Turfgrass Crop Coefficients in the U.S.

Consuelo C. Romero, Ph.D.
Researcher. Agricultural and Biological Engineering Department. Institute of Food and Agricultural Sciences. University of Florida, Gainesville, FL 32611, USA.
ccromero@ufl.edu

Michael D. Dukes, Ph.D.
Associate Professor, Agricultural and Biological Engineering Department. Institute of Food and Agricultural Sciences. University of Florida, Gainesville, FL 32611, USA.
mddukes@ufl.edu

Abstract. *Turfgrass crop coefficients are used for irrigation consumptive use permitting as well as the basis for irrigation scheduling in many areas of the U.S. However, there have been limited studies to determine crop coefficients for turfgrass. This paper summarizes crop coefficients available in the literature and indicates the need for future crop coefficient determination.*

Keywords: crop coefficient, warm-season turfgrass, cool-season turfgrass.

Introduction

According to a turfgrass industry survey, 18,207 km^2 (1,820,700 ha) of turf existed in Florida in 1991-92. Industry sales and services amounted to approximately $7 billion during that time (Hodges et al., 1994). In 2003, Morris estimated that there were 202,300 km^2 (20,230,000 ha) of turf in the U.S., with approximately 67% found in home lawns Florida has the second largest withdrawal of ground water for public supply in the U.S. (Solley et al., 1998). The most recent estimation of the turf area in the USA was presented by Milesi et al. (2005), reporting a total estimated turfgrass area of 163,800 km^2 (+/- 35,850 km^2 for the upper and lower 95% confidence interval bounds-equivalent to 16,380,000 +/- 3,885,000 ha), which include all residential, commercial, and institutional lawns, parks, golf courses, and athletic fields (Fender, 2006). The study was based on the distribution of urban areas from satellite and aerial imagery. If considering the upper 95% confidence interval bound, that would represent 199,650 km^2 (19,965,000 ha) and this estimate reasonably compares to the estimates of Morris (2003).

Estimates in Florida indicate that 30-70% (FDEP, 2001) of residential per capita water use is for landscape irrigation. Landscape ordinances and water conservation rebate programs from Texas, Arizona and California promote the use of water conserving plant species and the reduction in the amount of landscape area planted to turfgrass in urban landscapes. Little evidence was available to document the impacts of these ordinances and programs on reductions in water as of 2003 (Havlak, 2003). However, a study funded by Tampa Bay Water that suggests that landscape water conservation ordinances are not consistently enforced resulting in poor compliance in Southwest Florida. Thus, there are likely minimal water conservation benefits (Tampa Bay Water, 2005).

Turfgrass provides functional (i.e. soil erosion reduction, dust prevention, heat dissipation, wild habitat), recreational (i.e., low cost surfaces, physical and mental health) and aesthetic (i.e. beauty, quality of life, increased property values) benefits to society and the environment (Fender, 2006; King and Balogh, 2006). However, critics of grass maintain it not only wastes time, money and resources, but even worse, that efforts to grow grass results in environmental pollution. Critics recommend the total replacement with what are termed ‘native plants’ (Fender, 2006).

The water requirements of most turfgrasses have been established by scientific study (Beard and Green, 1994). Water use of turfgrasses is the total amount of water required for growth and transpiration plus the amount of water lost from the soil surface (evaporation), but because the amount of water used for growth is so small, it is usually neglected (Huang, 2006; Augustin, 2000). Most of the water transpired through the plant moves through openings in the leaves called stomates, which results in a cooling effect resulting from the evaporation process. The amount of water lost through transpiration is a function of the rate of plant growth and several environmental factors, such as soil moisture, temperature, solar radiation, humidity and wind. Transpiration rates are higher in arid climates than in humid climates because of the greater water vapor deficit between the leaf and the atmosphere in dry air. Thus, transpiration losses may be as high as 10 mm of water per day in desert climates during summer months; whereas in humid climates under similar temperature conditions, the daily losses may be only 5 mm of water per day (Duble, 2006). The application of water to turfgrass in amounts exceeding its requirements can be attributed to human factors, not plant needs (Beard and Green, 1994).

Crop coefficients (K_c's) used in irrigation are the ratio of actual evapotranspiration (ETa) to reference ET. Reference ET (ETo) is the ET that is calculated from a surface of actively growing grass that is maintained at 12 cm and is well-watered (Allen et al., 1998). Once K_c's have been generated, only estimates of ETo are required to estimate ETa needed for scheduling irrigation (Allen et al., 1998). Thus, using different ETo equations will generate different K_c values, which is one reason the ASCE EWRI Standardized Reference ET methodology was developed (Allen et al., 2005). Allen et al. (2005) stated "there can be considerable uncertainty in K_c-based ET predictions due to uncertainty in quality and representativeness of weather data for the ETo estimate and uncertainty regarding similarity in physiology and morphology between specific crops and varieties in an area and the crop for which the K_c was originally derived.

Crop coefficients can vary substantially over short time periods, so monthly averaged coefficients are normally used for irrigation scheduling (Carrow, 1995). These coefficients can be averaged to yield quarterly, semi-annual, or annual crop coefficients (Richie et al., 1997), although averaging K_c's reduces monthly precision and turfgrass may be under-irrigated during stressful summer months. Factors influencing K_c for turfgrasses are seasonal canopy characteristics, rate of growth, and soil moisture stress that would cause coefficients to decrease, root growth and turf management practices (Gibeault et al., 1989; Carrow, 1995).

Scientific irrigation scheduling regimes which calculate irrigation water requirements based on ETa have been suggested as one means of improving irrigation management of turfgrass (Brown et al., 2001). ETo data are available from public weather networks in different regions of U.S.; however, access to reliable K_c's becomes a limiting factor when implementing scientific irrigation scheduling systems for turfgrass.

The objective of this study is to perform a literature review showing reported crop coefficients for both warm and cool season grasses available in the U.S.

Methods

A review of the literature was performed to summarize K_c's determined for both warm and cool season grasses. Many studies have been conducted on turfgrass water use with a wide variety of methods. In most of the studies, weather data were not reported. Therefore, K_c values could not be calculated. In addition, turfgrass water loss data was assembled for Florida conditions.

Literature review

Many literature sources and agencies reference warm and cool season turfgrass K_c's developed in California in the early 1980's as reported by Gibeault et al. (1989). These K_c values were developed and documented in a series of publications, none of which appear in the peer reviewed literature, thus they are difficult to find in some cases. Turfgrass K_c's will exhibit considerable variation during the growing season which is due in part to plant cover, growth rate, root growth and stage of the plant development and turf management practices (Gibeault et al., 1989; Brown et al., 2001). K_c data for warm-season grasses included common and hybrid Bermudagrasses, St. Augustinegrass, Bahiagrass, Centipedegrass, Zoysiagrass, and Seashore Paspalum. K_c values for cool-season turfgrasses included Kentucky bluegrass, Perennial ryegrass, Tall Fescue, mixed grasses, shortgrass and sagebrush-grass.

One of the most comprehensive studies provided an estimate of Penman crop coefficients for various grasses grown in southeastern U.S. was presented by Carrow (1995), including Tifway bermudagrass (*Cynodon dactylon* X *C. transvaalensis*), common bermudagrass [*C. dactylon* (L.) Pers.], Meyer Zoysiagrass (*Zoysia japonica* Steud), common Centipedegrass [*Eremochloa ophiuroides* (Munro.) Hack.], Raleigh St. Augustinegrass [*Stenotaphrum secundatum* (Walt.) Kuntze], and Rebel II and Kentucky-31 tall fescue (*Festuca arundinacea* Schreb.). The study was conducted in Griffin, GA on research plots, during 1989 and 1990, where these seven turfgrasses (including warm-season and cool-season turfgrasses) are commonly used in the mid- to upper Southeast region. Reference crop evapotranspiration (ETo) was determined by the FAO modified Penman equation, which is described by Doorenbos and Pruitt (1984) as:

$$ETope = c[W \text{ X } Rn + (I-W) \text{ X } f(u) \text{ X } (ea-ed)],$$

Where ETope is reference evapotranspiration (mm), c is adjustment factor to compensate for the effect of day and night weather condition, W is temperature related weighing factor for the effect of radiation on ETo (mm), I is irrigation (mm), Rn is net radiation in equivalent evaporation (mm), f(u) is a wind function, ea is saturation vapor pressure of air at the mean daily air temperature (kPa) and ed is actual vapor pressure of air at the mean daily air temperature (kPa). Actual evapotranspiration (ETa) was derived from daily soil water extraction data from TDR soil moisture probes obtained during dry-down periods following irrigation or rainfall events when no drainage occurred. According to the author, the irrigation regime imposed moderate to moderately severe stress on the turfgrass but this would be representative of most home lawn irrigation regimes. ETa was determined by soil-water balance method. Therefore, K_c was calculated dividing ETa by the FAO modified Penman ETo. For all grasses, coefficients varied substantially over short time periods, but data was presented as monthly averages. Tifway bermudagrass exhibited the least variation (0.53-0.97 for K_c) and Meyer Zoysiagrass the most (0.51-1.14 for K_c). In general, warm-season species ranged from 0.67 to 0.85, while cool-season grasses were 0.79 and 0.82 (Table 1). A similar study using cool-season and warm-season grasses under warmer conditions (California) was presented by Meyer and Gibeault (1987). They developed a set of crop coefficients for Kentucky bluegrass, perennial ryegrass, tall fescue (cool-season grasses) and hybrid bermudagrass, zoysiagrass and seashore paspalum (warm-season grasses), that could be used by California turfgrass managers to determine on-site water use by both type of turfgrasses. Crop coefficients ranged from 0.60 to 1.04 for cool-season turfgrasses, and from 0.54 to 0.79 for warm-season grasses. ETc was calculated as the actual applied water divided by the extra water factor (EWF_{90}), which was 1.35. EWF_{90} is the amount of water needed to apply 1 inch

(2.5 cm) to 90% of the area. In this experiment the coefficient of uniformity, CUs – 87% and EWF90 =1.35:

$$EWF90 = 1/[1-(t^{\sigma}/X')$$

Where *t* = probability value from statistical table related to the number of cans in the test and the percentage of the area that must receive a unit amount of water (90%). Σ is a function of individual can value, the mean of all values (X') and number of cans. ETc was for the 100% ET regime, since 60% and 80% were also tested. ETo was calculated using the modified Penman equation (Doorenbos and Pruitt, 1977).

Meyer et al. (1985) used data from a study reported by Marsh et al. (1978) to develop the California K_c's. The authors report that the K_c values were developed by a Bureau of Plant Industry (BPI) evaporation pan measurement adjusted to a standard Class A pan and then adjusted to ETo based on factors presented by Doorenbos and Pruitt (1977). Thus, there were several adjustment factors based on generalized literature values rather than quantitative measurements. Furthermore, the ETc data reported by Marsh et al. (1978) were developed by measuring the irrigation application on tensiometer controlled field plots. This study was conducted during different years for warm and cool season grasses. Regarding the cool season grass study, the authors note "Evaporation was greater and rain less during these three years than during the previous study with warm season grasses". Thus, the California K_c values were developed with uncertain and general ETo values and it is likely the plots were not "well-watered" during the entire study.

Another study using bahiagrass (*Paspalum notatum* Flugge) was presented by Jia et al. (2007). Daily K_c values were determined for July 2003 through December 2006 in central Florida, where the eddy correlation method was used to estimate crop evapotranspiration (ETc) rates. ETo was calculated using the standardized reference evapotranspiration equation. Monthly K_c values were low in the winter time (dormant grass status) although the K_c values also decreased in the summer time from peak values in May (Table 1). In the southern area of Florida, the water budgets of a monoculture St. Augustinegrass (*Stenotaphrum secundatum* Waltz Kuntze cv.

‘Floratam’) and an alternative ornamental landscape were compared (Park and Cisar, 2006). ETc was determined by a water balance equation and ETo was estimated using the McCloud method. The average wet season crop coefficient for St. Augustinegrass was 0.30; however, for the dry season the crop coefficient increased to 0.51. These values are much lower than other literature values for warm season grass likely due to the over-estimation of ETo by the McCloud method (McCloud, 1955).

A study carried out in the humid northeast (Rhode Island) using Kentucky bluegrass (*Poa pratensis* L., ‘Baron’ and “Enmundi’), Red fescue (*Festuca rubra*), Perennial ryegrass (*Lolium perenne*) and hard fescue (*Festuca ovina*) during 1984 and 1985 showed that the mean crop coefficients ranged from 0.97 for hard fescue to 1.05 for Baron Kentucky bluegrass, as shown in Table 1 (Aronson et al., 1987). And, as a conclusion, an averaged K_c value of 1.0 would be appropriate for irrigation scheduling on all the grasses studied. K_c values were obtained dividing ETc data from weighing lysimeters, and ETo computed from two predictive methods, the modified Penman equation (Burman et al., 1980) and pan evaporation. The exact form of the equation used was:

$$ETo = [\ \Delta/\ (\Delta + \gamma)] + [\gamma/\ (\Delta + \gamma)]15.36\ wf(ea - ed)$$

Where ETo is reference crop ET in J m^{-2} day^{-1}; Δ is the slope of the vapor pressure – temperature curve in kPa/^{o}C; γ is the ppsychometer constant in kPa/ ^{o}C; Rn is net radiation in J $m^{-2}day^{-1}$; G is soil heat flux to the soil in J $m^{-2}day^{-1}$, wf is the wind function (dimensionless); and (ea-ed) is the mean daily vapor pressure deficit in kPa.

Monthly crop coefficients for bermudagrass (*Cynodon dactylon* (L.) Pers.) overseeded with perennial ryegrass (*Lolium perenne* L.) were presented by Devitt et al., 1992. Lysimeters were installed at two golf courses and at a park in Las Vegas, NV. Each site was equipped with an automated weather station. Crop coefficients were calculated by dividing monthly ETa by Penman calculated ETo values. The greatest variability in the K_c values (all sites) occurred during the winter months (December to February) and only during this period did both the high management turf (golf courses) and the low management turf (park) have similar K_c values (Table 1). Significant differences were observed the rest of the year as the K_c values for the golf course sites were fit to a bell-shaped curve; the park site had a somewhat flat K_c response. Since the same mixed grass was grown at each site and because the soil type and water quality were similar, differences on Kc values were attributed to cultural management input, especially the fertilizer input. Nitrogen was applied at a rate 3 to 5 times higher, iron 6 to 8 times higher and phosphorus 13 to 24 times higher on the golf courses than on the park site.

Brown et al. (2001) developed Penman Monteith crop coefficients for warm-season 'Tifway' bermudagrass (*Cynodon dactylon* L. X *C. transvaalensis* Davy) in summer and overseeded 'Froghair' intermediate ryegrass (*Lolium perenne* X *L. multiflorum*) in winter at Tucson, AZ. Froghair is a new intermediate ryegrass which is designed for the overseeding market in the Southern regions of the U.S. Intermediates are genetic crosses using annual ryegrasses and perennial ryegrasses in the parentage (www.turfmerchants.com/varieties/TMi_**Froghair**.html). They related daily measurements of ETa obtained from weighing lysimeters to reference evapotranspiration (ETo) computed by means of the simplified form of the FAO Penman Monteith Equation (Allen et al., 1994, 1998):

$$ET_o = \{[0.408\Delta\ (R_n - G)] + [\gamma\ 900/(T+273)\ U_2\ (e_s{}^o - e_a)]\}/\ \Delta + \gamma(\ 1 + 0.34\ U_2)$$

where ET_o is the reference evapotranspiration rate in mm d^{-1}, T is mean air temperature in ^oC, and U_2 is wind speed in m s^{-1} at 2 m above the ground (and RH or dew point and air temperature are assumed to be measured at 2 m above the ground, also). Equation 3 can be applied using hourly data if the constant value "900" is divided by 24 for the hours in a day and the R_n and G terms are expressed as MJ m^{-2} h^{-1}.

For overseeded bermudagrass, a constant K_c of 0.8 would be effective for estimating ETa during the summer months, but not for non-overseeded bermudagrass, which has extended periods of slow growth and lower ETa during the spring and fall. Monthly K_c's for overseeded 'Froghair' intermediate ryegrass varied from 0.78 (Jan) to 0.90 (Apr), which showed that winter K_c's were dependent upon temperature (Table 1). Another study reporting K_c values for Tifgreen and Midiron hybrid bermudagrasses

(*Cynodon dactylon* (L.) Pers. X *C. transvaalensis* Davy), and Texturf-10 common bermudagrass (*Cynodon dactylon*) growing at plot level from sod in Tucson, Arizona (Garrot and Mancino, 1994), showed average K_c values ranging from 0.57 to 0.64 with Midiron being lowest and Texturf-10 being highest. Irrigation was made only when the turf showed symptoms of wilt. Time periods between irrigation events were referred to as soil dry down cycles (DDC). Turfgrass water use (ETa) was determined using two methods: (i) through the determination of gravimetric soil moisture from soil cores (0 to 90 cm depth, using 30 cm intervals) taken at the beginning (48 h after irrigation) and end of each DCC. The K_c's were calculated by dividing the actual consumptive use (derived from the gravimetric samples) by the cumulative ETo [modified Penman equation (Doorenbos and Pruitt, 1977)]. Daily K_c values varied, however, from as high as 1.50 to as low as 0.10. As soil water became limiting during the course of a DDC, K_c values declined, sometimes to < 0.10. These values depended mostly on the availability of water but very high values always occurred when solar radiation was low. This study implemented deep and infrequent irrigation regime under fairway conditions, when the turf showed symptoms of wilt and keeping the overall turfgrass quality above acceptable. Thus, the stress imposed during this study likely violated the "well-watered" concept.

A similar experiment applying deficit irrigation but using cool-season turfgrasses was presented by Ervin and Koski (1998) in Fort Collins, CO. Kentucky bluegrass (KBG, *Poa pratensis* L.) and tall fescue (TF, *Festuca arundinacea* Schreber) turfs were subjected to increasing levels of drought through the use of a line-source irrigation system with the idea to develop water-conserving crop coefficients (K_c) to be used with Penman equation estimates of alfalfa (*Medicago sativa* L.). Their research indicated that water conservation can be encouraged while still maintaining acceptable turfgrass quality by irrigating every 3 days with K_c values in the range of 0.60 to 0.80 for KBG and 0.50 to 0.80 for TF (Table 1).

Crop coefficients for rangeland were also determined (Wight and Hanson, 1990). This study used lysimeter-measured ET to determine K_c's under non-limiting water conditions from mixed grass (*Agropyron smithii* as dominant species), shortgrass

(*Bouteloua gracilis* as dominant species), and sagebrush-grass (*Artemisia arbuscula* as dominant species). From seasonal plots of daily ET/reference ET, lysimeter-measured ET, and daily precipitation, time periods were identified, following periods of precipitation, that met the conditions for determining K_c. The sites were South Dakota, Wyoming and Idaho, respectively. The K_c values were relatively constant among the 3 study sites and over most of the growing season ranging from 0.75 to 0.90 (Table 1). According to the conclusions, these are crude estimates because the soil water requirements necessary for the determination of K_c are seldom fully met, and it is difficult to determine when these conditions occur.

Results and discussion

Available K_c data for cool-season and warm-season turfgrasses for different locations in the U.S are presented in Table 1. The study period length, the methodology to determine K_c and the reference are specified. K_c data were plotted on graphs according to the turfgrass type (cool- or warm-season). Monthly K_c values for the summer months (May to October) and for the winter months (November to April) are shown in Figures 1 and 2.

Table 1: Summary chart showing turfgrass species, average K_c, methodology used to determine ET and K_c and respective references.

Turfgrass species	K_c	Study period length	Methodology	Reference/ Location
Bahiagrass	Jan (0.35) Feb (0.35) Mar (0.55) Apr (0.80) May (0.90) Jun (0.75) Jul (0.70) Aug (0.70) Sep (0.75) Oct (0.65) Nov (0.60) Dec (0.45)	July 2003 through December 2006	ETc: Eddy correlation method. ETo: Standardized reference ET equation. K_c: ETc/ETo	Jia et al., 2007. Central Florida.
St. Augustinegrass	Wet season (0.30) Dry season (0.51)	4 years	ETc: Water balance. ETo: McCloud method. K_c: ETc/ETo	Park and Cisar, 2006. South Florida.
Overseeded froghair ryegrass (Nov-May) – Winter (3-yr avg.)	Nov (0.82) Dec (0.79) Jan (0.78) Feb(0.79) Mar (0.86) Apr (0.90) May (0.85)	Nov. 1994 to Sept. 1997.	ETc: lysimeters (water balance). ETo: Penman-Monteith equation. K_c: ETc/ETo	Brown et al., 2001. Tucson, AZ.
Tifway bermudagrass (Jun-Sept) – Summer (3-yr avg.)	Jun(0.78) Jul (0.78) Aug (0.82) Sep (0.83)			
Kentucky Bluegrass	0.60 to 0.80	1993 to 1994	ETr: (Kimberly-Penman combination eq.) Eta: 80% ETr K_c: Eta/ETr	Ervin and Koski, 1998. Fort Collins, CO.
Tall fescue	0.50 to 0.80			
Tifway bermudagrass	0.67			
Common bermudagrass	0.68	First season: from 26 June to 10 Oct 1989 (data on the left)	ETc: soil moisture content (TDR_s) during dry-down periods when no drainage occurred.	Carrow, 1995. Griffin, GA.
Meyer zoysiagrass	0.81			
Common centipedegrass	0.85			
Raleigh St Augustinegrass	0.72	Second season: from 5/4/90 to 11/2/90 (data on the right)		
Rebel II tall fescue	0.79		ETo: Penman equation. K_c = ETc/ETo	
Kentucky-31 tall fescue	0.82			
K_c values are annual				

Turfgrass species	K_c	Study period length	Methodology	Reference/ Location
Bermudagrass/ Perennial rye	Jan (0.44) Feb (0.43) Mar (0.67) Apr (0.76) May (0.74) Jun (0.89) Jul (0.89) Aug (0.82) Sep (0.82) Oct (0.77) Nov (0.81) Dec (0.51)	1987 to 1989 (two golf course sites)	ETc: lysimeters (water balance). ETo: Penman equation. K_c = ETc/ETo.	Devitt et al., 1992. Las Vegas, NV.
Hybrid and common Bermudagrass:		1989 to 1991	Water use determined by gravimetric method. ETa=actual water use ETo (mod. Penman) K_c =Eta/ETo	Garrot and Mancino, 1994. Tucson, AZ.
Texturf-10	0.64	These are annual K_c s		
Tifgreen	0.60			
Midiron	0.57			
Bermudagrass/ Perennial rye	Jan (0.40 Feb (0.33) Mar (0.45) Apr (0.54) May (0.48) Jun (0.58) Jul (0.52) Aug (0.60) Sep (0.56) Oct (0.54) Nov (0.60) Dec (0.45)	1987 to 1989 (park site)	ETc: lysimeters (water balance). K_c = ETc/ETo	Devitt et al., 1992. Las Vegas, NV.
Mixed grass, shortgrass and sagebrush-grass	0.82 0.79 0.85	46 days at Newell (1969,1971) 86 days at Gillete (1968-1970) 121 days at Reynolds (1977-1984)	ETc: lysimeter (ETc was separated into an evaporation component [EP] and a transpiration component [Tp]. ETref: Jensen-Haise K_c = ETc/JHET	Wight and Hanson, 1990. Newell, SD. Gillette, WY. Reynolds, ID.

Turfgrass species	K_c	Study period length	Methodology	Reference/ Location
Kentucky bluegrass	July (1.03) Aug (0.84) Sept (1.0)	From July to September, 1984-1985	ETc: weighing lysimeters K_c: 1) Modified Penman equation	Aronson et al., 1987. Kingston, RI.
Red fescue	July (0.98) Aug (0.83) Sep (0.99)			
Perennial grass	July (1.05) Aug (0.88) Sept(1.02)			
Hard fescue	July (0.98) Aug (0.80) Sep (0.94)			
Cool season grasses	Jan (0.61) Feb (0.64) Mar (0.75) Apr (1.04) May (0.95) Jun (0.88) Jul (0.94) Aug (0.86) Sep (0.74) Oct (0.75) Nov (0.69) Dec (0.60)	Aug. 1981 to Dec. 1983	ETa: equals the actual applied water divided by the extra water factor (EWF90), which was 1.35 for this case. ETo= calculated using modified Penman equation. K_c: ETc/ETo	Meyer and Gibeault, 1987. Riverside, CA.
Warm-season grasses	Jan (0.55) Feb (0.54) Mar (0.76) Apr (0.72) May (0.79) Jun (0.68) Jul (0.71) Aug (0.71) Sep (0.62) Oct (0.54) Nov (0.58) Dec (0.55)			

In general, all grasses had substantial changes in crop coefficient values during the respective study periods (Figures 1 and 2). In Florida, bahiagrass K_c's varied throughout the year with a peak in May, when wind was strongest, cloud cover is lightest, and vapor pressure deficit was highest (Jia et al., 2007, Figure 2). They decreased in the summer due to weakening of these three variables with respect to ET. K_c's developed by Carrow (1995) showed increases in September (Figure 2), in spite of the moderate severe stress to the turf in the field plots. Apparently, the prolonged dry-down periods in August and early September resulted in a proliferation of roots within a moist soil zone deep in the soil profile and resulting in high ET values. An average of August and October coefficients may be better than the September coefficients for scheduling irrigation in September. Brown et al. (2001) concluded that within season K_c's may be relatively constant. They noted that K_c's were more variable in the summer season where cloud cover became more frequent, which supports findings by Jia et al. (2007). Also, different climates will have different green up and dormancy periods and these differences are reflected on the K_c values. These differences are evident in the comparison of K_c's developed by Brown et al. (2001) in Tucson and values developed by Devitt et al. (1992) in Las Vegas using bermudagrass. In summary, the results are mixed but it does appear that cool-season turfgrasses use up to 20% more water than warm-season turfgrasses.

Warm-season turfgrasses exhibited lower K_c values compared to the cool-season turfgrasses, reflecting their low water-use rates. Both types of turfgrasses overlapped ranges of K_c values in some circumstances; however, a uniform crop coefficient cannot be used for all grasses since every species does not perform in the same way, according to most of the references. On the other hand, Aronson et al., (1987) recommended a K_c value of 1.0 for irrigation scheduling on all the grasses they studied (Kentucky bluegrass, Red fescue, Perennial ryegrass and Hard fescue.

Some K_c values in the literature were developed under limited irrigation and it is likely the plots were not "well-watered" during the entire study as part of their objectives. These K_c values may be appropriate for water conservation in the location of the study, but should not be extended to other regions of the U.S. (Carrow, 1995; Garrot and Mancino, 1994; Meyer and Gibeault, 1987).

According to the ASCE manual (Allen et al., 2005) the calculation of crop evapotranspiration (ETc) requires the selection of the appropriate crop coefficient (K_c) for use with the standardized reference evapotranspiration, either for a short crop

(ETos) of tall crop (ETrs). New recommended abbreviations for crop coefficients developed for use with ETos would be denoted as K_{co}, and K_{cr} if ETrs is used.

$$ETc = K_{co} * ETos \qquad \text{or} \qquad ETc = K_{cr} * ETrs$$

Grass-based crop coefficients should be used with ETos. K_c values that can be used with ETos without adjustment are reported in FAO-56 (Allen et al., 1998) and ASCE Manual 70 (Jensen et al., 1990)

Finally, there is a need for seasonal adjustments when using K_cs for irrigation scheduling. So, to effectively use weather-based irrigation scheduling, turfgrass managers must select crop coefficients based on month and turfgrass species.

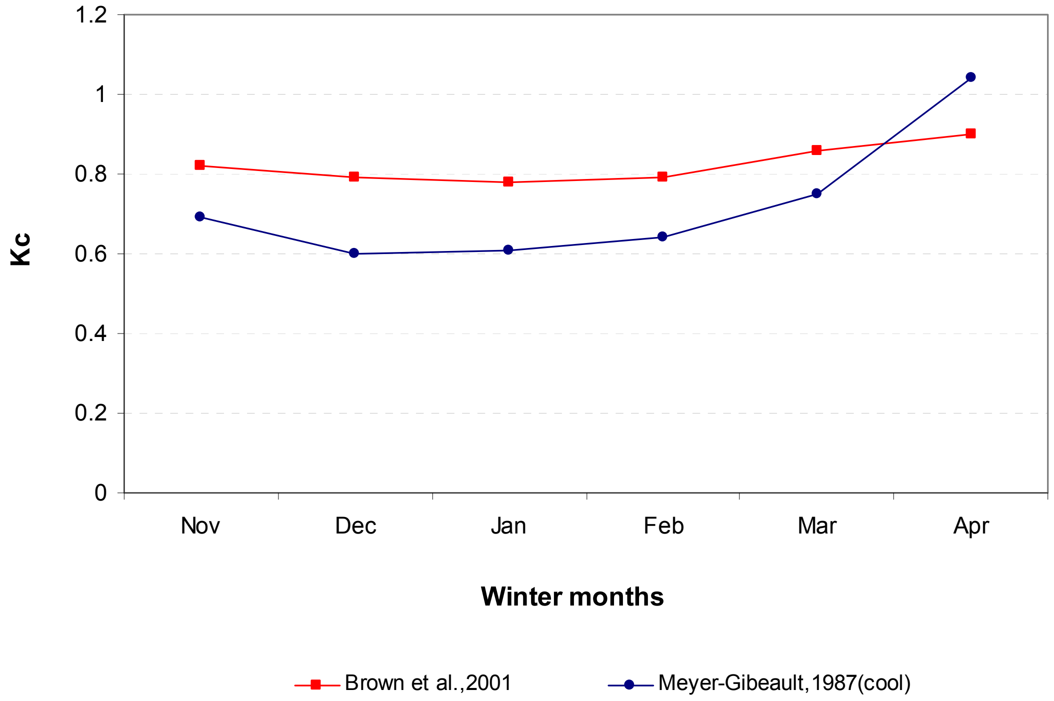

Figure 1: K_c values for cool-season turfgrasses according to different references.

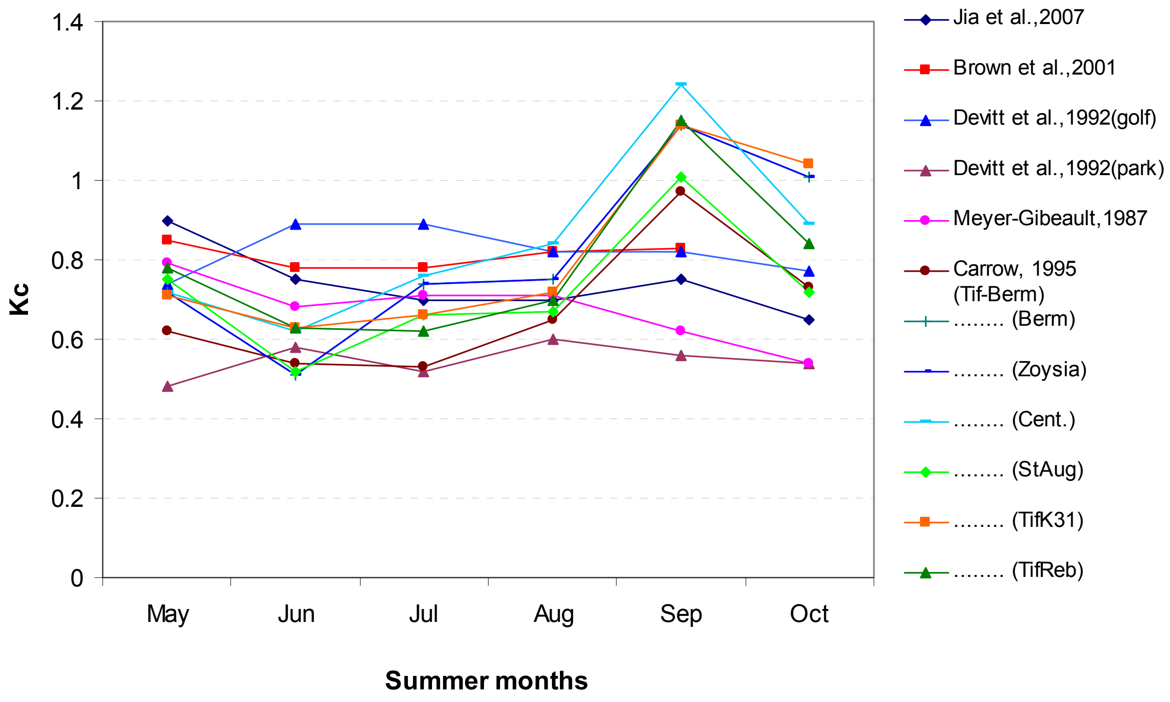

Figure 2: K_c values for warm-season turfgrasses according to different references.

Conclusions

- Crop coefficient values for warm-season and cool-season turfgrasses can be found in a wide variety of literature. Those published in peer reviewed literature were available and discussed in the present paper; others, however, published in other sources were difficult to find and access.

- A variety of methods were used to determine turfgrass K_c values across the various studies reviewed here. Many of these varying methods impact the resulting K_c values. For example, differences in ET_o estimation impact many of the literature K_c values; however, the Penman methods will likely agree the closest. In addition a number of studies used slightly stressed turfgrass conditions for K_c development and these values should be avoided.

- For warm season grasses, K_c values developed by Jia et al (2007), Brown et al (2001), and Devitt et al. (1992) appear to follow accepted methodology for K_c determination of warm-season turfgrass.

- In general, all turfgrasses (warm-season and cool-season) had substantial changes in crop coefficient values over the time period when measurements were conducted.
- The results are mixed but it does appear that cool-season turfgrasses use up to 20% more water than warm-season turfgrasses when water is not limiting.
- It is important to understand the seasonal water use over a period of repeated years rather than relying only on short study periods. Seasonal water use differences can be attributed to different green up periods in the spring and dormancy periods in the fall and winter across grass varieties. The different growth periods across different climatic regions impact the K_c values.
- Crop coefficients based on month and turfgrass species must be selected to effectively use weather-based irrigation scheduling.

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