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Crop coefficient for drip-irrigated cotton in a Mediterranean environment

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Abstract A 3-year study was conducted in the eastern Mediterranean region of northern Syria to develop crop coefficient, K_c, for drip-irrigated short-season cotton (*Gossypium hirsutum* L.). Two sets of K_c curves were determined, the generalized K_c published by the UN's Food and Agriculture Organization (FAO) that was adjusted for local climate, and the locally developed K_c as the ratio of measured cotton evapotranspiration to calculated reference evapotranspiration. The adjusted FAO K_c curves were the same for the 3 years. However, the locally developed K_c curves not only differed among the 3 years, but also from the adjusted FAO K_c. During the mid-season stage, the adjusted FAO K_c was 24% higher than the locally developed value of 1.05. Variations in locally developed K_c values were caused by normal year-to-year variations in irrigation timing and amount, suggesting sensitivity of K_c that cautions against the use of locally developed K_c based on limited data (i.e., a single season). On the season, the overestimation of crop evapotranspiration by using adjusted FAO K_c was substantial and equivalent to 150 mm water or about two additional irrigations per season. Results caution against blind application of published FAO K_c curve, suggesting some local or regional calibration for increased accuracy.

Introduction

Cotton (*Gossypium hirsutum* L.) production in the semi-arid eastern Mediterranean region, including northern Syria, is of concern because of the limited water resources and overexploited aquifers. In Syria, rapid increases in irrigated land (majority as ground water irrigation) and inadequacies in agricultural water delivery, use, and management practices contribute most to the national imbalance in water supply and demand (Varela-Ortega and Sagardoy 2003; Salman 2004; Jamal et al. 2006). Irrigation applications are nearly twice as high as cotton water requirements with a national average of 15,000 m^3 ha^{-1} per season. Nearly three-fourths of cotton fields are irrigated by flooding of small basins. Because of over-irrigation, water productivity in the traditional surface-irrigated lands is about 0.2–0.25 kg m^{-3} of seed cotton per applied water (or 0.07–0.09 kg m^{-3} for lint cotton). These values are two to three times lower than most cotton producing regions in the world, such as Argentina, Turkey, and USA (see e.g., review in Grismer 2002 of studies by Hunsaker et al. 1998; Ayars et al. 1999; and others).

Because of the need to sustain agricultural production, the Syrian government adopted a national irrigation modernization plan in 2001, which encourages farmers to change to modern irrigation techniques (like drip and sprinkler irrigation) by providing technical support and tax-free low-interest loans. Although the adoption of modern irrigation systems is slow (i.e., national data show less than

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5% of cotton land as drip irrigated), there is a great desire among Syrian cotton growers to convert to drip irrigation because of its potential to conserve water and reduce pumping cost, labour, and other inputs (Janat 2004). These benefits have been demonstrated in Syria, with research showing 35 to about 100% irrigation savings using drip and up to 50% increase in yield using drip with fertigation as compared to traditional surface irrigated cotton (Al-Darir 1998; Janat and Somi 2001). Besides improving irrigation system efficiency, there is a need for effective on-farm water management, i.e., proper scheduling of irrigation (Farahani et al. 2006). The most fundamental requirement of scheduling is the determination of crop evapotranspiration (ET_c).

A popular method used to estimate ET_c is the crop coefficient (K_c) algorithm (e.g., in the UN's Food and Agriculture Organization (FAO) article-24 by Doorenbos and Pruitt 1977). In this approach, an experimentally determined coefficient (K_c) is multiplied by evapotranspiration from reference vegetation (ET_o) to compute ET_c, or

$$ET_c = K_c \times ET_o \qquad (1)$$

Doorenbos and Pruitt (1977) recommended the use of accepted equations to compute ET_o (defined for short green grass with ample supply of soil water). More recently, the FAO-56 (Allen et al. 1998) promotes the more superior Penman-Monteith (P-M) combination equation. Tables of K_c values derived from field and lysimeter ET_c measurements are provided in literature (see e.g., Doorenbos and Pruitt 1977; Wright 1979, 1981, 1982; Jensen et al. 1990; Martin and Gilley 1993).

The practical simplicity of using the K_c approach is indisputable, but the adoption of generalized K_c curves can lead to errors (Hunsaker et al. 2003). Since local development of K_c is a difficult task, most practitioners rely on the published values. This may be unwise because of the empirical nature of K_c that may limit its transferability into locations where the local climate and management factors deviate from the conditions in which the tabulated value was developed. The K_c approach is advocated in Syria, but no K_c curve has been locally developed, and the performance of the generalized K_c values is unknown.

The objective of this study is to develop the K_c curve for drip-irrigated cotton in northern Syria using detail soil, plant, and climate measurements for the period 2004–2006. The locally developed K_c curves are compared with generalized FAO K_c values adjusted for local climate and management. The possible sources of errors in using the published K_c and the difficulties in developing local K_c curves are discussed.

Materials and methods

Site description and soil characteristics

This study was done in cooperation with Syria's Cotton Research Administration as part of a broader experiment examining the effects of varying soil water regimes on water use efficiency of irrigated cotton (*Gossypium hirsutum* L.) in the cotton-wheat rotation system over the period 2004–2006. This paper presents data from the fully irrigated plots only. The study was conducted at Tel Hadya station (36° 01′N, 36° 56′E, and 284 m above mean sea level), the research headquarters of the International Center for Agricultural Research in the Dry Areas (ICARDA), located 35 km south of Aleppo, in northern Syria. The prevailing eastern Mediterranean climate in northern Syria is characterized with a single rainy season (Kassam 1981), starting in the fall and extending through the spring, during which the mean rainfall is 351 mm. There is limited rainfall in May and June and almost none in summer when irrigation is needed for a profitable production.

Soil at Tel Hadya is generally deep, 1.5–2.0 m, classified as fine clay (montmorillontic, thermic, Chromic Calcixerert), with volumetric water contents at field capacity and wilting point determined at 38 and 22%, respectively (Ryan et al. 1997).

Crop practices

The short season cotton variety 'Aleppo-118' was similarly managed over the 3-year study. This variety is characterized by high productivity, good gin average, and tolerance to *Verticillium* wilt. The experimental plots (10 m wide by 13.3 m long) were sown by hand, with seeds spaced 0.2 m apart on 0.7 m flat rows. Table 1 summarizes the planting and harvest dates for the 3 years. There were three rates of nitrogen (N) applications, 200, 150, and 100 kg N ha^{-1}. Each nitrogen treatment was replicated three times, for a total of nine plots. Nitrogen application (46% N urea) was split, with 1/5th applied at planting and the rest fertigated on three occasions during each season. Adequate phosphorus (P_2O_5) was broadcasted prior to sowing and based on pre-season soil testing. The field was monitored for insects and diseases and chemicals were applied as needed. Weed control was achieved using manual and chemical methods. Seed cotton was harvested by hand on two occasions (Table 1), in order to duplicate local farm practices, with the first picking producing more than 70% of the total yield. For analysis, the period from 6 May (one day after emergence, DAE) to the second picking on 24 September (142 DAE) was selected as the best

Table 1 Summary of planting and harvest dates for the 2004–2006 growing seasons

	2004	2005	2006
First irrigation (effective planting date[a])	4 May	3 May	4 May
Last irrigation	29 Aug	1 Sep	24 Aug
First hand-pick harvest	12 Sep	15 Sep	13 Sep
Second hand-pick harvest	3 Oct	25 Sep	23 Sep
Length of growing season (first irrigation to second harvest)	151	143	141

[a] Sowing occurred in dry soils 1–2 days before the first irrigation

representation of the growing season in the 3 years, providing a fixed duration for comparative purposes.

Irrigation management

The replicated plots were irrigated to meet full crop water requirements using well water applied through a drip irrigation system. The irrigation system was designed and managed to ensure uniform application. Polyethylene drip laterals (16 mm inside diameter) were installed after sowing in every plot (except in 2004 where the drip system was made ready after the first irrigation with a mobile irrigation system), laid along every crop row with emitters (rated at 4 L h^{-1} discharge) spaced every 0.4 m on the laterals, and operated at plot-inlet pressures between 110 and 150 kPa. Observations of emitter wetting patterns after irrigations showed complete closure between adjacent emitters on the same lateral and more than 85% closure between the rows. The applied water per plot was measured using mechanical flow meters installed at plot-inlets, occasionally verified against multiple measurements of emitter flow rates.

Soil water content was periodically monitored using neutron scattering. Prior to sowing, an aluminum access tube was installed in the center of each plot to a depth of 1.80 m. Soil water content was measured using an on-site calibrated neutron probe (Type IH-II, Didcot Instruments, Co, Ltd., Abington, UK) at a minimum of weekly intervals, for 30–35 readings per season. Measurements were made for each 0.15 m layer in the soil profile to the bottom of access tube, except the top 0.15 m, which was measured gravimetrically. Irrigation was initiated when soil water in the top three to four soil layers approached, but never dropped below, 50% of available soil water (difference between field capacity and wilting point water contents) and refilling the profile to field capacity. The first irrigation was applied after sowing, the second irrigation about 35 days after, while the irrigation season ended by late August, allowing late-season soil water drawdown to expedite boll opening (Table 2).

FAO-56 K_c curve

The general shape of the K_c curve (shown later in Fig. 5) resembles the changes in the vegetation and ground cover during plant development and maturation that affect the ratio of ET_c to ET_o. FAO-56 identifies the K_c curve by the following four crop growth stages:

- Initial-season: Period from planting to approximately 10% ground cover,
- Crop development: Period from 10% ground cover to effective full cover or peak water use (which ever comes first),
- Mid-season: Period from effective full cover to the start of maturity, with the latter often marked by the beginning of ageing, yellowing or senescence of leaves, and leaf drop associated with decline in water use, and,
- Late-season: Period from the start of maturity to harvest or end of water use.

The K_c curve is constructed knowing the duration of each growth stage in addition to K_c values for the initial stage ($K_{c\text{-ini}}$), the mid-season stage ($K_{c\text{-mid}}$), and at the time of harvest ($K_{c\text{-end}}$). Determination of crop growth stages and their subsequent matching with the four FAO-defined

Table 2 Drip irrigation scheduling (frequency and amounts) for the 2004 to 2006 growing seasons

	Irrigation sequence during the season									
	1	2	3	4	5	6	7	8	9	10
2004—Irrigation date	4 May	12 Jun	28 Jun	12 Jul	21 Jul	2 Aug	10 Aug	18 Aug	29 Aug	–
Amount, mm	45	115	80	100	100	120	80	80	80	–
2005—Irrigation date	3 May	6 Jun	30 Jun	12 Jul	19 Jul	28 Jul	4 Aug	14 Aug	22 Aug	2 Sep
Amount, mm	50	70	80	95	65	100	80	100	90	80
2006—Irrigation date	4 May	12 Jun	3 Jul	11 Jul	20 Jul	31 Jul	8 Aug	17 Aug	24 Aug	–
Amount, mm	60	80	80	60	120	100	100	100	60	–

growth stages is not straightforward for indeterminate species such as cotton. It is also noted that cotton top growth continues if the season is not terminated by soil water drawdown or chemical application to induce defoliation or desiccation. This latter method is common to many cotton-producing regions worldwide, but not in Syria. The duration of each crop growth stage was determined from field observations and varied by up to 5 days in the 3 years, averaging 39, 34, 30, and 39 days for the length of initial, development, mid-season, and late-season growth stages (Table 3).

In FAO-56, the generalized K_c values for cotton are $K_{c\text{-ini}} = 0.35$; $K_{c\text{-mid}} = 1.15–1.20$ (average = 1.17); and $K_{c\text{-end}} = 0.70$ to 0.50 (average = 0.60). FAO-56 suggests various adjustments of these K_c values caused by local variations in climate, soil and irrigation management. The $K_{c\text{-ini}}$ values are generally below 0.4 for average wetting frequencies, but may approach values as high as 1.0–1.2 (FAO-56) for high frequency irrigations. For the experimental site, FAO-56 recommends (page 118 for fine textured soil) adjusting $K_{c\text{-ini}}$ to a value of 0.2, because of high evaporative demand (average ET_o for May was 7.4 mm per day) and infrequent wetting events.

The FAO-56 K_c values are expected in a sub-humid climate having average daily minimum relative humidity (RH_{min}) values of about 45% and calm to moderate wind speed (u_2) averaging 2 m s^{-1}. At the experimental site, average RH_{min} and u_2 during the mid-season were 31% and 5.3 m s^{-1} (2004), 30% and 5.2 m s^{-1} (2005), and 27% and 5.5 m s^{-1} (2006), respectively. To account for the lower humidity and higher wind conditions, the $K_{c\text{-mid}}$ value of 1.17 was corrected for each year using the FAO-56 recommended correction formulae

$$K_{c-mid} = K_{c-mid\ unadjusted} + [0.04(u_2 - 2) - 0.004(RH_{min} - 45)](h/3)^{0.3} \tag{2}$$

with measured mean values for RH_{min}, u_2, and h (crop height, m). A similar adjustment was made for $K_{c\text{-end}}$. The measured crop height varied between 0.75 and 0.80 m during these two growth periods. The FAO recommended adjustments increased K_c values for the mid- and end-season, reflecting the hot and dry climate conditions (Table 4).

Table 4 Generalized FAO K_c values adjusted for local climate and the locally developed K_c values for cotton

	2004	2005	2006	Mean
Adjusted FAO K_c				
$K_{c\text{-ini FAO}}$	0.20	0.20	0.20	0.20
$K_{c\text{-mid FAO}}$	1.30	1.29	1.31	1.30
$K_{c\text{-end FAO}}$	0.70	0.71	0.71	0.71
Locally developed K_c				
$K_{c\text{-ini Local}}$	0.38	0.32	0.18	0.29
$K_{c\text{-mid Local}}$	1.05	1.05	1.04	1.05
$K_{c\text{-end Local}}$	0.67	0.95	0.35	0.66

Cotton evapotranspiration

Soil water budget method was used to estimate crop evapotranspiration. This involved measuring the components of the water balance equation for a control volume defined by soil profile of given root zone depth and written as:

$$ET_{c-Meas} = P + I - D - R - \Delta S \tag{3}$$

where $ET_{c\text{-Meas}}$ denotes measured crop evapotranspiration, P is precipitation, I is irrigation, D is deep percolation below the root zone (or an upward flow, if negative, into the root zone in case of a shallow water table), R is runoff (or run-on, if negative, in case of surface flow into the area under consideration), and ΔS is the change in soil profile water storage (the period ending minus the period beginning soil profile water), with all variables in units of equivalent mm water and determined for each period between two consecutive soil water measurement days. The reliability of $ET_{c\text{-Meas}}$ estimates from the soil water budget method depends on the measurement or estimation

Table 3 Calendar and cumulative heat unit (Growing Degree Day, GDD) periods for the four cotton growth stages

Growth stage	Duration of growth stage	GDD (°C)[a]
Initial	39 days (6 May–13 Jun), emergence to 10% cover (8–10 leaf)	380
Development	34 days (14 Jun–17 Jul), 10% cover to max bloom	381–810
Mid-season	30 days (18 Jul–16 Aug), max bloom to first few open bolls	811–1,220
Late-season	39 days (17 Aug–24 Sep), first few open bolls to second picking	1221–1,670

Emergence to flowering is about 70 days, to first open is 95 days, and to start of maturity is 110 days

[a] Using a base temperature of 12.5°C, with upper and lower cutoff temperatures of 30 (T_{upper}) and 12.5°C (T_{lower}) (Sammis et al. 1985). Heat units were computed for the 3 years using measured daily minimum (T_{min}) and maximum (T_{max}) air temperature values in $GDD = (T_{max} + T_{min})/2 - 12.5$, If $T_{max} > 30°C$ then $T_{max} = T_{upper}$, and If $T_{min} < 12.5°C$ then $T_{min} = T_{lower}$

accuracy of the variables in the right-hand side of the equation.

Deep percolation (or upward flow) is the most difficult variable to quantify and accounts for most mass balance errors in estimating $ET_{c\text{-}Meas}$. No shallow water tables existed at the study site, thus only percolation below the root zone was of concern. One source of mass balance errors is when the depth of the profile measured by the neutron probe is less than the wetting front by irrigation, with deep percolation, if any, undetected through the bottom of the profile (Wright 1990). In this study, the access tubes were installed up to 1.80 m, to provide sufficient depth for detection of potential deep percolation. An analysis of the soil profile water content measurements revealed negligible changes in soil water in layers below 1.20–1.35 m depth (Fig. 1 for 2006), suggesting limited percolation. Profile data also show that over 95% of root water extraction was from soil layers above the 1.20 m depth. For analysis, $ET_{c\text{-}Meas}$ for cotton was thus calculated from Eq. 3 using the entire 1.80 m profile for each period between two consecutive soil water measurements. Measured precipitation was less than 5 mm during summer in each of the 3 years, and thus no appraisal of its effective portion was made. The drip-irrigation system produced no runoff, with R equaling zero for analysis.

Meteorological data and reference evapotranspiration

Daily values of precipitation, minimum and maximum air temperature and relative humidity, wind speed at 2 m height, and solar radiation were measured at an automated weather station inside the research center with a grass surface. Using the on-site climate data, daily ET_o was computed with the Penman-Monteith equation as described in FAO-56 (Fig. 2).

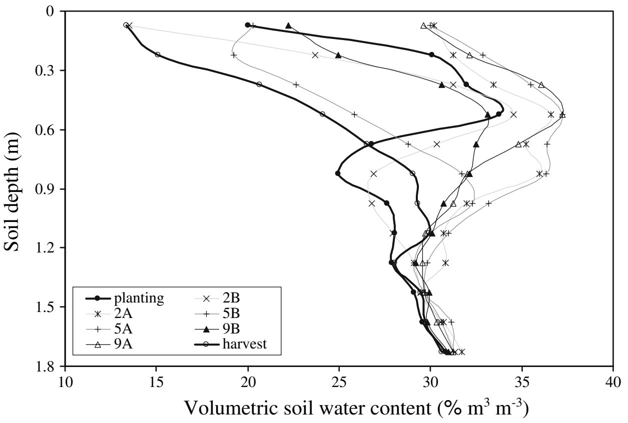

Fig. 1 Profile soil water content at planting (4 May) and harvest (24 Sep) and at 1 day before and 2 days after the second (12 Jun), fifth (20 Jul), and ninth (24 Aug) irrigation events in 2006. (*2B*, *5B*, and *9B* denote measurement at one day before, and *2A*, *5A*, and *9A* denote measurement at 2 days after, the second, fifth, and ninth irrigation events)

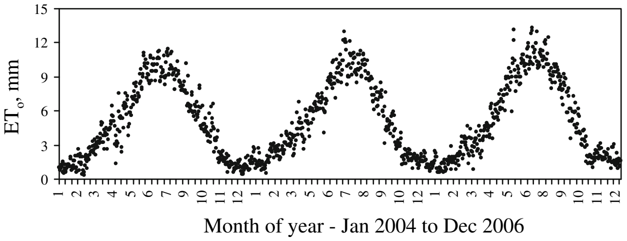

Fig. 2 Calculated daily reference evapotranspiration (ET_o) at Tel Hadya experimental site for the period 2004–2006

Locally developed K_c curve

Crop coefficient curves were locally developed for each of the three seasons by first determining average $K_{c\text{-}ini}$ and $K_{c\text{-}mid}$ values as the ratio of cumulated $ET_{c\text{-}Meas}$ to cumulated ET_o for the initial- and mid-season growth stage periods, respectively. The $K_{c\text{-}end}$ was then determined by maintaining an $ET_{c\text{-}Meas}$ mass balance (for the late-season period) while calculating the slope of the descending K_c. The locally developed K_c values are referred to as $K_{c\text{-}ini\ Local}$, $K_{c\text{-}mid\ Local}$, and $K_{c\text{-}end\ Local}$ (Table 4) to be distinguished from the previously determined adjusted FAO K_c values (i.e., $K_{c\text{-}ini\ FAO}$, $K_{c\text{-}mid\ FAO}$, and $K_{c\text{-}end\ FAO}$).

Results and discussion

Irrigation and evapotranspiration

Seasonal irrigation amounts were 800, 810, and 760 mm, while mean seasonal $ET_{c\text{-}Meas}$ values were 895, 927, and 813 mm in 2004, 2005, and 2006, respectively (Table 5). Variability in the $ET_{c\text{-}Meas}$ values across plots was small each year (see Fig. 3 for 2004 data), with standard deviation ranging narrowly between 14 and 17 mm. Mean seasonal $ET_{c\text{-}Meas}$ was on the average 88 mm higher than the seasonal irrigation, reflecting the seasonal contribution of soil water. Compared to literature, the 3-year average $ET_{c\text{-}Meas}$ value of 878 mm in northern Syria is higher by about 90 mm than those reported for the medium maturity cotton in northern High Plains of Texas (Howell et al. 2004) and near Menemen, in western Turkey (Allen 2000), even though the season is shorter (by about 20 days) and the $K_{c\text{-}mid}$ value of 1.05 is smaller than their reported range of 1.15–1.30.

Seasonal ET_o values were 1204 and 1224 mm in 2004 and 2005, respectively, but increased to 1336 mm in 2006.

Table 5 Seasonal applied irrigation water, measured cotton evapotranspiration ($ET_{c\text{-Meas}}$), and calculated Penman-Monteith reference evapotranspiration (ET_o) in northern Syria

	Irrigation	$ET^a_{c\text{-Meas}}$		
		Mean	Std Dev	ET_o
	mm	mm	mm	mm
2004	800	895	14	1204
2005	810	927	14	1224
2006	760	813	17	1336
Mean	790	878	–	1244

[a] $ET_{c\text{-Meas}}$ values represent mean of nine plots per year (three replications of each of three N rate applications). Growing season length is 142 days (6 May–24 Sep)

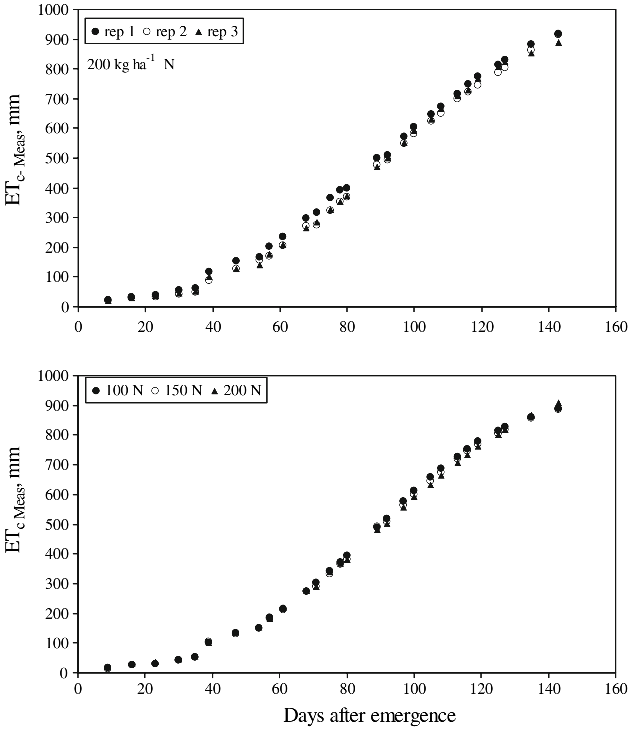

Fig. 3 Cumulated measured ET_c for replicated plots of the same N application (*top*) and for plots with different N applications (*bottom*) in 2004

The higher demands were caused by higher daily wind speed (by an average of 0.5–1.1 m s^{-1}), and lower relative humidity (by 4–6%), during mid-season in 2006 as compared to 2004 and 2005. In spite of the higher ET_o in 2006, measured ET_c was lower by 82–114 mm in 2006 as compared to 2004 and 2005, respectively. More than half of this difference occurred during the late-season stage (the period 104 to 142 DAE), mainly because of wetter soil environments in 2004 and 2005 than in 2006. This is illustrated in Fig. 4 showing volumetric water content in the top 0.3 m soil for the three seasons. It is noted that there were three irrigation events during the late-season stage in 2005 for a total of 270 mm as compared to two irrigations in 2004 and 2006 for a total of 160 mm in each year. This plus the fact that the last irrigation was applied later in 2004 (29 Aug) and 2005 (2 Sep) than in 2006 (24 Aug) created wetter soil environments in the former years for enhanced late-season evaporation. The late-season variations in soil wetness had a significant effect on $ET_{c\text{-Meas}}$ and the locally developed $K_{c\text{-end Local}}$ value. For instance, $ET_{c\text{-Meas}}$ during the late-season stage was 306 mm in 2005, but a smaller value of 223 mm in 2006.

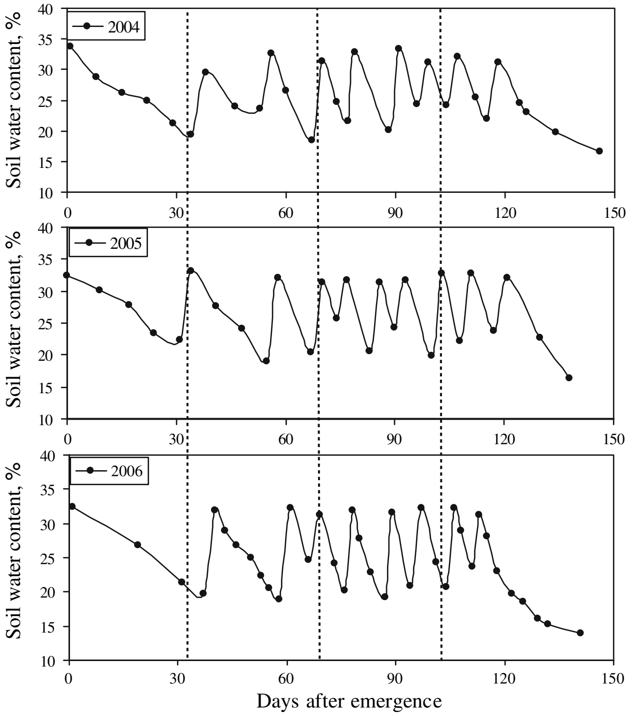

Fig. 4 Volumetric soil water content in the top 0.3 m soil during the 2004–2006 cotton-growing seasons. (the three *vertical lines* mark the beginning of development, mid-season, and late-season growth stages)

FAO versus the locally developed K_c curves

The ratio of $ET_{c\text{-Meas}}$ to ET_o versus time defines the seasonal trend of locally developed K_c (shown in Fig. 5 for 2006), where the spikes are due to high rates of evaporation from wet soil following irrigation events. These locally developed K_c curves are compared to the adjusted FAO curves in Fig. 6 for the 3 years. The adjusted FAO curves were basically the same for the 3 years, with $K_{c\text{-ini FAO}} = 0.20$, $K_{c\text{-mid FAO}} = 1.30$, and $K_{c\text{-end FAO}} = 0.71$. The locally developed K_c curves not only differed considerably among the 3 years, but were also different than the adjusted FAO K_c values. Deviations between the adjusted FAO and locally developed K_c values ranged between −47 and

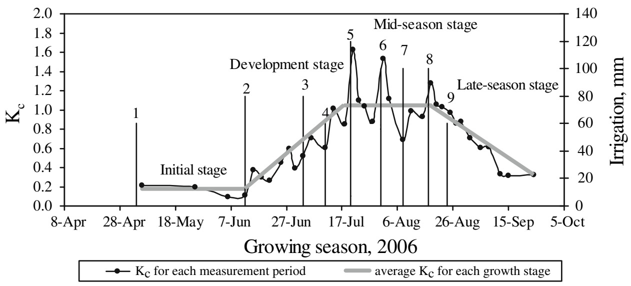

Fig. 5 Seasonal trend of K_c calculated as the ratio of $ET_{c\text{-Meas}}$ to ET_o for each period between two consecutive soil water measurement days during the 2006 cotton-growing season (symbols mark the beginning of each soil water measurement period). (The *thick grey line* is the average K_c for each growth stage period.) (*Vertical lines* show irrigation applications, 1 through 9, and amounts.)

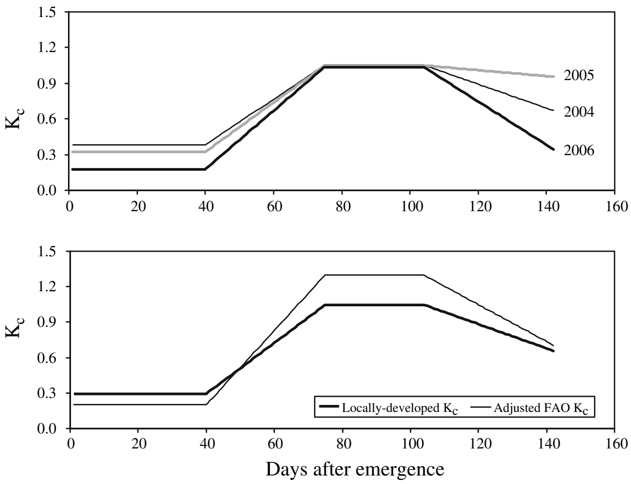

Fig. 6 Locally developed K_c curves for the 2004–2006 growing seasons (*top*), and their average curve compared to adjusted FAO K_c curve (*bottom*)

103%, with the widest deviations occurring for the initial- (ranging from −47 to 1%) and late- (ranging from −25 to 103%) season stages. For the mid-season stage, the locally developed $K_{c\text{-mid}}$ values were very similar (1.04 and 1.05), but lower by about 24% than the adjusted FAO $K_{c\text{-mid}}$ value of 1.30. Hunsaker (1999) developed K_c for short season cotton in Arizona finding higher K_c values than the ones proposed in FAO-56. Similarly, cotton K_c values were up to 35% higher in Arizona and California than those reported in FAO-56 (Grismer 2002). In contrast, the locally developed K_c values in this study are generally lower than the adjusted FAO values, i.e., by 24% for mid-season stage. The $K_{c\text{-end Local}}$ values found in this study are generally high (except in 2006), but comparable to those reported by Grismer (2002) with values of 0.87 for Sacramento and San Joaquin valleys and 0.95 for California desert counties. When transpiration is terminated by top-kill practices, the $K_{c\text{-end}}$ is substantially reduced, e.g., to values of 0.1–0.2 (Howell et al. 2004).

Table 6 Summary of measured cotton evapotranspiration and topsoil water content for the late-season growth stage in 2004–2006

Late-season growth period[a]	2004	2005	2006
Mean $ET_{c\text{-Meas}}$, mm d^{-1}	6.5	8.1	5.9
Volumetric soil water content (top 0.3 m), % m^3 m^{-3}	24.1	26.1	22.6
$K_{c\text{-end Local}}$	0.67	0.95	0.35
Total $ET_{c\text{-Meas}}$ during the late-season period, mm	248	306	223

[a] Late-season growth period is from 17 Aug to 24 Sep (104–142 DAE for a total of 39 days)

The results show considerable level of sensitivity of the K_c methodology to normal year-to-year irrigation management variations during the early sparse canopy conditions and late season senescence. For instance, the average daily $ET_{c\text{-Meas}}$ and volumetric surface water content (top 0.3 m soil) values for the late-season period (Table 6) were highest in 2005 (8.1 mm d^{-1} and 26.1%) and lowest in 2006 (5.9 mm d^{-1} and 22.6%). The consequence of this is reflected in the calculated $K_{c\text{-end Local}}$ that was also highest (0.95) in 2005 and lowest (0.35) in 2006, with an intermediate value (0.67) in 2004. The results translate to an average 17% increase in $K_{c\text{-end Local}}$ value for each percent increase in topsoil water content. This sensitivity is known in literature, i.e., previously addressed in Jensen et al. (1990) and Allen et al. (1998), and suggests the use of multiple years of data to construct a more representative K_c curve. The average of the three locally developed K_c curves (Fig. 6) is thus preferred for scheduling of drip-irrigated cotton in northern Syria. Since most farming practices in Syria are suboptimal, the above-suggested average K_c values may need to be lowered for field applications. For instance, $K_{c\text{-mid}}$ values developed originally under pristine cropping conditions required a 6% reduction in southern California (Allen et al. 2005) and 15% in western Turkey (Allen 2000) because the assumed optimal conditions did not prevail.

Crop coefficient as a function of thermal units (i.e., Growing-Degree-Days, GDD) has been suggested to improve accounting for climate variability and enhancing transferability of K_c curves (Sammis et al. 1985; Slack et al. 1996; Hunsaker 1999; Howell et al. 2004). Cumulative GDD values were computed (Table 3), suggesting the required 380, 430, 410, and 450 degree days (°C) for the initial-, development-, mid-, and late-season growth stages. The average cumulative GDD for the cotton season was 1680°C in northern Syria, a value similar to data from the semi-arid New Mexico, USA (Sammis et al. 1985), but higher than those in northern Texas (Howell et al. 2004).

Predicted and measured crop evapotranspiration

The performance of the adjusted FAO K_c curves is evaluated by using Eq. 1 to predict ET_c (referred to as $ET_{c\text{-FAO}}$) and compared with measured ET_c (i.e., $ET_{c\text{-Meas}}$) values. The comparison is presented in Fig. 7, showing that use of the adjusted FAO K_c overestimated ET_c in all 3 years and during all growth stages (except in the initial stages in 2004 and 2005). On the average, $ET_{c\text{-FAO}}$ per growth stage underestimated the measured values by 30% for the initial stage and overestimated by 23, 24, and 19% for the development, mid-season, and late-season growth stages, respectively. It is noted that the highest measured ET_c occurred during the mid-season stage for a total of 320 mm and the lowest during the initial stage for a total of 87 mm.

As pointed out by Farahani et al. (2007) "How precisely does ET_c need to be since irrigation application (depth or volume) and inherently field soil and crop variability can be much greater than ET_c errors?" With care, using an appropriate model for ET_o and reliable K_c generally produces estimates of ET_c within the accuracy of most field-irrigation systems to deliver water (Jensen et al. 1990). In this study and on the seasonal basis, $ET_{c\text{-FAO}}$ overestimated $ET_{c\text{-Meas}}$ by 10, 10, and 33% in 2004, 2005, and 2006, respectively, for an average of 17% (or 150 mm water) for the 3 years. Considering that the average irrigation amount per event was 85 mm in the 3 years, the overestimation of ET_c by using the adjusted FAO K_c curve is substantial and equivalent to about two additional irrigations per season.

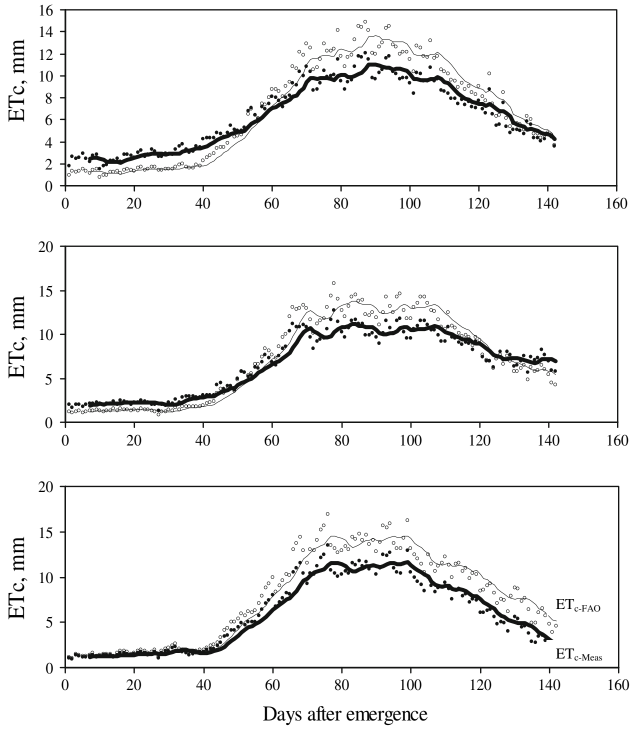

Fig. 7 Measured and predicted (multiplying adjusted FAO K_c by ET_o) cotton evapotranspiration during the 2004–2006 growing seasons. (Measured values are the result of multiplying locally developed K_c by ET_o.)

Conclusions

The development of K_c curve for cotton was pursued because of its simplicity, wider appeal to extension personnel, and limited data requirements for irrigation scheduling and water management. Two sets of K_c curves were developed, the generalized K_c values published by FAO that were adjusted for local climate, and the locally developed K_c curves as the ratio of measured ET_c to ET_o for the 3 years. The locally developed K_c curves not only differed among the 3 years, but also from the adjusted FAO K_c values. The initial- and end-stage K_c values appear to be the most susceptible to local variations than the mid-season value, presumably because of lower canopy cover and higher soil evaporation following wetting. Because of this, use of multi-year data is suggested for K_c development. The use of the adjusted FAO K_c values overestimated seasonal crop evapotranspiration by 10–33%, thus cautioning against their blind application without some verification.

Since neither the in-season soil water measurements, nor the use of computerized irrigation scheduling programs are yet adopted by Syrian farmers, the help of local extension service in an effective irrigation scheduling is needed. A practical approach might require a dedicated effort from extension to measure, compute, and publicize daily or weekly crop water requirements for the main crops in the area. The K_c curves developed herein can enhance that effort. It is noted that the experiment reported herein was conducted at ICARDA experiment station, which resembles optimal (i.e., pristine) cropping conditions as compared to many farming practices in the region. For on-farm practices under less than optimal conditions, lower K_c values than those reported herein are most likely required. Similar experiments under farming conditions are needed for that purpose.

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