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Determination of Water Requirement and Crop Coefficient for Sorghum (*Sorghum bicolor L.*) at Melkassa, Ethiopia

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Abstract

Knowledge of crop evapotranspiration (ET_c), the combined process of evaporation and plant transpiration, is important in agriculture for scheduling farm operations and designing and managing irrigation and drainage systems. Development of crop coefficient (K_c) can enhance crop evapotranspiration (ET_c) estimates in specific crop growth stages. However, locally determined K_c information is not available for many important crops in Ethiopia. This research was, therefore, conducted to determine growth stage specific K_c and crop water use for sorghum (Sorghum bicolor L.) var. Gambella-1107 at the Melkassa Agricultural Research Center which is located in a semi arid climate zone in Ethiopia. Drainage type lysimeter was used to measure Gambella-1107 crop water use under water balance system on a clay loam soil and local weather data were used to determine the reference evapotranspiration (ET_o). Crop coefficient was developed from measured ET_c and ET_o calculated using weather data. The growth stages of the crop were assessed as the seasonal change of plant height (pH), leaf area (LA) and leaf area index (LAI). The yield obtained was 5.3 t ha^{-1} and the measured LAI were 0.2, 4.2, 4.9 and 1.6 at the initial, development, mid-season and late season stages, respectively. The maximum LAI was achieved when the plants reach their maximum height at mid-season stage with high crop evapotranspiration due to leaf enlargement that increases transpiration. The measured ET_c values were 53.8, 138.5, 214.4, and 94.0 mm during the initial, development, mid-season and late-season stages, respectively, and the seasonal total value was 500.7 mm. The calculated K_c values for the crop were 0.45, 0.83, 1.18 and 0.78 during the initial, development, mid-season and late-season stages, respectively. These values were greater than those reported in FAO publication for sorghum varieties which could be a result of soil, climate and crop genetic differences. This suggests the need for developing site-specific K_c values for proper irrigation management.

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INTRODUCTION

Water is one of the natural renewable resources essential for economic and social development. Yet, water resources have been taken for granted as a free good to be used at will, with little or no regard to the long-term consequences of its mismanagement. However, many voices have raised a note of alarm for some time now. For example, conferences have been held on environmental concerns including water, and UNESCO is focusing on the looming crisis of Fresh Water (Abu-Zeid and Hamdy, 2002).

The hydrological cycle describes the constant movement of water above, on and below the Earth's surface. The cycle operates across all scales, from the global to the smallest stream catchment (Smith, 1998) and involves the movement of water along evapotranspiration, precipitation, surface runoff, subsurface flow, and groundwater pathways. Evapotranspiration (ET) is usually the largest component of the hydrologic cycle, given that most precipitation that falls on land is returned to the atmosphere. Globally, about 60% of annual precipitation falling over the land surface is consumed by ET. Quantification of ET is used for many purposes, including crop production, water resources management, and environmental assessment. In agriculture, accurate quantification of ET is important for effective and efficient irrigation management (Irmak, 2009). The ET data for agricultural crops has become increasingly important in irrigation as well as in water resources management. It is dependent not only on the meteorological elements, but also on factors related to the crop, soil environment and management (Abu-Zeid and Hamdy, 2002).

Agricultural water users must plan an annual water budget in semi arid and arid lands and areas where water usage is regulated due to ecological protection programs, limited resources and competitive demand (Barrett, 1999). It is reasonable to expect that an improved crop water requirement estimate may make a substantial change in system size specifications and profitability. Sustainability of irrigated agriculture both environmentally and economically depends primarily on the efficiency of irrigation water, including crop water requirement and delivery and on-farm systems, management of degraded soils and water re-use (Howell, 2001). Therefore, a better management of water in irrigated agriculture is necessary to enhance crop production while preserving soil and water quality.

The semi arid areas in Ethiopia cover 301,500 square kilometers (km^2), which is 27% of the country and represent the crop production zone suffering from a serious moisture stress (Engida, 2000). It is in these areas that food insecurity and famine has always been reported (IGAD and FAO, 1995). Shortage of rainfall is normally reported as the cause of famine in Ethiopia. However, supplementary irrigation such as small irrigation and water harvesting methods have been undertaken to cope with the water stress problem during the crop growing period (maize and sorghum) in Adama and Miesso Districts (Degefie *et al.*, 2004). Most of these adaptive measures are undertaken at farm level.

Unreliable and poor distribution of rainfall is one of the major causes for low yield of sorghum in Ethiopia and it is a staple food crop for millions of people who live in the dry land areas of the country. So, farmers and private sales are now opting for the production of this crop under supplemental and/or full irrigation. Under such situation, crop specific water requirement is a key parameter in providing growers with information to select varieties for production and to determine the timing and quantity of irrigation events. Availability of experimentally determined crop coefficient and crop water requirement is important for proper irrigation scheduling, efficient water management, optimum yield and profit. However, there is a lack of locally determined crop coefficient for sorghum varieties used by the producers and hence difficult to determine the water requirement of the crops. Therefore, this study was conducted to determine the crop water requirement and develop crop coefficient for a sorghum variety at different growth stages.

MATERIALS AND METHODS

Description of the Experimental Site

The experiment was conducted at the Melkassa Agricultural Research Center (MARC), Central Rift Valley of Ethiopia, which is 15 km southeast of Nazareth town located at 8^o 24' N and 39^o 21' E with an altitude of 1550 meter above sea level (MoA, 2000). The main rainy season for this site is during the summer from June to September (*Kiremt*) which contributes about 69% of its annual rainfall and the second short rainy season (*Belg*) is from March to May which covers nearly 24%. The third season, which is from October to January (*Bega*), is dry most of the time but contributes around 7% of the annual rainfall especially during October and January for the late cessation of *Kiremt* and early onset of *Belg* seasons, respectively. For the period 1977-2006, the annual average rainfall is 702 mm and it ranges from 450 to 918 mm. The peak months are July and August with an average rainfall of 157.5 and 161.6 mm, respectively. The long-term mean rainfall for the *Bega*, *Belg* and *Kiremt* seasons is 52, 166 and 482.5 mm, respectively. For the period 1977-2006, the daily mean maximum and minimum temperatures are 28.5 and 13.8 °C, respectively. The mean maximum temperature is between 30.9 °C during May and 26.2 °C during August (Gebru and Abebe, 2011). According to the recent agro-ecological zones classification of Ethiopia (MoA, 2000), the Melkassa Hypo Calcic Regosol ecotope falls in the zone termed hot to warm semi arid lowlands. Loam and clay loam soil textures are the dominant textural classes (MARC, 1995; Tsion *et al.*, 2009).

Experimental Setup

One drainage type lysimeter located 100 m away from the Meteorological Station of the Melkassa Agricultural Research Center was used for the study. The lysimeter used was rectangular in shape with 2 m^2 area and effective soil depth of 100 cm and additional 100 cm layers, 20 cm rock, 20 cm gravel and 20 cm sand pack underneath which collects excess water from the upper soil and discharge it to the drainage collector placed in the working chamber through a drainage pipe. The lysimeter has champers for aeration and drainage pipes connected to water collecting tank which is placed in the working area underneath the lysimeter. The heights of the lysimeter rims are maintained near the ground level to minimize the boundary layer effect in and around the lysimeter. However, the rims of lysimeter were protruded 20 cm above the soil surface so that no surface runoff water enters into the lysimeter.

Soil Sampling and Analysis

Approximately 200 grams of soil sample was taken from inside the lysimeter at an interval of 15 cm up to 105 cm depth for determination of soil physical properties like soil texture, bulk density (BD), field capacity (FC) and permanent wilting point (PWP). Particle size distribution was determined using the Bouyoucos hydrometer method. Bulk density was determined by taking undisturbed soil sample from the site using core sampler method. The water content at FC and PWP were determined by the pressure plate apparatus technique whereas total available water (TAW) was obtained by subtracting PWP from FC (Ryan *et al*., 2001).

$$\mathrm{TAW} = \left(\frac{\mathrm{FC} - \mathrm{PWP}}{100}\right) \mathrm{x\ BD\ x\ d} \qquad (1)$$

where TAW = Total available water (cm), FC = Field capacity (%), PWP = Permanent wilting point (%), BD = Bulk density (g cm^{-3}) and d = Depth of root zone (cm).

The physical properties of the experimental soil (texture, bulk density, field capacity, permanent wilting point and total available water) are determined. The soil textural class was clay loam within the soil profile considered. The values of FC, PWP and TAW were 31.26%, 16.35% and 14.90%, respectively, while the average bulk density was 1.13 g cm^{-3} per meter.

Neutron Probe Calibration

The neutron probe was calibrated based on the procedure given in the user manual (Model 503DR CPN Hydro probe). The instrument allows rapid and periodically repeated measurements of volumetric wetness of a soil at different depths. During the calibration of the neutron probe, access tubes, volume sample, a scale and oven were used. Two aluminum access tubes were installed at depth of 105 cm at two points. This was done by digging a hole with an auger, and the aluminum access tube was driven into the hole. Wet and dry points were established to obtain wide range of moisture and to make it possible for the probe to read these ranges.

Probe readings in the tube in count ratio or rat (count/standard count) unit and volume sampler in pairs around the tube (within 15 cm of the tube) were taken at the desired depth. Parallel to the neutron probe measurements, soil samples were taken at 15 cm interval up to 105 cm soil depth with the same depth of neutron probe readings using an auger and soil water at 15 cm soil depth was calculated using the gravimeter method (user manual). The probe reading in count ratio (rat) versus the volume samples data was plotted and entered into an Excel spread sheet, a trend line created with its slope and, displayed its R^2 value. The coefficients of the linear equation (a and b) obtained from the fitted curves were used to convert neutron probe readings to soil moisture readings in unit of 15 cm depth of water per 15 cm of soil depth.

Input Data Collection for Water Balance

Soil Moisture Measurement

After calibrating the neutron probe, soil moisture content was monitored daily using the neutron probe sensor at an interval of 15 cm to a depth of 105 cm through one access tube installed within the lysimeter whereas the top 15 cm soil depth was measured gravimetrically.

Irrigation Application

Irrigation water was applied to the crop when 55% depletion of the available soil moisture occurred within the crop root zone (Doorenbos and Kassam, 1979; Allen *et al*., 1998). This 55% depletion was considered for the effective root zone of the crop (one meter). Similar irrigation amount at this depletion was given to the crop inside and outside the lysimeter to ensure uniform plant growth. The application of irrigation was carried out with known volume of buckets by converting the 55% depletion into volume of water. The amount of applied irrigation water was calculated using the following formula (Brouwer *et al*., 1985):

$$\mathrm{V = A\ x\ D} \qquad (2)$$

where V = Amount of water to be added (m^3), A = Surface area of lysimeter (m^2), and D = Depth of application (m).

Climatic Parameters and Drainage

Rainfall, sunshine hours, air temperature, relative humidity and wind speed values were collected daily from the Meteorological Station located 100 m away from the lysimeter. Drainage was collected from water tanks that collect water underneath the lysimeter using graduated buckets.

Crop Planting and Protection

Before sowing, the lysimeter was moistened by pre-irrigation to facilitate early growth and normal root growth. Eighteen plants of Gambella-1107 sorghum variety were sown on 28/05/2011 inside the lysimeter. The same variety was sown around the lysimeter in order to maintain a similar environment. The total plot size of lysimeter inside and outside was 5 x 6 m with a net area of 2 x 1 m. The row and inter row spacing used were 75 and 15 cm, respectively. Recommended doses of 50 kg/ha Urea (46% N) and 100 kg/ha DAP (46% P_2O_5 and 18% N) were applied to the crop at knee height stage and the time of sowing using row band placement by hand, respectively. Plants were protected from sorghum 'shoot fly' by applying the chemical insecticides of 'Endosulfan', by keeping fields cleared and frequently monitored. The crop was harvested on 09/10/2011.

Agronomic and Yield Data Collection

Plant height, leaf area and root length were collected. Among the growth parameters plant height and leaf area were measured at each growth stage from five random plants from the plot. Leaf area was determined using the methods described by Sticker *et al*. (1961) and Mass *et al*. (1987) as follows:

$$\mathrm{LA} = \mathrm{W} \times \mathrm{L} \times 0.75 \tag{3}$$

where LA = Leaf area (cm^2), W = Maximum leaf width (cm), L = Leaf length (cm) and 0.75 = Correction factor for sorghum. Leaf area index (LAI) was calculated as the ratio of leaf area of the five sampled plants to the area of land occupied by these plants (Diwaker and Oswalt, 1992).

In order to monitor the effective root zone at different growth stages, root length was observed during each growth stages and measured at the end of the crop growing season by uprooting sample plants. The root reached to 105 cm soil depth during the growing season.The grain yield per plot was measured after harvesting the net plot area and then the grain yield was adjusted to 12.5% moisture content by electronic moisture tester and converted it to on hectare basis. In addition to this, 1000 seeds from the plot was counted by electrical seed counter and weighed with electrical sensitive balance.

Determination of Crop Evapotranspiration and Reference Evapotranspiration

The ET_c at any given time was calculated using the water balance or water budget equation (Khan *et al*., 1993; Allen *et al*., 1998) as:

$$\mathrm{ET_c} = \mathrm{I} + \mathrm{RF} - \mathrm{D} \pm \Delta\mathrm{S} \tag{4}$$

where ET_c = Crop evapotranspiration, I = Irrigation applied (mm), RF = Rainfall received in the season (mm), D = Drainage (mm) and ΔS = Change in soil water (mm).

The reference evapotranspiration of the site under consideration for each growth stage of the crop was estimated using CROPWAT 4 windows version 4.2. This program uses sunshine hours, air temperature (maximum and minimum), relative humidity and wind speed at 2 meter height to calculate ET_o using the Penman-Monteith equation (Allen *et al*., 1998).

Determination of the Crop Coefficient

The growing period was divided into four distinct growth stages: initial, development, mid-season and late-season. The K_c values at each crop stages were calculated using the following equation (Allen *et al*., 1998):

$$\mathrm{K_c} = \frac{\mathrm{ET_c}}{\mathrm{ET_o}} \tag{5}$$

where K_c = Crop coefficient, ET_c = Crop evapotranspiration (mm day^{-1}) and ET_o = Reference crop evapotranspiration (mm day^{-1}). The crop and reference evapotranspiration, crop coefficient and other crop parameters collected were analyzed using descriptive statistics and mean values are presented for most of the parameters.

RESULTS AND DISCUSSIONS

Yields

The yield obtained was 5.3 tones (t) ha^{-1}. This yield level for Gambella-1107 is higher than the reported yield of the same variety (2.5 - 3 t ha^{-1}) grown in semi arid areas including Gambella, Yabello, Jijga, Kobo and Shewa Robit (Kidane *et al*., 2010). A good yield under irrigation for sorghum is reported to be 3.5 to 5 t ha^{-1}using 12 to 15% moisture content (Doorenbos and Kassam, 1979). Gambella-1107 sorghum variety grain yields obtained from on-research field (3 - 5 t ha^{-1}) is substantially higher than that of on-farm field (2 - 3 t ha^{-1}) (EARO, 2004). The variation of yield obtained in this study with that of the reported yield performance is due to location and good water management during the whole growth stage of the crop.

Crop Growth Parameters

The observed length of crop growth stages during the trial were found to be 20, 30, 40 and 30 days for initial, crop development, mid-season and late-season stages, respectively, with a total growing period of 120 days. The growth of Gambella-1107 was assessed as the seasonal change of plant height, leaf area (LA) and leaf area index (LAI).

The LAI was lowest at initial stage due to small leaf area (Table 1). The LA and LAI as well as plant height increased consistently from initial to the development & mid-season stages. The maximum LAI was achieved when the plants reach their maximum height at mid-season stage with high crop evapotranspiration due to leaf enlargement that increases transpiration. At this stage of plant development, LA and LAI started to decrease, whereas plant height remained relatively constant for the rest of the season. The decrease in LA and LAI was due to the maturity of the crop associated with leaf ageing, senescence and dropping of leaves.

Table 1: Growth stage wise leaf area, leaf area index, plant height and ET_c of Gambella-1107 grown in a lysimeter at Melkassa.

Growth stage	LA (cm^2)	LAI	pH (cm)	ET_c
Initial	270.0	0.2	25.8	53.8
Development	4740.2	4.2	130.5	138.5
Mid-season	5564.9	4.9	189.0	214.4
Late season	1768.4	1.6	189.0	94.0

LA = Leaf area, LAI = Leaf area index, pH = Plant height and ET_c = Crop evapotranspiration

Crop Evapotranspiration

The decadal and seasonal ET_c of sorghum Gambella-1107 variety and the components of the water balance are presented in Table 2. The crop received a seasonal total of 76.2 and 610.8 mm of water in the form of irrigation and rainfall, respectively. However, 177.1 mm of water was lost from the soil in the form of drainage (Table 2).

Table 2: Decadal values of water balance components and crop evapotranspiration

Ten days water balance components				
DAP	**I (mm)**	**RF (mm)**	**D (mm)**	**ΔS (mm)**
10	21.9	7.0	0.0	-0.4
20	23.6	33.5	10.0	-21.9
30	30.7	6.9	0.0	19.7
40	0.0	73.2	24.5	-8.8
50	0.0	42.0	5.5	4.8
60	0.0	62.4	0.0	-0.5
70	0.0	10.6	0.0	41.7
80	0.0	109.3	0.0	-61.3
90	0.0	44.5	17.0	24.7
100	0.0	108.0	35.1	-41.4
110	0.0	92.4	65.3	7.7
120	0.0	21.0	19.8	26.4
Total	**76.2**	**610.8**	**177.1**	**-9.2**

DAP = Days after planting, I = Irrigation, RF = Rainfall, D = Drainage and ΔS = Change in soil moisture storage.

The decadal ET_c values ranged from 25.2 to 61.9 mm. Higher ET_c values were recorded from 30-90 days after planting as compared to the values in the beginning and end of the crop life cycle. The fluctuation in ET_c throughout the season is expected because of changes not only in the crop development but also daily changes in weather parameters such as radiation, humidity, wind speed and temperature. Crop evapotranspiration increases with increasing air temperature and solar radiation, the two primary drivers of ET (Irmak, 2009). The total water requirement of the studied sorghum variety was found to be 500.7 mm (Table 1). This total ET_c of the variety considered in this study was within the range of previous reports such as 450 - 650 mm (Doorenbos and Kassam, 1979) and 491 - 533 mm (Piccinni *et al*., 2006) while exceeds the range (210 - 293 mm) reported by Sheng-Feng *et al*. (2006).

Computation of water requirement based on crop growth stage indicated differential water requirement of the crop throughout the course of crop development. The measured ET_c values were 53.8, 138.5, 214.4 and 94.0 mm during the initial, development, mid-season and late season stages, respectively (Table 1). The highest water requirement was recorded at the mid-season stage followed by the development stage while the lowest was observed at the initial growth stage. The lowest crop water requirement at the initial stage is mainly due to the low crop leaf area development (Table 1) with a low transpiration capacity. On the other hand, the rapid reduction in ET_c in the late season stage was due to the physiological deterioration of leaves because of aging. The period of maturity coincides with the period of less water demand because of drying of leaves and minimum leaf area available for transpiration (Kassam *et al*., 1975).

Reference Evapotranspiration

The ET_o attained its maximum during the initial crop growth stage which could be attributed to the high evaporative demand of the atmosphere (Figure 1). There was a decrease in ET_o from the initial to the end of the late season stage with fluctuating trend which was attributed to the variability of climatologically factors during the growing season.

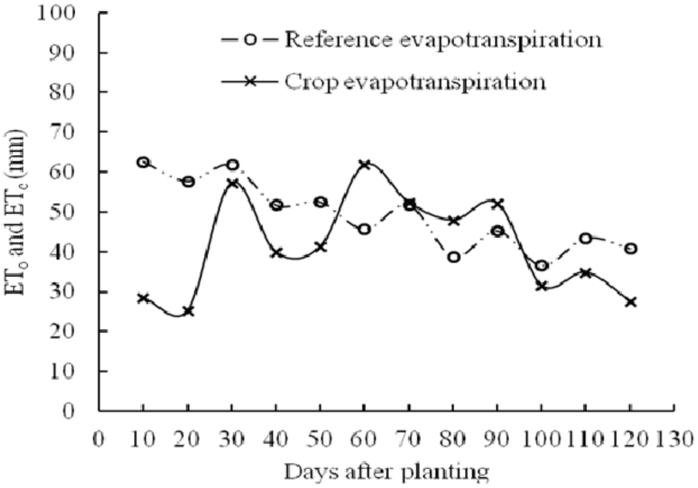

Figure 1: Decadal crop evapotranspiration (ET_c) of Gambella-1107 and reference evapotranspiration (ET_o) as a function of days after planting for the crop at Melkassa.

Moreover, the ET_c exceeded ET_o from 60 - 90 days after planting which coincided with the mid-season stage of the crop demand for high water use due to flowering, grains formation and filling. The rapid decrease in ET_c from the end of mid-season to late season stage (Figure 1) was due to leaf senescence and to the completion of grain formation and filling thereby limiting transpiration. The crop water use declined from the mid-season to the late season stage which is attributed to the cessation of leaf growth and a corresponding decrease in water demand (Allen *et al*., 1998).

Crop Coefficient

The curve presented in Figure 2 represents the changes in the K_c over the length of the growing season. The shape of the curve represents the changes in the vegetation and ground cover during plant development and maturation that affect the ratio of ET_c to ET_o. The decadal K_c increased from the initial to development stages while reached its highest and relatively remained constant at the mid-season stage (Figure 2). The K_c declined rapidly during the late season stage. Higher K_c values were recorded from 60-90 days after planting as compared to the values in the beginning and end of the crop life cycle. The maximum K_c value was 1.35 at 60 days after planting for the reason that low evaporative demand of the atmosphere (ET_o) and rainfall that increases ET_c.

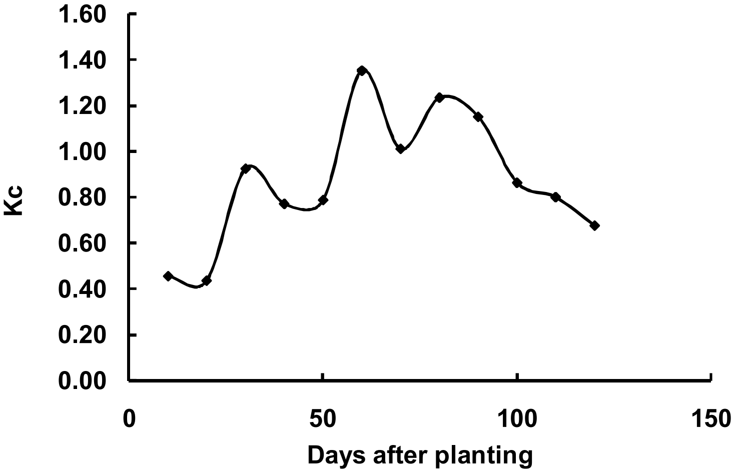

Figure 2: Decadal course of crop coefficients (K_c) for Gambella-1107 grown in a lysimeter at Melkassa.

It can be observed that there was high variation in K_c values among stages (Table 3). This is because the K_c values change very rapidly with the changes in crop development (Table 3). The K_c value ranged from 0.45 at the initial growth stage to 1.18 at the mid-season stage.

Table 3: Stage wise crop coefficient (K_c) values during the growing season.

	Initial	Development	Mid-season	Late season
K_c	0.45	0.83	1.18	0.78
FAO K_c	0.40	0.70 – 0.75	1.0 – 1.15	0.75 – 0.80

K_c = Crop Coefficient and FAO = Food and Agricultural Organization.

The K_c values initially were higher (Table 3) due to a high evaporation from the wetted topsoil in a semi arid environment. The arid and semi arid zones have long hours of bright sunshine which leads to high radiation incidence leading to higher ET rate (Indinoba *et al.,* 2008). During the initial period, the leaf area is small, and ET is predominately in the form of soil evaporation. Consequently, the advancement of K_c values reflected the effects of crop growth, development and physiology on ET_c (Allen *et al*., 1998). The increase in K_c values from the initial stage up to the mid-season stage was due to increases in leaf area and plant height (Table 1). The K_c values increased radically as the crop developed and covered the ground very effectively. Hence, the amount of water extraction increased with plant growth which in turn increased the ET_c. the rate of which is at the maximum level when the plant is fully developed (Irmak, 2009).

The K_c values declined from the mid-season stage to the late season stage (Figure 3). This was accounted for the leaf aging and senescence. Senescence is usually associated with less efficient stomatal conductance (Miderios *et al*., 2001) and decreased leaf surface (Villabos *et al*., 2004) due to the effects of aging which restricts transpiration causing a reduction in K_c (Allen *et al*., 1998).

The sorghum K_c values obtained in this experiment were higher in the first three consecutive crop growth stages from the range of those recommended by FAO while at the late season stage it was within the range of the values reported in FAO publications (Table 3). For sorghum, Allen *et al*. (1998) reported K_c values between 1.0 - 1.10 at the mid-season and 0.55 at the late season stages. Bashir *et al*. (2006) the estimated K_c values at the initial, the development, the mid-season and the late season stages were 0.62, 0.85, 1.15 and 0.48, respectively. Piccinni *et al*. (2006) who worked on sorghum in lysimeter obtained K_c values of 0.40 at the initial, 0.80 at the mid-season and 0.75 at the late season stages. Sheng-Feng *et al*. (2006) reported K_c values of 0.44, 0.71, 0.87 and 0.62 at the initial, development, mid-season and late season stages, respectively, for sorghum variety grown in lysimeter. The variation of K_c values in this study with that of FAO and others could be due to the growing season, climate, crop variety, and soil differences. In support of this, Simon *et al*. (1998) reported seasonal differences in K_c of maize in Trinidad showing higher K_c values (1.13 to 1.41) in the wet season and lower values (0.73 to 0.94) in the dry season.

CONCLUSIONS

In finally, the ET_c and K_c of Gambella-1107 variety was evaluated at each growth stages for Melkassa and areas which have similar climate and soil characters. The values of ET_c and K_c obtained at Melkassa can be used for further studies related to water management like deficit irrigation and erratic rainfall for those areas with similar climate and soil conditions. Since ET_c and K_c are a function of crop characteristics, irrigation water management, climate conditions, local and agricultural practices, it should be localized and this result can be used for appropriate irrigation planning, to have accurate irrigation schedule, for deficit irrigation and hydrologic water studies.

According to the study, it was shown that estimates of crop water requirement made with locally determined crop coefficients differ from estimates of FAO publications and others. This emphasizes the strong need for local calibration of K_c for each crop variety. The results of ET_c and K_c show to be somewhat dependent on, crop variety, climate, location and growing season. The studied variety, K_c values obtained at Melkassa can be beneficial to areas with similar soil type, climate, and location as that of Melkassa.

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