ratio of the product of peak evapotranspiration (1.13 mm day^{-1}) and wetted area of each plant to the emission uniformity. The initial stage lasted 25 days under the environmental conditions in Ile-Ife and estimated field water requirement for the entire experimental field was 1,530 litres. The daily water requirement during the mid (40 days) and late (18 days) seasons were 6.69 and 3.83 mm day^{-1} respectively and using the same procedure, the estimated daily water needs per plant during these stages were 0.36 and 0.21 litres respectively.

Similarly, the total amount of water budgeted during these periods were 14,688 and 3,860 litres respectively. At the initial stage, the readily accessible soil moisture was 5.5 mm. Irrigation frequency was determined from the ratio of the readily available moisture to the peak water use of 1.13 mm day^{-1} and this gave an average of 5 days. Details of the experimental layout can be found in Adeboye *et al*. (2015).

Soil moisture

A 53 mm diameter steel core sampler set was used to collect soil samples at intervals of 10 cm from 0 to 60 cm at 7:00 am during each measurement (Ali, 2010). The samples were weighed immediately on the field, kept in sealed polythene bags before they were taken to the laboratory. The samples were oven-dried at 105 °C for about 48 hrs. The volumetric water content was determined by multiplying soil moisture content (%) by bulk density of each layer (Gardner, 1986). The volumetric soil moisture was converted to linear depth (mm) of water by multiplying it with the depth of each layer. There was rainfall in a few days during the fieldwork and this was built into the irrigation schedule by adding the effective rainfall to the plant available water and computing the number of days it would take the plant to use it. The same amount of water was applied until flowering when skipping of irrigation began. After 50% of the available water had been depleted, the crop was irrigated. The soil within the root zone was filled up to field capacity during irrigation.

The total available water was 110 mm m^{-1}. The irrigation requirement of the crop was determined using Eqn. 2 (Ali, 2010):

$$d = R - \sum_{i=1}^{n} \frac{(M_{fci} - M_{bi})}{100} \times A_i \times D_i \tag{2}$$

where:

d = net amount of irrigation applied (mm)
R = rainfall (mm)
M_{fci} = field capacity in the ith soil layer ($m^3\,m^{-3}$)
M_{bi} = moisture content prior to irrigation in the ith soil layer ($m^3\,m^{-3}$)
A_i = bulk density soil in the ith soil layer (g cm^{-3})
D_i = soil depth within the root zone (mm)
n = number of soil layers within the root zone

Irrigation frequency at each stage was determined from the ratio of the net water requirement to the peak water use (mm day^{-1}). The area irrigated by each dripper was determined from the ratio of the product of plant spacing and percentage of the cropped area irrigated to the number of the drippers at each emission. Only 30% of the cropped area was irrigated.

Crop water use

The soil water balance approach was used to determine the actual crop evapotranspiration (Ali, 2010). The moisture content was measured before irrigation in order to refill the soil at the root zone to field capacity. Runoff was measured by placing metallic boxes around plants within an area of 0.716 m^2 in replicates of each treatment.

The runoff within the area was directed towards a graduated plastic container and measured after each rainfall event. Daily effective rainfall was determined from the difference between daily rainfall and runoff (Ali, 2010). The contribution of the groundwater was ignored because the groundwater table was deeper than 10 m. The drainage below the root zone was not detected during the cropping seasons and therefore considered negligible under drip irrigation (Lovelli *et al.*, 2007). The change in the moisture in the root zone was determined from measurements of the soil moisture at the beginning and end of each stage of growth. Therefore, the seasonal crop water use was determined using Eq. 3 (Zhang *et al.*, 2017):

$$ET_c = I + R \pm \Delta S \tag{3}$$

where:
ET_c = seasonal crop water use (mm)
I = irrigation (mm)
R = rainfall (mm)
$\pm\Delta s$ = change in the soil moisture (mm)

Seasonal crop water use was determined by adding the water use at different stages together. The results of the effects of skipping of irrigation in the seasons can be found in Adeboye et al., (2015).

Leaf area index and crop coefficient

At average intervals of 7 days from 14 DAP in both irrigation seasons, the green LAI, above and below PARs were measured at 400 to 700 nm using AccuPAR LP 80 (Meter Group, USA) until maturity. Ten samples of the below and above PARs were taken from triplicates of each treatment by placing the probe (line sensor) perpendicularly to the rows above and below the plant canopy. Total of 14 consecutive measurements of LAIs were made in the two irrigation seasons. The canopy cover (CC) was determined by using the ratio of the PAR_{below} to the PAR_{above} (Eq. 4):

$$CC = 1 - \left(PAR_{below} / PAR_{above} \right) \times 100 \tag{4}$$

The daily *CC* was determined by interpolation of the measured values. The actual crop coefficient (k_{ci}) was determined from the combination of tau (τ) and *CC* by using the approaches of William and Ayar, Meter Group (Williams and Ayars, 2005; Decagon, 2015). In addition, *FAO* k_c was determined by using the FAO-56 approach. The *FAO* k_c during the **mid-season** and late stage were determined using Eqs. 5, and 6 (Allen *et al.*, 1998):

$$K_{c\ mid} = K_{c\ mid\ (Tab)} + \left[0.04(u_2 - 2) - 0.004(RH_{\min} - 45) \right] \left(\frac{h}{3} \right)^{0.3} \tag{5}$$

$$K_{c\ end} = K_{c\ end\,(Tab)} + \left[0.04(u_2 - 2) - 0.004(RH_{\min} - 45) \right] \left(\frac{h}{3} \right)^{0.3} \tag{6}$$

The k_c for other days within the growing seasons was determined by interpolation. Daily crop water use was determined from the product of k_c and reference evapotranspiration (ET_o). The ET_o was determined by FAO 56 method for grass using the Eq. 7.

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma\left(\frac{900}{T + 273} \right) u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.3u_2)} \tag{7}$$

where:

ET_o = reference evapotranspiration (mm d^{-1})
R_n = net radiation at the crop surface (MJ m^{-2} d^{-1})
G = soil heat flux density (MJ m^{-2} d^{-1})
γ = psychometric constant (KPa $^oC^{-1}$)
T = mean of the monthly maximum and minimum air temperatures (^oC)
u_2 = wind speed at 2 m height (m s^{-1})
e_s = saturated vapour pressure (KPa)
e_s = actual vapour pressure (KPa)
e_s-e_a = saturated vapour pressure deficit (KPa)
Δ = slope vapour pressure curve (KPa $^oC^{-1}$)

Heat unit approach rather days after planting was used to determine the growing degree-days (GDD) because of the annual variability of the weather in the study area, and to allow transfer of the crop coefficients from one region to the other. The GDD was determined using Eq. 8 (McMaster and Wilhelm, 1997):

$$GDD_i = (t_{\max} - t_{\min})/\ 2 - THR \tag{8}$$

THR = lower threshold temperature at which plant growth stops (°C)
t_{max} = maximum temperature during the day (°C)
t_{min} = minimum temperature during the night (°C)
GDD_i = Growing degree-days on day *i* (°C day).

The crop coefficients were plotted against the cumulative GDD. Regression analysis was used to generate models for crop coefficients and evapotranspiration, LAI, and CC. In addition, comparisons were made between the actual crop coefficients and k_c estimated using the FAO approach.

Statistical analysis

SigmaPlot was used to do regression analysis of the data and generate relationships between parameters at 5% significance level.

RESULTS and DISCUSSION

Crop Coefficient

There was variability in the k_{ci} and *FAO* k_c during the seasons. During flowering, *FAO* k_c ranged from 1.14 to 1.29 and was lower than the k_{ci} (1.04-1.46) in the two seasons (Figs. 1 and 2). The peak *FAO* k_c was 1.29 during pod initiation and seed filling and was lower than k_{ci} when irrigation was skipped during pod initiation (1.30-1.48) and seed filling (0.82-1.48). At maturity, *FAO* k_c (0.49-1.19) was lower than k_{ci} when irrigation was skipped at maturity.

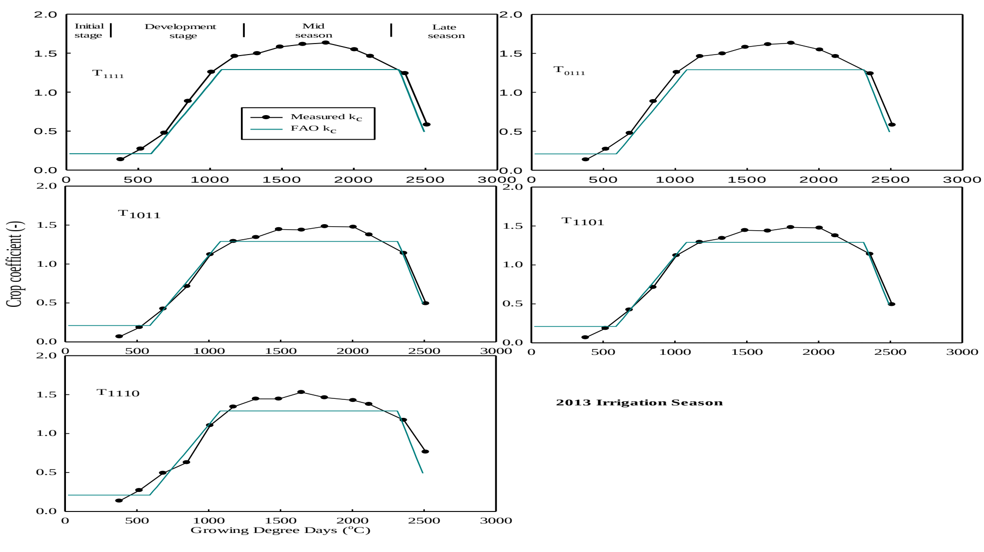

Figure 1. Crop coefficient of soybeans as a function of growing degree-day in the year 2013 irrigation season

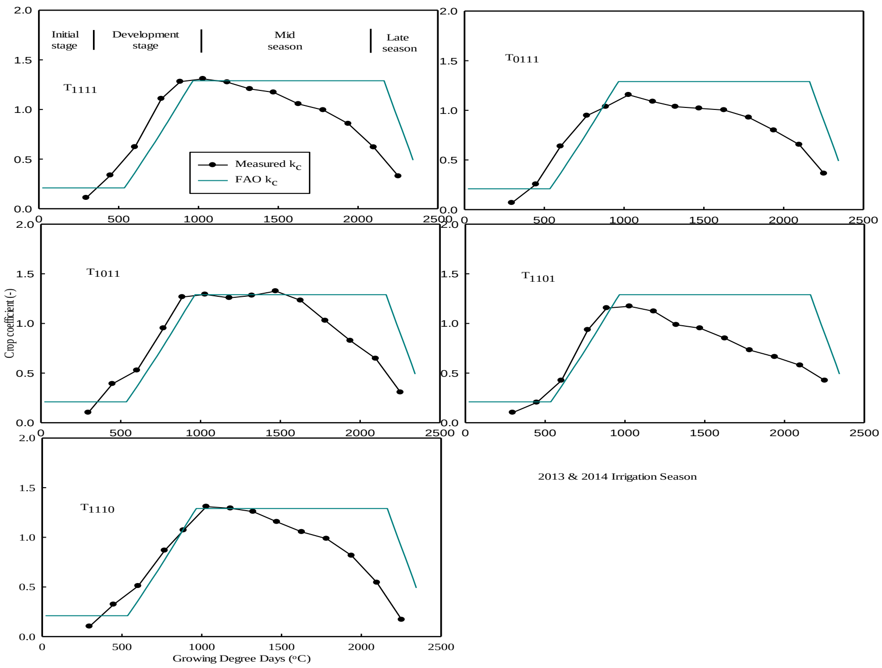

Figure 2. Crop coefficient of soybeans as a function of growing degree-day in the year 2013/2014 irrigation season

The k_{ci} was low in the early stages, but increased gradually until it reached the peak during mid-season and later descended at maturity (Fig. 1). In the first season, the k_{ci} during flowering ranged from 1.26-1.37 (43-55 DAP) while k_{ci} for the fully irrigated crop ranged from 1.15-1.45 and the peak k_{ci} for T_{0111} was higher than that of T_{1111} by 2.2%. However, the range of k_{ci} for T_{1011} and T_{1111} were the same. The k_{ci} during pod filling for T_{1101} ranged from 0.82-1.48 (35-101 DAP), while that of the fully irrigated ranged from 1.16-1.45 and the peak k_{ci} (1.50) was higher than the peak k_{ci} for the fully irrigated soybeans by 3.3%. However, the k_{ci} for T_{1110} ranged from 0.77-1.11 (102-109 DAP) while for T_{1111} ranged from 0.49-1.14 and the peak k_{ci} for T_{1110} was lower than that of T_{1111} by 2.6%.

In the second season, the k_{ci} ranged from 0.99-1.16 (38-49 DAP) for T_{0111} while k_{ci} for the fully irrigated crop during flowering ranged from 0.83-1.34 and this indicate that the peak k_{ci} for T_{0111} was lower than that of T_{1111} by 13.4% (Fig. 4). The k_{ci} when irrigation was skipped during pod initiation ranged from 1.29-1.45 (50-58 DAP) while k_{ci} during flowering for T_{1111} ranged from 1.36-1.45 and the peak k_{ci} for T_{1011} reduced by 11%. Similarly, the k_{ci} of the crop when irrigation was skipped during seed filling (0.59-1.08; 59-99 DAP) was lower by 26% from the k_{ci} for the fully irrigated (0.59-1.45) crop during seed filling. The k_{ci} when irrigation was skipped during maturity ranged from 0.23-0.45 (101-109 DAP) and its peak k_{ci} was lower than that of the fully irrigated (0.22-0.54) crop during seed filling by 17%. Reductions in the k_{ci} were more evident in the second season than the first season when irrigation was skipped during reproductive stages.

Evapotranspiration and grain yields

There was variability in the water used by the crop at different growth stages and seasons. In the two seasons, T_{1111} had the highest estimated seasonal ET_c as expected. In 2013, the estimated ET_c during flowering is 64 mm crop while in 2013/2014 season, it was 50 mm. During pod initiation, 58 mm and 31 mm of water were used in the two seasons (Fig. 5). There was variability in the ET_c due to the evaporating power of the atmosphere.

During pod filling, ET_c were 291 and 130 mm in 2013 and 2013/2014 seasons respectively. The average daily ET_o before flowering until 40 DAP was about 4.56 mm day^{-1} and was higher than the average ET_c of 2.00 mm day^{-1}. The ET_c increased considerably to 4.59 mm day^{-1} at DOY 76 and reduced to 3.34 (DOY 88) during the flowering in 2013. During pod initiation and filling, the ET_c ranged from 10.2 mm day^{-1} (DOY 110) to 3.31 mm day^{-1} (DOY 131) with an average ET_c of 7.69 mm day^{-1}. The trend in the second season was similar to that of the first season. The ET_o ranged from 1.70 mm day^{-1} (DOY 359) to 2.8 mm day^{-1} (DOY 2, 2014) during flowering with an average ET_o of 1.66 mm day^{-1}. The ET_c increased from 3.53 mm day^{-1} (DOY 354) to 5.29 mm day^{-1} (DOY 19, 2014). Towards the end of the cropping seasons, the ET_o was higher than the ET_c and the reason for this occurrence is not clear (Fig. 3).

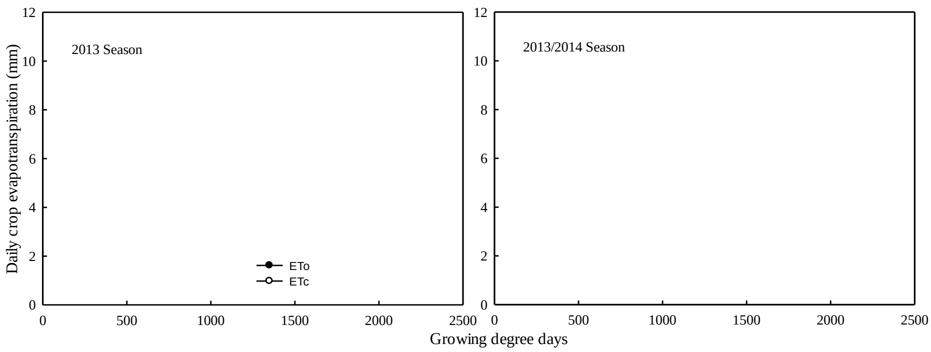

Figure 3. Estimated daily crop water use of drip irrigated soybeans without skipping the irrigation at any of the growth stages (T_{1111})

Crop coefficient and daily evapotranspiration

There were high coefficients of determination between crop coefficient and ET_c use in the seasons: ($0.73 \leq r^2 \leq 0.76$; 1.44 mm $\leq SEE \leq$ 1.53 mm; $p < 0.0001$) in the 2013 irrigation season and ($0.82 \leq r^2 \leq 0.84$; 0.42 mm $\leq SEE \leq$ 0.51 mm; $p < 0.0001$; Standard Error of Estimate) in 2013/2014 irrigation season (Fig. 4). These mean that k_c accounted for about at least 73% of the variability in the daily crop water use. The slopes and intercepts of the relationship were high and statistically similar in each season. The SEE was lower in the second season compared with the first.

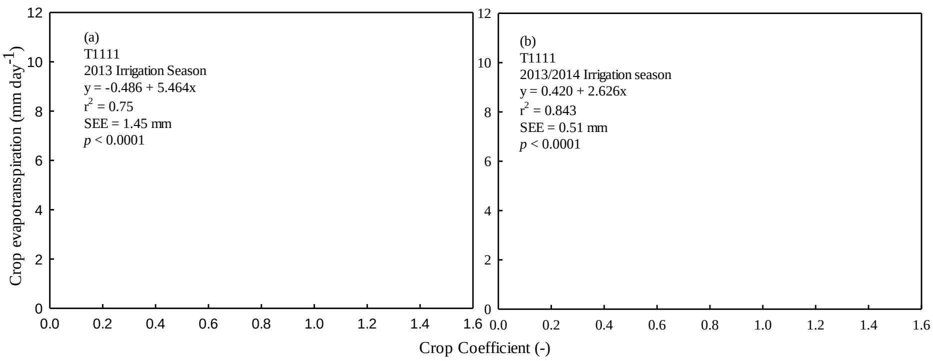

Figure 4. Estimated crop evapotranspiration and crop coefficients of fully irrigated soybeans in the two seasons

Leaf area index and crop coefficient

The exponential equations described excellently the relationship between crop coefficient and LAI in the two seasons (Figs. 5 and 6). The coefficients of determination ranged from 0.93 to 0.97 with $SEE \leq 0.69$ (Fig. 5) and from 0.87 to 0.94 with low $SEE \leq 0.31$ (Fig. 6). These imply that the LAI is responsible for about 97% variability in the crop coefficients of soybeans. The slopes ranged from 1.39 to 2.07 (Fig. 6) and the regression coefficients were highly significant with $p \leq 0.0001$ even when the data were pooled together. Many authors have shown that k_c is significantly correlated with LAI (Medeiros *et al.*, 2001) and leaf area (Williams and Ayars, 2005). This analysis indicates that equations reasonably describe the relationship of the crop coefficient and the LAI for the crop in the stated study area under the prevailing environmental conditions.

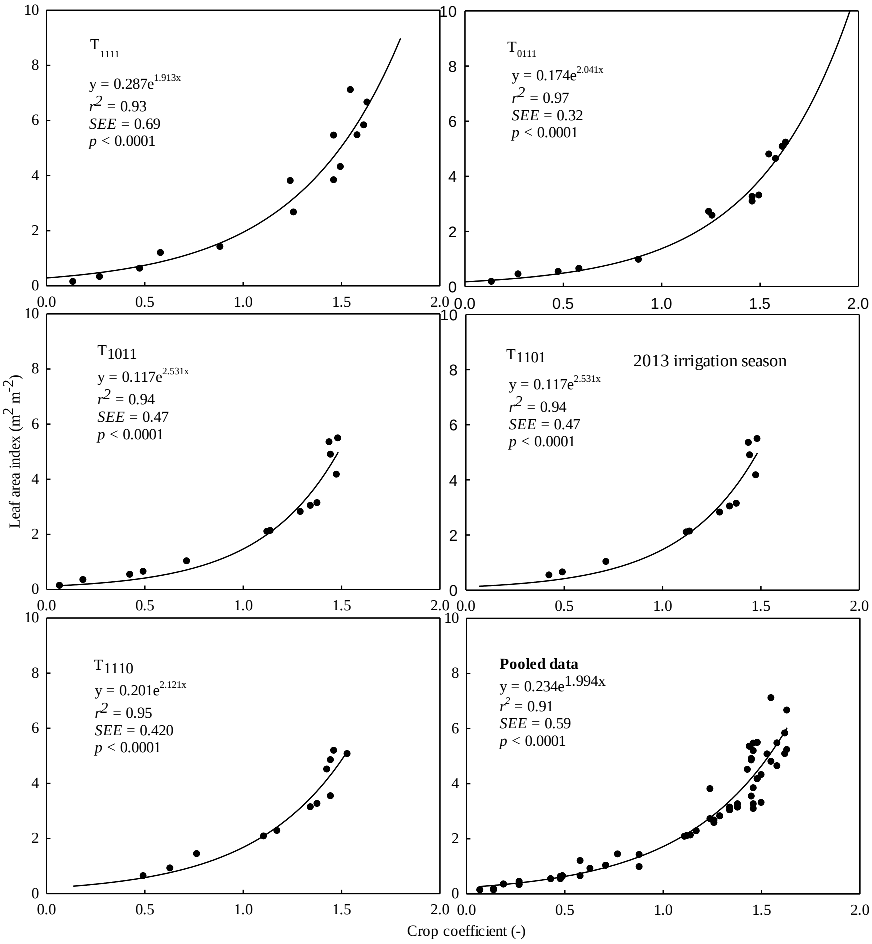

Figure 5. Leaf area index and crop coefficient of soybeans in the year 2013 irrigation season

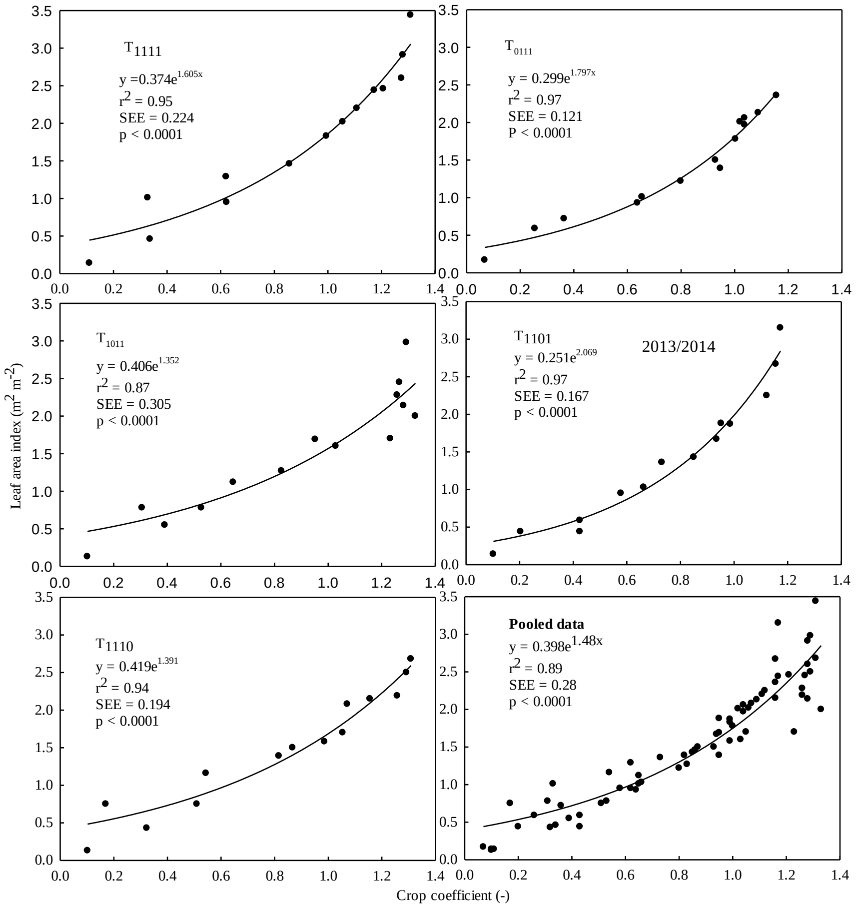

Figure 6. Leaf area index and crop coefficient of soybeans in the year 2013/2014 irrigation season

Crop coefficient and canopy cover

The *CC* increased rapidly after it reached 10% in the two seasons. The peak CC ranged from 87% for T_{1110} to 95% for T_{1111} in the 2013 irrigation season. However, it was low in the 2013/2014 season; it ranged from 67% for T_{1101} to 77% for T_{1111}. The CC decreased in the late season due to senescence, and the rate of decrease was very rapid in T_{1110}. The k_{ci} and LAI are highly and significantly linearly related ($0.89 \leq r^2 \leq 0.97$; $p < 0.0001$). The slope ranges from 0.017 to 0.17 with intercept very close to zero in the first season (Fig. 7). In the second season, the coefficient of determination varied from 0.93 to 0.96 with low *SEE* and the intercept very close to zero.

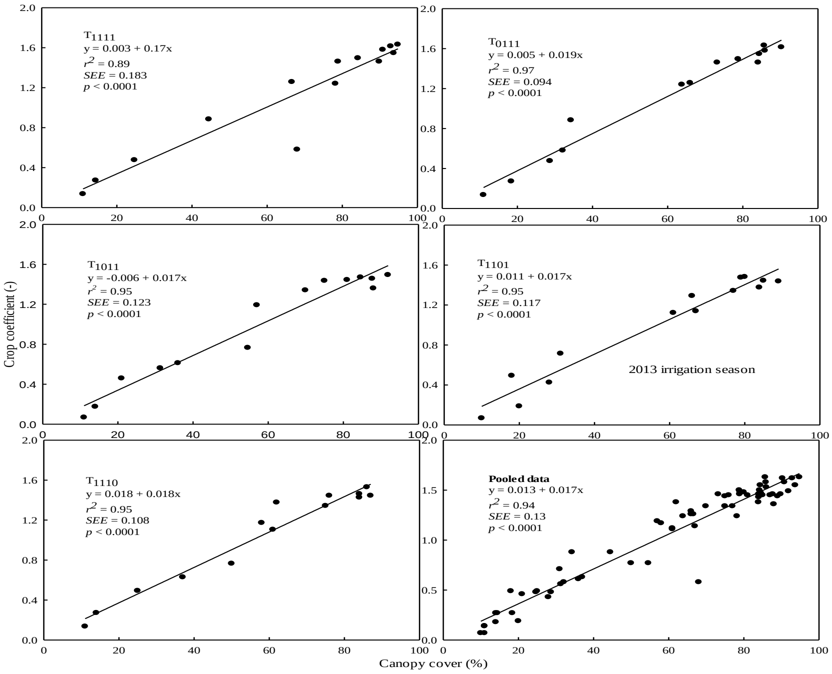

Figure 7. Crop coefficient and canopy cover of drip-irrigated soybeans in the year 2013 irrigation season

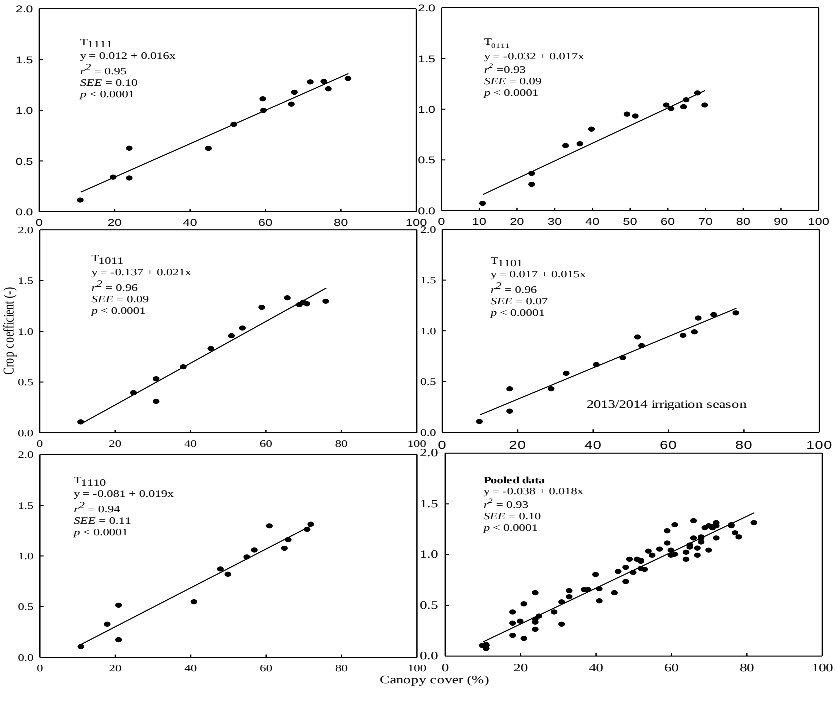

Figure 8. Crop coefficient and canopy cover of drip-irrigated soybeans for full irrigation and skipping of the irrigation during flowering, pod initiation, pod filling and maturity in the year 2013 irrigation season

The seasonal crop evapotranspiration using k_{ci} ranged from 497 mm for T_{1101} to 538 mm for T_{1111} in 2013. However, ET_c ranged from 221 mm for T_{1101} to 268 mm for T_{1111} in the 2013/2014 season. The seasonal ET_c was nearly the same for T_{1101} and T_{1110} in 2013. This is because the pod filling stage is very long, it overlaps into the maturity stage of the crop and a large amount of water is required by the crop to complete the process. The period of maturity was short and the crop used a small amount of water. The ET_c for T_{0111} during flowering reduced by 4.7, and 4.4% from ET_c of T_{1111} in 2013 and 2013/2014 irrigation seasons respectively. During pod initiation, ET_c for T_{1011} reduced by 0.42 and 9.8% compared with full irrigation in the two seasons. The ET_c during pod filling for T_{1101} in 2013 and 2013/3014 season reduced by 3.4 and 29.2% respectively. At maturity, the ET_c for T_{1110} was higher than that of full irrigation by 15.6% whereas in 2013/2014 irrigation season, the ET_c was almost the same. The variability in the ET_c indicates that ET_o plays a prominent role in determining the crop water use during each stage of growth. Therefore, during flowering and pod initiation, the recommended peak k_{ci} values are 1.46 and 1.48 respectively while during seed filling and maturity, peak k_{ci} values are 1.48 and 1.21 respectively to avoid water stress. Soybeans growers in the study area may find it challenging to use the k_{ci} and LAI relationship in managing their water resources for crop production. This is due to the challenges of instrumentations and time taken to take measurements, especially with variability in the weather conditions. However, the farmers may prefer the k_{ci} and CC relationship because it is more convenient to estimate visually the *CC* in the absence of sophisticated instrumentation. In order to ensure proper management of water for production of soybeans under full and deficit irrigation conditions in the dry seasons, a linear graph of crop water use versus k_{ci} was developed in this study. Care needs to be taken in the use and transfer of the linear curves because of the variability of the weather conditions from one location to the other and over the years.

CONCLUSION

Field experiments were carried out on soybeans for two dry seasons in order to determine the effects of water stress on the crop coefficient. The k_c when water was skipped for seven days during flowering reduced by 13.4% compared to fully irrigated soybeans. The k_c during pod initiation ranged from 1.30 to 1.48 in the two irrigation seasons and reduced from that of the fully irrigated treatment by 11%. The k_c during pod filling for T_{1111} ranged from 0.88 to 1.48 in the two seasons and reduced by 26% from that of full irrigation. During maturity, k_c ranged from 0.77 to 1.21 and reduced by 17% from that of full irrigation. The crop coefficient of soybeans reduced when irrigation was skipped during flowering, pod initiation, pod filling and maturity of the crop in the two irrigation seasons. Daily crop evapotranspiration reduced during skipping of water application. Daily crop water use increased progressively from 10% canopy cover and got to the peak during seed filling, after which it reduced to the minimum during maturity. There was strong linear correlation between the crop coefficient, and daily evapotranspiration and canopy cover.

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REFERENCES

Adeboye O.B., Schultz B., Adekalu K.O. & Prasad K., 2015. Crop water productivity and economic evaluation of drip-irrigated soybeans (Glyxine max L. Merr.). *Agriculture & Food Security*, 4(1), 1-13. 10.1186/s40066-015-0030-8.

Ali M.H. 2010. Fundamentals of irrigation and on-farm water management. Springer, Berlin.

Allen, R.G., Pereira, L.S., Raes, D. Smith, M., 1998. Crop Evapotranspiration-Guidelines for computing crop water requirements. *Irrigation and Drainage Paper.* Food and Agriculture Organization, Rome, Italy.

de Medeiros G.A., Arruda F.B., Sakai E.l. & Fujiwara M. 2001. The influence of crop canopy on evapotranspiration and crop coefficient of beans (*Phaseolus vulgaris L.*). *Agricultural Water Management*, 49(3), 211-224. https://doi.org/10.1016/S0378-3774(00)00150-5.

Decagon D.I. 2015. Using AccuPAR to Find Crop Coefficients for Irrigated Grapevine Production.

Doorenbos J. Pruitt & W.O. 1977. Crop water requirements, Irrigation and Drainage No. 24. Food and Agriculture Organization, Rome, Italy.

Gardner W.H. 1986. Water Content. In: A. Klute (Editor), *Methods of Soil Analysis: Part 1-Physical and Mineralogical Methods.* Soil Science Society of America Book Series. Soil Science Society of America, American Society of Agronomy, Madison, WI, pp. 493-544.

Ghinassi G. 2008. Manual for performance evaluation of sprinkler and drip irrigation systems, ICID Publication No. 94. International Commission on Irrigation and Drainage, Delhi, India, 119 pp.

Hanson B.R. May D.M. 2006. Crop coefficients for drip-irrigated processing tomato. *Agricultural Water Management*, 81(3), 381-399. https://doi.org/10.10 16/j.ag wat.20 05.04.007.

Justice C.O. Townshend & J.R.G. 2002. Special issue on the Moderate Resolution Imaging Spectroradiometer (MODIS): A new generation of land surface monitoring. *Remote Sensing Environment*, 83, 1-12.

Kamble B. Irmak A. 2008. Assimilating Remote Sensing-Based ET into SWAP Model for Improved Estimation of Hydrological Predictions., Proceeding of the 2008 IEEE International Geoscience and Remote Sensing Symposium, Boston, USA.

Kang S., Gu B., Du T. & Zhang J. 2003. Crop coefficient and ratio of transpiration to evapotranspiration of winter wheat and maize in a semi-humid region. *Agricultural Water Management*, 59, 239–254.

Kashyap P.S. & Panda R.K. 2001. Evaluation of evapotranspiration estimation methods and development of crop-coefficients for potato crop in a sub-humid region. *Agricultural Water Management*, 50, 9-25.

Lovelli S., Perniola M., Ferrara A. & Di Tommaso T. 2007. Yield response factor to water (Ky) and water use efficiency of Carthamus tinctorius L. and Solanum melongena L. *Agricultural Water Management*, 92(1–2), 73-80. http://dx.doi.org/10. 1016/j.agwat.2 007.05.005.

Marin F.R. Angelocci L.R. Nassif D.S.P., Costa L.G., Vianna M.S. & Carvalho K.S., 2016. Crop coefficient changes with reference evapotranspiration for highly canopy-atmosphere coupled crops. *Agricultural Water Management*, 163 139–145. doi.org/10.1016/j.agwat.2015.09.010.

Marsal J., Johnson S., Casadesus J., Lopez G., Girona J. & Stöckle C. 2014. Fraction of canopy intercepted radiation relates differently with crop coefficient depending on the season and the fruit tree species. *Agricultural and Forest Meteorology,* 184(Supplement C), 1-11. doi.org/10.1016/j.agrformet.2013.08.008.

McMaster G.S., & Wilhelm W.W. 1997. Growing degree-days: one equation, two interpretations. *Agricultural and Forest Meteorology*, 87(4), 291-300. http://dx.doi.org/10.1016/S0168-1923(97)00027-0.

Medeiros G.A., Arruda F.B., Sakai E. & Fujiwars M. 2001. The influence of crop canopy on evapotranspiration and crop coefficient of beans (*Phaseolus vulgaris L.*). *Agricultural Water Management*, 49, 221-224.

Michael A.M. 2008. *Irrigation Theory and Practice,* Vikas Publishing House PVT, New Delhi, 768 pp.

Payero J.O. & Irmak S. 2013. Daily energy fluxes, evapotranspiration and crop coefficient of soybean. *Agricultural Water Management*, 129, 31– 43. http://dx.doi.org/10.1016/j.agwat.2013.06.018.

Pereira A.R., Camargo M.B.P.d. & Villa Nova, N.A., 2011. Coffee crop coefficient for precision irrigation based on leaf area index. *Bragantia* 70, 946-951.

Pereira L.S. Perrier A. Allen F.G. & Alves I. 1999. Evapotranspiration: concepts and future trends. *Journal of Irrigation and Drainage Engineering,* 125, 45-51.

Rai R.K. Singh V.P. & Upadhyay A. 2017. *Way Forward to Improve Irrigation Efficiency, Planning and Evaluation of Irrigation Projects*. Academic Press, pp. 605-611.

Reinders F.B. & Niekerk A.S.V. 2018. Technology Smart Approach to Keep Drip Irrigation Systems Functional. *Irrigation & Drainage*, 67(1), 82-88. doi:10.1002/ird.2191.

Richter B. 2014. Taking Stock of Our Water Budgets, Chasing Water: A Guide for Moving from Scarcity to Sustainability. Island Press/Center for Resource Economics, Washington, DC, pp. 19-35.

Suyker A.E. & Verma S.B. 2009. Evapotranspiration of irrigated and rainfed maize–soybean cropping systems. *Agricultural & Forest Meteorology*, 149(3), 443-452. https://doi.org/10.1016/j.agrformet.2008.09.010.

Williams L.E. & Ayars J.E. 2005. Grapevine water use and the crop coefficient are linear functions of the shaded area measured beneath the canopy. *Agricultural & Forest Meteorology*, 132(3-4), 201-211.

Williams L.E., Phene C.J., Grimes D.W. & Trout T.J. 2003. Water use of young Thompson Seedless grapevines in California. *Irrigation Science*, 22, 1-9.

Zhang X., Qin W., Chen S., Shao L. & Sun H. 2017. Responses of yield and WUE of winter wheat to water stress during the past three decades-A case study in the North China Plain. *Agricultural Water Management,* 179, 47-54. http://dx.doi.org/10.1016/j.ag wat.2016.05.004.