REVIEW OF TURFGRASS EVAPOTRANSPIRATION AND CROP COEFFICIENTS

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emerging technologies for sustainable irrigation

A Tribute to the Career of
Terry Howell, Sr.

ABSTRACT. *This review summarizes available data related to turfgrass evapotranspiration (ET_c) and crop coefficients (K_c) for both warm-season and cool-season grasses. Daily, monthly, or seasonal ET_c rates and K_c values determined at different locations in the U.S. are shown in this review, as well as the methods used to determine or estimate these values. Warm-season turfgrasses are characterized by their lower ET_c rates compared to cool-season turfgrasses. Results showed that ET_c is highly variable, not only between species but within same species. For example, 'Tifway' bermudagrass, a warm-season turfgrass, showed ET_c values of 1.78 mm d^{-1} in central Florida and 4.83 mm d^{-1} in Colorado, whereas zoysiagrass showed an ET_c value of 9.40 mm d^{-1} in Texas. On the other hand, creeping bentgrass showed an ET_c value of 3.3 mm d^{-1} for 'Pennlinks' variety, while 'Seaside' showed an ET_c value of 10.7 mm d^{-1}, both in Nebraska. This variability was affected by genotype and plant morphological characteristics but was also due to weather conditions. Variability was also observed in turfgrass K_c. Minimum and maximum monthly K_c values for cool-season grasses were estimated as 0.05 and 1.05, respectively; for warm-season grasses, monthly K_c values ranged from 0.28 to 0.99. The lowest reported K_c values within a turfgrass species could serve as selection criteria to breed new varieties resistant to drought or contributing to water savings. Evapotranspiration rates and crop coefficients should be used with awareness of the local conditions under which the values were developed.*

Keywords. *Cool-season turfgrasses, Crop coefficient, Crop evapotranspiration, Reference evapotranspiration, Warm-season turfgrasses.*

Turfgrasses are considered an integral part of landscape ecological systems (Roberts et al., 1992) that provide functional, recreational, and aesthetic benefits to society and the environment (Fender, 2006; King and Balogh, 2006). In the U.S., turfgrass has become an important crop based on the acreage planted, with the largest sector of turfgrass being residential lawns (Bremer et al., 2012). The most recent estimation of the turfgrass area in the U.S. was given by Milesi et al. (2009). They estimated urban irrigated area in the conterminous U.S. from the most conservative 4,503,668 ha (U.S. Census based) to 9,602,148 ha based on a relationship between remote sensing-derived built-up area and turfgrass area. The total estimated turfgrass area in the U.S. obtained from various methods is 11,172,171 ha (USGS-based), 16,163,436 ha (NOAA-based), 7,263,980 (U.S. Census-based), and 14,564,101 (U.S. Census based). The study was based on the distribution of urban areas from satellite and aerial imagery. Morris (2003) estimated 20.2 million ha of turf in the U.S. on residential lawns (66.7%), golf courses (20%), and sport fields, parks, playgrounds, cemeteries, and highway roads (13.4%). The annual economic value of all turfgrass is estimated to be $40 billion. Critics argue that efforts to grow turfgrass result in excessive use of water and pesticides, leading to environmental pollution (Fender, 2006). Water consumption is influenced by turfgrass species, cultivar, and variety, as well as climate, water quality, irrigation management, cultural management, soil type, and aesthetics (Leinauer and Devitt, 2013). Estimation of turfgrass water consumption through the use of equations has also been shown to give highly variable values, so a standardized equation has been strongly recommended to reduce errors (Allen et al., 2005a). On the other hand, K_c values are adjustment factors that allow estimation of turfgrass evapotranspiration (ET_c) from reference evapotranspiration (ET_o), which is necessary to schedule irrigation (Aamlid et al., 2015).

The objective of this article is to present a review of turfgrass ET_c and K_c data and the diverse methods and procedures used to determine these values for both warm-season and cool-season turfgrasses in the U.S.

TURFGRASS OVERVIEW

Turfgrasses are classified into two groups based on their

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climatic adaptation: warm-season grasses, which are adapted to tropical and subtropical areas, and cool-season grasses, which are adapted to temperate and sub-arctic climates (Huang, 2006). Warm-season grasses use significantly less water than cool-season species. Warm-season grasses become active in mid-spring, with optimum growth at temperatures between 27°C and 35°C, which can develop in the hot, dry weather of mid-summer, and they become dormant in the winter. Some well-known species of warm-season grasses are bahiagrass (*Paspalum notatum*), St. Augustinegrass [*Stenotaphrum secundatum* (Walt) Kuntze], bermudagrass (*Cynodon dactylon*), zoysiagrass (*Zoysia* spp.), buffalograss [*Buchloë dactyloides* (Nutt.) Engelm.], centipedegrass [*Eremochloa ophiuroides* (Munro) Hack], and seashore paspalum (*Paspalum vaginatum*).

Cool-season grasses are generally more susceptible to moisture stress than warm-season grasses (Duble, 2014). This difference in water use derives from changes in the photosynthetic process that occurs in grasses that evolved in hot, dry conditions. These changes, which include modifications to biochemical reactions and internal leaf anatomy, greatly enhance the photosynthetic efficiency of warm-season species and help reduce water use. Increased photosynthetic efficiency means that the plants can maintain high levels of carbohydrate production and continue to grow even when their stomates are partially closed. This partial closure of the stomates slows the plant's water use. Cool-season grasses cannot maintain sufficient carbohydrate production for plant growth unless their stomates are nearly wide open; when water is limited, transpiration rates for cool-season grasses are generally higher than those of warm-season grasses (Gibeault et al., 1989). Cool-season grasses are active primarily during the spring and fall, when average daytime temperatures are cool (between 18°C and 24°C) and precipitation is adequate. They become dormant in the hot, dry conditions of summer and in the freezing cold of winter. Some well-known cool-season grasses are creeping bentgrass (*Agrostis stolonifera*), Kentucky bluegrass (*Poa pratensis*), perennial ryegrass (*Lolium perenne*), and tall fescue (*Festuca* spp.).

MEASUREMENT OF EVAPOTRANSPIRATION

Evapotranspiration (ET) is the loss of water from the soil through the combined processes of evaporation (from soil and plant surfaces) and plant transpiration. It can be measured using hydrological approaches such us lysimeters, which provide a direct measurement of ET and are frequently used to study climatic effects on turf growth. Lysimeters can be grouped into three categories: (1) non-weighing, constant water table types; (2) non-weighing, percolating types; and (3) weighing types. Large lysimeters (>0.6 m^2 surface area) are the standard instrument for measuring ET (Slatyer and McIlroy, 1961). For reliable measurements, lysimeters need to meet several requirements. First, they must have enough depth to allow normal root growth and contain an undisturbed soil profile (if the soil profile is disturbed, water movement and retention are likely to be different and may not be representative of field conditions). In addition, the vegetation inside and outside the lysimeter should be kept as similar as possible. To diminish the effect of the lysimeter rim on ET measurements, the lysimeter wall thickness, the gap between the inner and outer walls, and the height of the lysimeter rim relative to the soil surface should be as a small as possible. Finally, to reduce the oasis effect, there should be sufficient windward fetch distances of similar vegetation and soil moisture regimes (Allen et al., 1991).

Although lysimeters have been the standard method to determine ET, newer methods such as eddy covariance (e.g., Jia et al., 2009) and surface renewal (Snyder et al., 2015) have been used to determine ET for turfgrasses. Disadvantages of both approaches include relatively expensive equipment, regular maintenance (particularly in humid climates) and extensive data processing, and a need to close the energy balance (e.g. Twine et al., 2000) for eddy covariance. Surface renewal is a method for determining the sensible heat flux density; the surface energy balance is then solved for latent heat flux (ET) (Paw U et al., 1995; Spano et al., 2000). Similar to eddy covariance but to a lesser degree, expensive equipment is required, and appropriate analytical skills are needed to determine ET. Soil water balance is an indirect method that consists of assessing the incoming and outgoing water flux into the crop root zone over some time period (Allen et al., 1998). ET is obtained as a residual in the water balance equation, with a complete expression as:

$$\mathrm{ET} = I + P - RO - DP + CR \pm \Delta SF \pm \Delta SW \tag{1}$$

where I is irrigation, P is precipitation, RO is surface runoff, D is deep percolation, CR is capillary rise, ΔSF is change in subsurface flow in the root zone, and ΔSW is change in soil water content over the time period.

Many researchers have used mini-lysimeters in field studies (Grimmond et al., 1992). The advantages of mini-lysimeters are that they: (1) permit measurement of the evaporative flux from smaller areas, (2) create less environmental disturbance during installation, and (3) are less expensive to install than large lysimeters. Mini-lysimeters have been adopted due to their reduced installation and management costs and good measurement accuracy (Oke, 2004), although there are a number of potential sources of error due to confined root systems, altered internal soil drainage, etc. In general, the effect of error sources on the accuracy of ET measurements is inversely related to the surface area of the lysimeter (Dugas and Bland, 1989).

ANALYTICAL MODELS TO ESTIMATE ET

A large number of empirical methods have been developed over the last 50 years to estimate ET from different climatic variables. These methods have proved very useful in actual crop ET estimation because they take into account both the canopy properties and meteorological conditions (Szeicz and Long, 1969). Some of these methods are derived from the well-known Penman equation (Penman, 1948) to determine evaporation from open water, bare soil, and grass based on a combination of an energy balance and an aerodynamic formula, given as:

$$\lambda \mathrm{E} = [\Delta(R_n - G)] + (\gamma \lambda \mathrm{E}_a)/(\Delta + \gamma) \tag{2}$$

where λE is the evaporative latent heat flux (MJ m^{-2} d^{-1}), Δ is the slope of the saturated vapor pressure curve ($\delta e^\circ/\delta T$, where e° is saturated vapor pressure in kPa, and T is the temperature in °C, usually taken as the daily mean air temperature), R_n is net radiation flux (MJ m^{-2} d^{-1}), G is sensible heat flux into the soil (MJ m^{-2} d^{-1}), γ is the psychrometric constant (kPa $°C^{-1}$), and E_a is the vapor transport of flux (mm d^{-1}, where 1.0 mm d^{-1} = 0.039 in. d^{-1} = 1.0 kg m^{-2} d^{-1}). Penman (1948) defined E as "open water" evaporation.

Various derivations of the Penman equation included a bulk surface resistance term (Monteith, 1965), and the resulting equation is now called the Penman-Monteith equation, which may be expressed for daily values as:

$$\lambda \mathrm{ET}_o = \frac{[\Delta(R_n - G)] + [86{,}400\rho_a C_p(e_s^\circ - e_a)]/r_{av}}{\Delta + \gamma(1 + r_s/r_{av})} \qquad (3)$$

where ρ_a is air density (kg m^{-3}), C_p is the specific heat of dry air, e_s° is the mean saturated vapor pressure (kPa, computed as the mean e° at the daily minimum and maximum air temperature in °C), r_{av} is the bulk surface aerodynamic resistance for water vapor (s m^{-1}), e_a is the mean daily ambient vapor pressure (kPa), and r_s is the canopy surface resistance (s m^{-1}).

EMPIRICAL EVAPOTRANSPIRATION MODELS

The water consumption of plants is estimated as a fraction of reference ET (ET_o):

$$\mathrm{ET} = K_c \times \mathrm{ET}_o \qquad (4)$$

where K_c is the experimentally derived crop coefficient, and ET_o is reference ET. Reference surfaces can vary from a short grass to alfalfa (Allen et al., 1998). Prior to the availability of weather data, pan evaporation was used in an alternative form of this equation in which K_c was replaced with K_p and ET_o was replaced with E_{pan}, where K_p is a pan coefficient and E_{pan} is evaporation from some type of evaporation pan (Allen et al., 1998). The accuracy of ET_c estimation with a reference surface depends on the reference chosen and the method used to evaluate reference ET (Rana and Katerji, 2000).

ET_{REF} REFERENCE CROP DETERMINATION

An updated equation, the FAO-56 Penman-Monteith equation, was recommended by Allen et al. (1998). Allen et al. (1998) simplified equation 2 by using some assumed constant parameters for a clipped grass reference crop that is 0.1 m tall. For this new reference ET equation, the assumed definition of the reference crop was "a hypothetical reference crop with an assumed crop height of 0.1 m, a fixed surface resistance of 70 s m^{-1}, and an albedo value of 0.23" (Smith et al., 1992). The new equation is:

$$\mathrm{ET}_o = \frac{[0.408\Delta(R_n - G)] + \left[\gamma \frac{900}{(T+273)} U_2(e_s^\circ - e_a)\right]}{\Delta + \gamma(1 + 0.34U_2)} \qquad (5)$$

where ET_o is the reference ET rate (mm d^{-1}), T is the mean air temperature (°C), and U_2 is the wind speed at 2.0 m above the ground (m s^{-1}; RH or dew point and air temperature are assumed to be measured at 2.0 m above the ground level or converted to that height to ensure the integrity of the computations). Equation 4 can be applied using hourly data if the constant value of 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}.

In 1999, the ASCE Environmental and Water Resources Institute (EWRI) was asked by the Irrigation Association to propose a standardized equation for estimating the parameters to gain consistency and wider acceptance of ET models (Howell and Evett, 2006). The principal outcome was that two equations, one for a short crop such as clipped grass (ET_{os}) and another for a tall crop such as alfalfa (ET_{rs}), were developed for daily (24 h) and hourly time periods. The ASCE-EWRI standardized reference ET equation (Allen et al., 2005a), based on the FAO-56 Penman-Monteith equation (eq. 4) for a hypothetical crop, is given as:

$$\mathrm{ET}_{\mathrm{ref}} = \frac{[0.408\Delta(R_n - G)] + \left[\gamma \frac{C_n}{(T+273)} U_2(e_s^\circ - e_a)\right]}{\Delta + \gamma(1 + C_d U_2)} \qquad (6)$$

where $\mathrm{ET}_{\mathrm{ref}}$ is the standardized reference ET for a short reference crop (grass, ET_{os}) or a tall reference crop (alfalfa, ET_{rs}) in units of mm d^{-1} for a daily time step or mm h^{-1} for an hourly time step, C_n is the numerator constant for the reference crop type and time step, and C_d is the denominator constant for the reference crop type and time step (see table 1 for values of C_n and C_d).

TURF EVAPOTRANSPIRATION

The water requirements of most turfgrasses have been established by scientific studies (Beard and Green, 1994). Water use by turfgrasses is the total amount of water required for growth and transpiration of the plant plus the amount of water lost from the soil surface (Huang, 2006; Augustin, 2000). The amount of water lost through transpiration is a function of the rate of plant growth and several environmental factors, including 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. Transpiration losses may be as high as 10.2 mm of water per day in desert climates during summer months; in humid climates, the daily losses may be only 5.1 mm of water under similar temperature conditions (Duble, 2014). In table 2, the most commonly used cool-

Table 1. Values for C_n and C_d in equation 5 (after Allen et al., 2005a).

Calculation	Short Reference Crop (ET_{os})		Tall Reference Crop (ET_{rs})		Units for	Units for
Time Step	C_n	C_d	C_n	C_d	ET_{os} and ET_{rs}	R_n and G
Daily	900	0.34	1600	0.38	mm d^{-1}	MJ m^{-2} d^{-1}
Hourly, daytime	37	0.24	66	0.25	mm h^{-1}	MJ m^{-2} h^{-1}
Hourly, nighttime	37	0.96	66	1.7	mm h^{-1}	MJ m^{-2} h^{-1}

Table 2. ET rates of warm-season and cool-season turfgrass species commonly used in North America (after Beard and Kim, 1989).

Relative Ranking	ET_c Rate (mm d^{-1})	Cool-Season Turfgrasses	Warm-Season Turfgrasses
Very low	<6	-	Buffalograss
Low	6 to 7	-	Bermudagrass hybrids, Blue grama, Bermudagrass, Centipedegrass, Zoysiagrass
Medium	7 to 8.5	Hard fescue, Chewings fescue, Red fescue	Bahiagrass, Seashore paspalum, St. Augustinegrass, Zoysiagrass
High	8.5 to 10	Perennial ryegrass	-
Very high	>10	Tall fescue, Creeping bentgrass, Annual bluegrass, Kentucky bluegrass, Italian ryegrass	-

season and warm-season turfgrass species are categorized according to their ET_c rates (Beard and Kim, 1989).

Many studies have shown how turfgrass water use varies by species, genotype, climatic conditions, plant density, water table depth, water availability, plant morphological characteristics, etc. (Ekern, 1966; Stewart and Mills, 1967; Stewart et al., 1969; Tovey et al., 1969; Kneebone and Pepper, 1984; Aronson et al., 1987a; Meyer and Gibeault, 1987; Kim and Beard, 1988; Green et al., 1990a, 1990b; Atkins et al., 1991; Bowman and Macaulay, 1991; Green et al., 1991; Brown, 2003). Table A1 in the Appendix presents a summary of published results based on direct measurement of ET, specifically using different types of lysimeters under different conditions. Table 3 lists the main methodologies used for ET_c determination.

Kim and Beard (1988) measured ET rates using 12 turfgrass species, including warm-season and cool-season grasses, growing in black plastic mini-lysimeters located in 1.5 m × 1.5 m turf plots that were constructed to ensure a natural environment surrounded each lysimeter under well-watered conditions. ET_c rates were determined by the water balance method in August 1982, May 1984, and September 1984. Significant differences were observed among different genera and within the same genus, such as *Zoysia*. St. Augustinegrass exhibited an ET_c rate of 5.84 mm d^{-1} due to a very low shoot density. The ET_c rate for bahiagrass was 6.35 mm d^{-1} when grown under non-limiting soil moisture due to its high leaf area. In contrast, 'Adelayd' seashore paspalum had an ET_c rate of 5.33 mm d^{-1} associated with a very rapid vertical leaf extension rate. Zoysiagrasses exhibited significant differences in ET_c rates due to the vertical leaf orientation. The three bermudagrasses ('Arizona common,' 'Tifgreen,' and 'Tifway') were in the low range due to low leaf areas. Low centipedegrass ET_c rates were related to a very slow vertical leaf extension rate.

Table 3. Most common methodologies used to determine ET_c, including turfgrass type and maximum and minimum ET_c values.

Methodology and Reference	Turfgrass Type	ET_c (mm d^{-1}) Min.	Max.
Mini-lysimeters / water balance			
Aronson et al., 1987a	Cool-season	2.29	4.06
Kim and Beard, 1988	Cool-season	5.08	7.11
Green et al., 1990a	Cool-season	7.37	12.45
Bowman and Macaulay, 1991	Cool-season	4.57	12.95
Green et al., 1990b	Warm-season	2.29	11.68
Atkins et al., 1991	Warm-season	3.81	5.84
Green et al., 1991	Warm-season	2.29	10.41
Large lysimeters / water balance			
Stewart and Mills, 1967	Warm-season	1.78	5.08
Stewart et al., 1969	Warm-season	2.29	2.79
Kneebone and Pepper, 1982	Warm-season	6.35	8.89
Kneebone and Pepper, 1984	Warm-season	3.81	8.89
Devitt et al., 1992	Warm-season	2.54	4.57
Eddy correlation			
Jia et al., 2008	Warm-season	0.51	5.08

Atkins et al. (1991) reported variations in ET_c rates among ten well-watered St. Augustinegrass genotypes in the field and in a controlled-environment chamber in Texas. The experiment was carried out using black plastic mini-lysimeter pots. ET_c rate estimations using a water-balance method were determined in September 1985, July and August 1986, and September 1987 for the field experiment. Averaged ET_c rates were lower in September 1985 (5.33 mm d^{-1}) than in August 1986 and September 1987 (12.95 and 14.22 mm d^{-1}, respectively). Overall, ET_c rate variation among these ten well-watered genotypes was not significant under field conditions. Genotypes 'TXSA 8202,' 'PI 410356,' and 'Texas common' showed an average ET_c rate of 4.5 mm d^{-1}, whereas 'Raleigh' showed the highest ET rate of 5.1 mm d^{-1}. However, the genotype effect was significant for ET_c rates due to the higher evaporative potential of the controlled-environment chamber. In this experiment, 'Texas common' and 'PI 410356' ranked lowest for ET_c at 6.7 and 7.3 mm d^{-1}, respectively, while 'TX 106' and 'TXSA 8218' ranked highest, both at 8.1 mm d^{-1}. St. Augustinegrass species had no significant intraspecies ET_c variation under well-watered field conditions. Another study using mini-lysimeters under both field and controlled-environment conditions was carried out for eleven zoysia genotypes under well-watered conditions (Green et al., 1991). Under field conditions, ET_c was evaluated in 1985, 1986, and 1987, and the results showed genotype 'KLS-11' ranking highest for ET_c with 4.7 mm d^{-1}, while genotype 'Belair' had the lowest ET_c with 3.8 mm d^{-1} (average of three years). The effect of genotype was not significant (table A1). ET_c rates were higher under controlled conditions, with genotype 'KLS-11' showing the lowest rate (8.4 mm d^{-1}) and genotype 'Emerald' showing the highest rate (10.3 mm d^{-1}). In this case, ET rate variation among genotypes was significant under the higher evaporative potential of the environmental chamber.

Feldhake et al. (1983) used weighable bucket lysimeters to measure ET_c rates of different cool-season and warm-season turfgrasses under the effects of mowing height and N fertilization under well-watered conditions. ET_c rates were 5.59 mm d^{-1} for 'Merion' Kentucky bluegrass, 5.84 mm d^{-1} for tall fescue, and 4.57 mm d^{-1} for both 'Tifway' and 'Common' bermudagrass. 'Merion' Kentucky bluegrass ET rates varied according to the mowing height from 4.83 mm d^{-1} (2.0 cm mowing height + N) to 5.33 mm d^{-1} (5.0 cm mowing height + N). When Kentucky bluegrass was deficient in N, the ET rate increased to 5.33 mm d^{-1}. In this case, ET was influenced by the type of grass, mowing height, and fertility. Aronson et al. (1987a) compared ET_c

for four cool-season turfgrasses under well-watered conditions: Kentucky bluegrass, perennial ryegrass, chewing red fescue, and hard fescue. ET_c was measured using weighing lysimeters. The average ET_c for all turfgrasses in the two-year study (July through September) was 3.81 mm d^{-1} for Kentucky bluegrass, 3.56 mm d^{-1} for red fescue, 3.81 mm d^{-1} for perennial ryegrass, and 3.05 mm d^{-1} for hard fescue. The same turfgrass species were tested under controlled conditions for their responses to drought stress (Aronson et al., 1987b) using small (25.4 cm dia.) lysimeters in a greenhouse with well-watered conditions for 80 days before drought tests began. The grasses were exposed to two consecutive drought stress periods. The first drought period was continued until visible signs of stress were observed, and the grasses were allowed to recuperate under well-watered conditions for three weeks until they recovered their initial turf quality scores. The second drought period was continued until plant death. Although no numerical results were published for water consumption, the most drought tolerant of the four grasses studied were the fescues. The perennial ryegrass and Kentucky bluegrass were the least drought tolerant and sustained substantial injury when the soil water potential declined to less than -125 kPa. According to these results, the range from -50 to -80 kPa may represent a threshold level of drought stress for cool-season grasses growing in this area, since characteristics such as ET, quality score, leaf growth rate, and leaf water potential showed marked changes under those soil water potentials. Tall fescue can develop a deeper, more extensive root system that is better able to extract deep soil moisture for continued transpiration, compared to Kentucky bluegrass (Ervin and Koski, 1998).

Another study using mini-lysimeters under controlled-environment conditions was carried out at College Station, Texas, for 12 cool-season turfgrasses: hard fescue, creeping bentgrass, sheep fescue, chewing fescue, creeping annual bluegrass, Kentucky bluegrass (cultivars 'Bensun,' 'Majestic,' and 'Merion'), perennial ryegrass, tall fescue (cultivars 'Rebel' and 'K-31'), and rough bluegrass (Green et al., 1990a). ET_c rates were based on three sequential measurements from each mini-lysimeter during 24 h under non-limiting soil moisture conditions. The highest ET_c was exhibited by Kentucky bluegrasses (12.19 mm d^{-1}) and the lowest by the fine-leafed fescues (7.62 mm d^{-1}); these results that agreed with those of Aronson et al. (1987b). Also testing cool-season turfgrasses, Salaiz et al. (1991) tested ten varieties of creeping bentgrass growing in mini-lysimeters installed in the field. ET rates in 1987 ranged from 3.2 mm d^{-1} for 'Pennlinks' on 22 May to a high of 10.7 mm d^{-1} for 'Seaside' on 25 June. During 1988, ET rates ranged from a low of 3.3 mm d^{-1} for 'National' on 3 October to a high of 9.9 mm d^{-1} for 'Seaside' on 10 June (table A1). The highest ET weekly values were measured in June and the lowest were measured in October in September for both years. In 1987, ET differed among cultivars by as much as 84% on 22 May, while in 1988 the greatest difference observed was 39% on 10 August.

Numerous studies have measured bermudagrass ET_c due to the prevalence of this grass on golf courses. Devitt et al. (1992) determined ET_c from lysimeters located on a park and on two golf course sites. The two-year (1988-1989) average ET rate at the golf course sites, one of them irrigated according to local management (control) and the other irrigated by input from an ET_c feedback system, was 1.50 m $year^{-1}$ (4.06 mm d^{-1}). In contrast, the park site had a two-year average ET_c of 1.07 m $year^{-1}$ (2.79 mm d^{-1}), which was 29% lower than the golf course sites. Differences were attributed to cultural management. In Tucson, Arizona, a study carried out using percolating lysimeters and testing high and low management treatments simulating (1) highly fertilized golf course fairways and commercial lawns and (2) minimal home lawn management showed no significant differences among three bermudagrasses (Kneebone and Pepper, 1982). 'Tifgreen,' 'Santa Ana,' and 'Seeded' bermudagrasses showed an average ET_c rate of 4.57 mm d^{-1} (1.65 m $year^{-1}$) under the high management treatment. Under the low management treatment, the average ET rate was 3.56 mm d^{-1} (1.30 m $year^{-1}$). Another study (Kneebone and Pepper, 1984) evaluated what maximum ET_c might be when excessive water was available to bermudagrass. This trial used percolating lysimeters and three different sand-soil mixes (19:1, 18:2, and 16:4), all of them providing good infiltration and drainage. Three irrigation levels (114.3, 243.8, and 363.2 mm $week^{-1}$) applied in increments of 58.4, 121.9, and 182.9 mm twice each week were used with each sand-soil mix. The results showed that increasing the availability of water, whether by irrigation level or by the water holding capacity of the sand-soil mix, in most cases increased ET for bermudagrass. Average ET_c rates were 4.32, 7.11, and 7.62 mm d^{-1} (30.99, 48.77, and 53.09 mm $week^{-1}$) for 114, 254, and 364 mm $week^{-1}$ application rates, respectively. Average ET rates were 5.08, 6.35, and 7.62 mm d^{-1} (35.81, 43.94, and 53.09 mm $week^{-1}$) for 19:1, 18:2, and 16:4 sand-soil mixes, respectively. The data showed that ET rates for bermudagrass turf can exceed pan evaporation by a considerable amount. Fu et al. (2004) determined actual ET rates (ET_a) for 'Meyer' zoysiagrass, 'Midlawn' bermudagrass, 'Falcon II' tall fescue, and 'Brilliant' Kentucky bluegrass twice weekly by measuring the mass change of lysimeters (10.1 cm in dia. × 25 cm depth PVC pots) using the water balance method. The lysimeters were under well-watered conditions and nitrogen fertilization. Experiments were carried out in 2001 and 2002. Bluegrass and tall fescue had similar ET_a rates in 2001 (5.6 and 5.7 mm d^{-1}, respectively), higher than both bermudagrass and zoysiagrass (4.1 and 3.9, mm d^{-1}, respectively). In 2002, tall fescue had the highest ET_a rate (5.9 mm d^{-1}) compared to bermudagrass (4.0 mm d^{-1}) and zoysiagrass (4.4 mm d^{-1}). Zoysiagrass showed higher ET_a values than bermudagrass (table A1).

Stewart et al. (1969) studied ET_c rate as a function of plant density and water table depth in south Florida using 'Tifway' bermudagrass growing in non-weighing evapotranspirometers. Depth to the water table was 0.6 m in the first year, 0.9 m in the second year, and 0.3 m in the third year of the three-year study. Water replacement ranged from well-watered conditions at a 0.3 m water table depth to partial stress at a 0.9 m depth. The plant cover treatments were established by killing part of the sod to give the preselected 0, 1/3, 2/3, and full sod cover treatments. An annual water balance showed a linear decrease between degree of plant cover and annual ET rate. ET rates increased with sod cover at the 0.6 m water table depth [from 0.41 m year^{-1} (1.02 mm d^{-1}) for no sod to 1.1 m year^{-1} (2.79 mm d^{-1}) for full sod] and at the 0.91 m water table depth [from 0.48 m year^{-1} (1.27 mm d^{-1})] for no sod to 0.89 m year^{-1} (2.29 mm d^{-1}) for full sod]. ET$_c$ rates decreased with sod cover for the 0.31 m water table depth [from 1.17 m year^{-1} (3.30 mm d^{-1}) for no sod to 1.07 m year^{-1} (2.79 mm d^{-1}) for full sod]. Evaporation from bare soil [1.17 m year^{-1} (3.30 mm d^{-1})] with a 1.22 m water table was about 11% greater than from full sod cover [1.07 m year^{-1} (2.79 mm d^{-1})] in 1967. The ground surface of this treatment was continuously moist, indicating that the capillary fringe reached the soil surface. Similar results were reported by Stewart and Mills (1967).

Similar results to those found at the park site by Devitt et al. (1992) were observed for both ‘Common’ and ‘Tifway’ bermudagrass in Georgia (Carrow, 1995) under field conditions. Irrigation was applied at 56% plant-available soil water depletion. The average ET$_c$ rate was 3.05 mm d^{-1} (1.12 m year^{-1}). Compared to other studies, the ET$_c$ rates were lower. Reasons could be that all the data reported by others were obtained in arid or semi-arid climates with lower humidity using non-limited soil moisture conditions compared to the humid Georgia conditions. Under arid conditions and turfgrass stress, water consumption by bermudagrasses was much lower than previously reported (Garrot and Mancino, 1994). This previous study, carried out in Arizona, showed that bermudagrasses varieties ‘Texturf-10,’ ‘Tifgreen,’ and ‘Midiron’ had mean ET rates of 2.54, 2.29, and 2.29 mm d^{-1} (0.91, 0.86, and 0.84 m year^{-1}), respectively, with infrequent irrigation under fairway conditions. The ET$_c$ rate was derived from gravimetric samples, and irrigation was applied only when the turf showed symptoms of wilt. The conclusions showed that bermudagrass growing in an arid environment, such as Arizona, can be maintained under fairway conditions with 0.84 to 0.91 m of water annually.

Under low home lawn management in Arizona, and using 1.0 m^2 lysimeter boxes, tall fescue and St. Augustinegrass used significantly more water than bermudagrass and zoysiagrass (1.8, 1.7, and 1.3 m year^{-1}), respectively (Kneebone and Pepper, 1982). Bermudagrass and zoysiagrass were dormant during the winter and spring, while tall fescue was still growing. St. Augustinegrass does not become dormant as quickly as bermudagrass and zoysiagrass during the winter. The low management resulted in a relatively low-quality turf, but the quality improved under high management. The data indicated that normal water use in Tucson might range from 1.3 to 1.7 m year^{-1} depending on management.

Crop ET rates were estimated for bahiagrass using the eddy correlation method (Jia et al., 2009) in central Florida, from July 2003 through December 2006, under well-watered conditions. This method overcomes the need to determine each component in the water balance, i.e., irrigation (I), drainage (D), and change in water storage (ΔS), by using the energy balance approach (Tanner and Greene, 1989). The results of this study showed that the highest average monthly ET rate (4.32 mm d^{-1}) occurred in May. The lowest average monthly ET rate (0.76 mm d^{-1}) occurred in January. Another study showed that bahiagrass used 11% more water than St. Augustinegrass under well-watered conditions (Dukes et al., 2008; Zazueta et al., 2000). However, water use rates for both grasses were similar when water was scarce (Dukes et al., 2008). Under water-stressed conditions, St. Augustinegrass may be stressed beyond the point of recovery, while bahiagrass may recover when water becomes available (Zazueta et al., 2000).

TURF CROP COEFFICIENT (K_c)

Allen et al. (1998) defined the crop coefficient (K_c) as the ratio of ET$_c$/ET$_o$. Their values for K_c represent ET under growing conditions with a high level of management and with little or no water stress or other ET-reducing stresses and thus represent what are referred to as potential levels for crop ET (Allen et al., 2005b). Once such coefficients have been generated, only estimates of ET$_o$ are required to estimate actual ET$_c$ needed for scheduling irrigation for a similar climate (Devitt and Morris, 2008). The availability of different equations to estimate ET$_o$ would provide more possibilities to estimate different K_c values, which is one reason the ASCE-EWRI standardized reference ET methodology was developed (Allen et al., 2005a). They stated the uncertainty in K_c-based ET predictions due to uncertainty in the quality and representativeness of weather data for ET$_o$ estimates. K_c can vary substantially over short 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 reduces monthly precision, and turfgrass may be under-irrigated during stressful summer months. Factors influencing crop coefficients for turfgrasses are seasonal canopy characteristics, rate of growth, soil moisture, and cultural management (e.g., cultivar, fertilization, irrigation, mowing, and fungicide application; Gibeault et al., 1989; Carrow, 1995). The U.S. Environmental Protection Agency (EPA), through its sponsored partnership program WaterSense, supported the need of using technologies with crop coefficients programmed into weather-based irrigation controllers for efficient irrigation. However, in many cases, controllers have been said to have “generous” default crop coefficients, leading to over-irrigation (EPA, 2007).

In the following paragraphs, several studies on crop coefficient determination for cool-season and warm-season turfgrasses under well-watered conditions are presented and discussed. K_c values determined under stress conditions are also reported, but these may be site-specific values and cannot be transferable to other locations. Table A2 in the Appendix presents a summary of the crop coefficient values from these studies.

A study in the southeastern U.S. (central Florida) developed crop coefficients for four warm-season turfgrass species (‘Tifway’ bermudagrass, ‘Empire’ zoysiagrass, ‘Floratam’ St. Augustinegrass, and ‘Argentine’ bahiagrass) during a three-year period (2008-2010) (Wherley et al., 2015). The authors showed actual ET (ET$_a$) was measured monthly from mini-lysimeters under well-watered conditions, while ET_o was calculated from the ASCE-EWRI standardized method using on-site weather station data. Crop coefficients were derived by dividing ET_a/ET_o during 30 measurement periods. For 17 of the 20 measurement periods, K_c did not differ significantly among the four species. Results showed that K_c ranges varied from 0.33 to 0.90 for bermudagrass, from 0.47 to 0.92 for bahiagrass, from 0.45 to 0.80 for St. Augustinegrass, and from 0.38 to 0.98 for zoysiagrass, and the minimum K_c was always found in December while the maximum K_c occurred in July. Overall average seasonal K_c values for bahiagrass, bermudagrass, and zoysiagrass were similar in 2008 (0.67, 0.66, and 0.68, respectively), and all were higher than St. Augustine (0.54). In the second and third years, bahiagrass had noticeably higher K_c values than the other three species (0.7 versus 0.53, 0.58, and 0.59 for bermudagrass, St. Augustinegrass, and zoysiagrass, respectively). In Texas, mean K_c values for St Augustinegrass growing in lysimeters (2.43 m long × 1.02 m wide × 0.68 m deep) were lower than those observed in central Florida (Pannkuk et al., 2010). The Texas study lasted from 2007 to 2008, and evaluations were done in early, middle, and late seasons (table A2) at two locations (San Antonio and College Station). K_c was calculated as the ratio of actual ET to reference ET (the modified Penman-Monteith equation). At San Antonio, the K_c values were 0.45, 0.52, and 0.62 for the early, middle, and late seasons, respectively, and the differences were non-significant. At College Station, the K_c values were 0.51, 0.27, and 0.24, respectively, and the differences were also non-significant.

A study using 'Flugge' bahiagrass was reported by Jia et al. (2009). Daily K_c values were determined for July 2003 through December 2006 in central Florida. The eddy correlation method was used to estimate crop ET rates under well-watered conditions. ET_o was calculated using the standardized reference ET equation (Allen et al., 2005a). Monthly K_c values were low in the winter because of the dormant grass status and high in the summer, although K_c values also decreased in summer from the peak values in May due to cloud-free conditions and the highest incoming solar radiation compared to the rest of the year. The multi-annual average K_c value was minimum in January (0.35) and maximum in May (0.90).

Jia et al. (2009), in addition to their K_c study under well-watered conditions, also calculated turfgrass K_c for southern Florida's warm-season turfgrasses with water use data from Stewart and Mills (1967) for well-watered conditions with the exception of a few time periods in the study. Reference ET values were calculated using climate data for Miami, Florida (NCDC, 2007), where the daily average solar radiation values were estimated using Hargreaves' equation (Allen et al., 1998). Calculated K_c values for southern Florida were higher than those in central Florida, especially in winter months. Annual K_c was 0.63 in central Florida and 0.76 in south Florida. This was likely due to growing conditions persisting all year in the southern part of the state, with higher temperatures compared to north Florida. The K_c value was maximum in May (0.99) and minimum in December (0.70).

Monthly crop coefficients for bermudagrass overseeded with perennial ryegrass were presented by Devitt et al. (1992). Two vacuum-drained lysimeters were installed at two golf courses and at a park in Las Vegas, Nevada. Each site was equipped with an automated weather station. One lysimeter was irrigated according to local management, and the other was irrigated by input from an ET feedback system. Crop coefficients were calculated by dividing monthly ET_a by Penman-calculated ET_o values. ET_c was much lower at the park site than at the golf course sites. The greatest variability in K_c (for all sites) occurred during the winter months (December to February), and the high-management turf (golf courses) and the low-management turf (park) had similar K_c values only during this period. Differences were observed for the rest of the year, as the K_c values for the golf course sites were fit to a bell-shaped curve while the park site had a somewhat flat K_c response. Because the soil conditions were similar at the sites, as well as the mixed grasses, the differences were attributed to cultural management. The park turf was stressed due to different nitrogen levels compared to the golf course sites.

Brown et al. (2001) developed Penman-Monteith crop coefficients for warm-season 'Tifway' bermudagrass in summer and overseeded 'Froghair' intermediate ryegrass in winter under golf course fairway conditions in Arizona. Intermediates are genetic crosses using annual ryegrasses and perennial ryegrasses in the parentage. The researchers related daily measurements of ET_c obtained from weighing lysimeters to reference ET (ET_o) computed by means of the simplified form of the FAO Penman-Monteith equation (Allen et al., 1994, 1998; eq. 6). Adequate fertilization and irrigation were considered. For warm-season overseeded bermudagrass, the minimum K_c occurred in June (0.78) and the maximum occurred in September (0.83). A constant K_c of 0.8 would be effective for estimating ET_c during the summer months but not for non-overseeded bermudagrass, which has extended periods of slow growth and lower ET_c during the spring and fall. Monthly K_c values for cool-season overseeded 'Froghair' intermediate ryegrass varied from 0.78 (January) to 0.90 (April), which showed that winter K_c values were dependent on temperature.

A study carried out in the humid northeast (Rhode Island) using Kentucky bluegrass ('Baron' and 'Edmundi' varieties), red fescue, perennial ryegrass, and hard fescue under well-watered conditions showed that the mean crop coefficients ranged from 0.97 for hard fescue to 1.05 for 'Baron' Kentucky bluegrass (Aronson et al., 1987a). An average K_c value of 1.0 was considered appropriate for irrigation scheduling for all the grasses studied. K_c values were obtained by dividing ET_c data from weighing lysimeters and ET_o computed from two predictive methods, the modified Penman equation (Burman et al., 1980), and pan evaporation. Salaiz et al. (1991) tested ten varieties of creeping bentgrass to determine how K_c varied weekly in a two-year study using mini-lysimeters (203 mm dia. × 203 mm depth) installed in a Nebraska field. Crop coefficients for 'Seaside' were >1 on all dates in 1987 and on 12 of the 14 dates in 1988 (table A2). Six cultivars in 1987 and four cultivars in 1988 had an average K_c value of >1.

The following studies were done under stress conditions.

Penman K_c values for various grasses grown in the southeastern U.S. were estimated by Carrow (1995), including 'Tifway' bermudagrass, common bermudagrass, 'Meyer' zoysiagrass, common centipedegrass, 'Raleigh' St. Augustinegrass, and 'Rebel II' and 'Kentucky-31' tall fescue. The study was conducted at plot level in Georgia; these seven turfgrasses grow widely in the middle to upper southeast region. Reference ET was determined by the FAO modified Penman equation (Doorenbos and Pruitt, 1984) for 18 measurement periods in 1989 and 1990. Crop ET (ET_c) was derived from daily soil water extraction data from TDR probes obtained during dry-down periods following irrigation or rainfall events when no drainage occurred. Moderate to moderately severe water stress was imposed on the turfgrass to represent most home lawn irrigation regimes, although this approach violated the "well-watered" conditions required for crop coefficient development (Allen et al., 1998). ET_c was determined by the soil-water balance method, and K_c was calculated dividing ET_c by ET_o (FAO modified Penman; Allen et al., 1998). For all grasses, coefficients varied substantially over short time periods. 'Tifway' bermudagrass exhibited the least variation (0.53 to 0.97 for K_c), and 'Meyer' zoysiagrass exhibited the most (0.51 to 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.

Another study comparing cool-season and warm-season turfgrasses was performed by Smeal et al. (2001) in New Mexico to formulate turfgrass crop coefficients. Smeal et al. (2001) determined K_c values for warm-season (bermudagrass, buffalograss, and blue grama) and cool-season (bluegrass, perennial ryegrass, and tall fescue) grasses seeded on individual plots. Sprinkler irrigation was applied and measured using catch-cans after each irrigation. Soil moisture measurements were taken every ten days during the active growing season, and grass was mowed weekly to a uniform height of 6.4 to 7.6 cm (8.9 to 10.2 cm for blue grama and grama/buffalograss mix). ET_c was calculated using a soil water balance equation, and ET_o was calculated by using the Samani and Pessarakly (1986) equation:

$$\mathrm{ET}_o = 0.0135(KT)(Ra)(TD)^{1/2}(TC + 17.8) \quad (7)$$

where $TD = T_{\max} - T_{\min}$ (°C), TC is average daily temperature (°C), and Ra is extraterrestrial radiation (mm d^{-1}). K_c was calculated as the ratio of actual ET to ET_o. Instead of monthly K_c values, Smeal et al. (2001) presented K_c values as a function of cumulative heat units or growing degree-days (GDD) to compensate for the effects of temperature on the initiation and duration of the active growing (green) period and on plant growth and development during the season. Two equations for K_c calculation based on GDD were presented:

For cool-season turfgrasses:

$$\begin{aligned} K_c = {} & (5.75 \times 10^{-4}\,\mathrm{GDD}) - (1.425 \times 10^{-7}\,\mathrm{GDD}^2) \\ & + (1.04 \times 10^{-11}\,\mathrm{GDD}^3) \end{aligned} \quad (8)$$

For warm-season turfgrasses:

$$\begin{aligned} K_c = {} & (0.00127 \times \mathrm{GDD}) - (8.399 \times 10^{-7}\,\mathrm{GDD}^2) \\ & + (1.614 \times 10^{-10}\,\mathrm{GDD}^3) \end{aligned} \quad (9)$$

Monthly K_c values were estimated using average monthly temperature from the area, considering base temperatures of 4°C and 16°C for cool-season and warm-season grasses, respectively. For cool-season turfgrasses, March had the lowest K_c value (0.05), and July had the highest value (0.72). Dormant conditions occurred from October to February. For warm-season turfgrasses, April had the lowest K_c value (0.28), and August had the highest (0.60). It seems that dormancy occurred from October to April.

A study carried out in California that compared cool-season and warm-season grasses under warm conditions (Meyer and Gibeault, 1987) showed set of crop coefficients for Kentucky bluegrass, perennial ryegrass, tall fescue (cool-season grasses) and for hybrid bermudagrass, zoysiagrass, and 'Seashore' paspalum (warm-season grasses) that could be used in California. Monthly crop coefficient data were developed to evaluate the responses of these species to 60% and 80% of replacement ET for water conservation. The K_c values ranged from 0.60 to 1.04 for cool-season grasses and from 0.54 to 0.79 for warm-season grasses. ET_c was calculated by multiplying pan evaporation (E_{pan}) by annual crop coefficients (K_p) that were determined from a previous study using applied water and evaporation pan data. ET_o was calculated using the modified Penman equation (Doorenbos and Pruitt, 1977).

A study reporting K_c values for 'Tifgreen' and 'Midiron' hybrid bermudagrasses and 'Texturf-10' common bermudagrass growing at plot level from sod in 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 supplied only when the turf showed symptoms of wilt. Time periods between irrigation events were referred to as soil dry-down cycles (DDC). The ET rate was determined using gravimetric soil moisture from soil cores (0 to 0.9 m depth, using 0.3 m intervals) taken at the beginning (48 h after irrigation) and at the end of each DCC. The K_c values were calculated by dividing the actual consumptive use (derived from the gravimetric samples) by the cumulative ET_o (modified Penman equation; Doorenbos and Pruitt, 1977). However, daily K_c values varied from as high as 1.50 to as low as 0.10, but average K_c values ranged from 0.57 to 0.64. 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. Another study applying deficit irrigation to cool-season turfgrasses in Colorado (Ervin and Koski, 1998) subjected Kentucky bluegrass and tall fescue to increasing levels of drought to develop water-conserving crop coefficients (K_c) for use with Penman equation estimates for alfalfa (*Medicago sativa* L.). The research indicated that water conservation can be encouraged while maintaining acceptable turfgrass quality by irrigating every three days, with K_c values in the range of 0.60 to 0.80 for Kentucky bluegrass and 0.50 to 0.80 for tall fescue.

WATER USE AS AFFECTED BY TURFGRASS CHARACTERISTICS AND CULTURAL FACTORS

Turfgrass ET_c rates vary among species and among cultivars within species depending on plant characteristics. Interspecies and intraspecies variations in ET_c rates can be explained by differences in stomatal characteristics, canopy configuration, growth rate, and characteristics of the roots. Turfgrass breeding during the last 25 years has increased emphasis on developing new varieties that require less water, are more tolerant of heat, cold, or salinity stresses, and have improved resistance to pests and disease (Kenna, 2008). Root characteristics associated with drought resistance include enhanced water uptake from deeper in the soil profile, root proliferation into deeper soil layers, and persistent root growth in the drying surface soil (Huang et al., 1997). Excessive irrigation, which keeps the root system saturated with water, can be harmful to the lawn (Trenholm et al., 2001).

Cultural factors and cultural practices also affect turfgrass water use. Increased mowing height and increased top growth can increase ET by increasing the roughness of the plant canopy surface, increasing the capacity for absorbing advective heat, and increasing root growth, which results in a greater soil water source to exploit (Kneebone et al., 1992). Any cultural practice that increases leaf surface area, internode length, and leaf extension (e.g., nitrogen fertilization) is expected to increase water use. Increasing the nitrogen application rate also increases ET (Feldhake et al., 1983). Soil compaction may affect ET_c more than the N source or N rate because it may not allow the root system to function adequately due to poor soil aeration, platy massive soil structure, and low infiltration, which results in reduced soil water holding capacity (Huang, 2006).

CONCLUSIONS

High variability in ET has been observed in both warm-season and cool-season turfgrasses, with cool-season turfgrasses having the potential to use more water than warm-season turfgrasses. However, it is difficult to establish minimum and maximum ET rates for a specific species because study results are highly variable due to climatic conditions, turfgrass species and variety, mowing height, and fertilization. K_c values also showed high variability between and within turfgrass species. In general, all turfgrasses had substantial changes in crop coefficient values over the period when measurements were conducted. In addition, because green up and dormancy vary between regions, K_c values may not be directly transferable unless adjusted. Crop coefficients should be developed under well-watered conditions, as the definition demands. Some reported K_c values were measured under stress conditions and are still called crop coefficients; however, these are specific values for specific conditions. Adding to the difficulty in transferring crop coefficient values across studies is the fact that multiple reference ET calculations have been used over time.

The standardization of an equation to estimate reference ET has been established by the ASCE Environmental and Water Resources Institute, and using this equation nationwide is desirable. The FAO and ASCE have identified disparities in potential ET computation procedures and have recommended using a standardized procedure; however, several forms of the Penman equation were often used to estimate reference ET. Many studies in this review also differed in their use of water consumption by turfgrasses. Some used actual ET or crop ET. Thus, this review offers an overview of turfgrass ET and crop coefficient studies; however, the reported ET rates and crop coefficients should be used with awareness of the local conditions under which these values were developed.

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APPENDIX

Table A1. Turfgrass species' mean daily ET rate (ET$_c$), methodology used to determine ET$_o$, water availability, and references.

Turfgrass Species	ET$_c$ Rate (mm d^{-1})	Study Period	Methodology and Water Availability	Reference and Location
Bahiagrass	Jan. (0.76) Feb. (0.76) Mar. (2.03) Apr. (3.56) May (4.32) June (3.30) July (3.05) Aug. (2.79) Sept. (2.29) Oct. (1.78) Nov. (1.52) Dec. (0.76)	July 2003 through December 2006.	Eddy correlation method; well-watered conditions.	Jia et al. (2009), central Florida
Kentucky bluegrass	5.6a/-	ET$_a$ values are averages of 27 dates from 4 June to 14 September 2001 and from 3 June to 3 September 2002.	ET$_a$ determined twice weekly by measuring changes in lysimeter mass using water balance method; well-watered conditions.	Fu et al. (2004), Rocky Ford, Kansas
Tall fescue	5.7a/5.9a			
Bermudagrass	4.1b/4.0b			
Zoysiagrass	3.9b/4.4b			
Bermudagrass overseeded with perennial ryegrass	3.81 to 4.57	Two-year study.	Lysimeter irrigated using ET feedback system; well-watered conditions.	Devitt et al. (1992), Nevada
	2.54 to 3.05		Lysimeter irrigated according to local management; well-watered conditions.	
Argentine bahiagrass	6.35f	Values are for: August 1982 / May 1984 / and September 1984. Letters indicate significant differences.	Water balance method (using black plastic mini-lysimeter inserted in open-end metal cylinders placed in the center of turfed plots; well-watered conditions.	Kim and Beard (1988), College Station, Texas
Texas common buffalograss	5.3a/4.6ab/4.4a			
Georgia centipedegrass	5.5abc/4.7ab/4.9bc			
Common bermudagrass:				
Arizona	5.8bcd/4.2a/4.9bc			
Tifgreen	5.4ab/4.6ab/5.2c			
Tifway	5.9de/4.1a/4.9bc			
Adalayd seashore paspalum	6.2ef/5.1b/4.7ab			
Meyer zoysiagrass	5.8cde/4.7ab/5.6d			
Emerald zoysiagrass	6.5f/4.9b/6.0e			
Texas common St. Augustinegrass	6.3f/4.8ab/5.6d			
Tall fescue	7.1g/5.1b/-			
Common blue grama	5.7bcd			
St. Augustinegrass (three-year avg.)		Individual measurements in the field in September 1985, July and August 1986, and September 1987 (values on the left) and in controlled-environment conditions in summer 1988 (values on the right).	Water balance method using black plastic mini-lysimeter pots; well-watered conditions.	Atkins et al. (1991), College Station, Texas
TXSA 8202	4.5/8.0			
PI 410356	4.5/7.3			
Texas common	4.5/6.7			
Floratam	4.6/8.0			
TX 106	4.7/8.1			
PI 410364	4.7/7.4			
TXSA 8262	4.9/7.9			
Floralawn	4.9/7.6			
TXSA 8218	4.9/8.1			
Raleigh	5.1/7.8			
ANOVA:				
Genotype (G)	NS/*			
Year (Y)	***/-			
G × Y	*/-			
Zoysia (three-year avg.)		Fall 1985, summer 1986, and summer 1987. Measurements in the field from May to October (values on the left). Measurements in glasshouse from November to April (values on the right). NS = genotype effect not significant	Water balance method using black plastic mini-lysimeters; well-watered conditions.	Green et al. (1991), College Station, Texas
Belair	3.8/8.9			
FC-13521	3.8/10.1			
Emerald	3.9/10.3			
El Toro	3.9/9.4			
KLS-05	4.0/8.7			
KLS-13	4.0/9.4			
Korean common	4.1/8.5			
PI 231146	4.2/9.5			
Meyer	4.4/9.9			
41-21-5	4.5/9.0			
KLS-11	4.7/8.4			
LSD$_{0.05}$	NS			

Table A1 (continued). Turfgrass species' mean daily ET rate (ET_c), methodology used to determine ET_c, water availability, and references.

Turfgrass Species	ET_c Rate (mm d^{-1})	Study Period	Methodology and Water Availability	Reference and Location
Creeping bentgrass	Min.-Max.	Measurements from May to October (1987 and 1988) on mini-lysimeters installed in the field.	ET_a (actual) determined using water balance method; well-watered conditions.	Salaiz et al. (1991), Mead, Nebraska
Seaside	4.0-10.7			
SR-1020	3.7-10.3			
Cobra	3.8-10.5			
Penncross	3.7-9.5			
Providence	3.6-9.3			
Penneagle	3.5-9.3			
Emerald	3.8-9.0			
Prominent	3.5-8.9			
National	3.3-8.8			
Pennlinks	3.3-8.5			
Kentucky bluegrass	3.56	July to September (1984 and 1985).	Water balance method using weighing mini-lysimeters.	Aronson et al. (1987a), Kingston, Rhode Island
Red fescue	3.56			
Perennial grass	3.81			
Hard fescue	3.05			
Cool-season perennial grasses:		ET rate measured every 24 h.	Water balance method using black plastic mini-lysimeters under controlled environment; well-watered conditions.	Green et al. (1990a), College Station, Texas
Hard fescue	7.37			
Creeping bentgrass	10.16			
Sheep fescue	9.40			
Chewing fescue	7.62			
Creeping annual bluegrass	9.91			
Kentucky bluegrass	12.45			
Perennial ryegrass	9.14			
Tall fescue	11.43			
Rough bluegrass	8.38			
Bermudagrass	6.35	26 November 1979 to 25 October 1980.	Water balance using 1 m^2 lysimeters; well-watered conditions.	Kneebone and Pepper (1984)
Cases under water-stressed conditions				
Bermudagrass	7.62	1977 to 1979.	Water balance using 1 m^2 lysimeters; well-watered and water-stressed.	Kneebone and Pepper (1982)
Zoysiagrass	7.11			
Merion Kentucky bluegrass		First experiment: 13 July to 4 October 1979.	Weighing lysimeter:	Feldhake et al. (1983), Ft. Collins, Colorado
	4.83		2 cm mowing height	
	5.33		5 cm mowing height	
Bermudagrass	3.56	Second experiment: 20 June to 28 August 1980.	Values are averages of two lysimeters.	
	4.83			
Merion Kentucky bluegrass	5.59	Third experiment: 8 June 1980 to 16 August 1981.	Well-watered conditions.	
Rebel tall fescue	5.84			
Tifway bermudagrass	4.57			
Common buffalograss	4.57			
Tifway bermudagrass	4.83/4.32	First season: 26 June to 10 October 1989 (values on the left). Second season: 4 May to 2 November 1990 (values on the right).	TDR_s; water-stressed conditions. K_c are annual values	Carrow (1995), Griffin, Georgia
Common bermudagrass	4.83/4.32			
Meyer zoysiagrass	4.57/4.32			
Common centipedegrass	4.32/4.06			
Raleigh St. Augustinegrass	5.08/4.32			
Rebel II tall fescue	5.08/4.32			
Kentucky-31 tall fescue	4.32/4.57			
Tifway bermudagrass		Full sod treatment:	Non-weighing evapotranspirometers; water-stressed conditions.	Stewart et al. (1969), Ft. Lauderdale, Florida
	2.79	1965		
	2.29	1966		
	2.79	1967		
		2/3 sod treatment:		
	2.29	1965		
	2.29	1966		
	3.05	1967		
		1/3 sod treatment:		
	1.78	1965		
	1.78	1966		
	3.05	1967		
Tifway bermudagrass		Depth to water table:	Non-weighing evapotranspirometers; water-stressed conditions. Values are five-year averages (1963-1967).	Stewart and Mills (1967), Ft. Lauderdale, Florida
	3.05	305 mm		
	2.79	610 mm		
	2.79	914 mm		

Table A2. Summary of turfgrass species, K_c values, methodology used to determine K_c, and references.

Turfgrass Species	K_c	Study Period	Methodology and Water Availability	Reference and Location
Bahiagrass (2008)	9 Apr. (0.78) a 21 Apr. (0.68) 5 May. (0.76) a 26 May. (0.78) 17 June (0.81) a 1 July (0.89) b 18 July (0.74) b 5 Aug. (0.67) 3 Sept. (0.76) a 24 Sept. (0.65) 18 Oct. (0.64) 8 Nov. (0.33) 19 Dec. (0.33) a	2008-2010	Turfgrasses monitored in PVC weight lysimeters (25 cm dia. × 33 cm deep) installed in the ground; well-watered conditions throughout the study. ET_c was gravimetrically determined twice monthly. ET_o was determined by the ASCE-EWRI standardized method (Allen et al., 2005a). $K_c = ET_c/ET_o$.	Wherley et al. (2015), central Florida
Bermudagrass (2008)	9 Apr. (0.74) ab 21 Apr. (0.67) 5 May (0.74) a 26 May (0.81) 17 June (0.81) a 1 July (0.92) b 18 July (0.77) b 5 Aug. (0.80) 3 Sept. (0.77) a 24 Sept. (0.64) 18 Oct. (0.56) 8 Nov. (0.32) 19 Dec. (0.21) b			
St. Augustinegrass (2008)	9 Apr. (0.54) b 21 Apr. (0.49) 5 May (0.52) b 26 May (0.63) 17 June (0.70) b 1 July (0.82) c 18 July (0.60) c 5 Aug. (0.60) 3 Sept. (0.51) b 24 Sept. (0.59) 18 Oct. (0.56) 8 Nov. (0.36) 19 Dec. (0.25) ab			
Zoysiagrass (2008)	9 Apr. (0.60) 21 Apr. (0.54) 5 May (0.68) 26 May (0.84) 17 June (0.79) 1 July (0.96) 18 July (0.98) 5 Aug. (0.83) 3 Sept. (0.87) 24 Sept. (0.75) 18 Oct. (0.63) 8 Nov. (0.59) 19 Dec. (0.38)			
Bahiagrass (2009)	9 Feb. (0.45) a 20 Mar. (0.36) 9 Apr. (0.74) a 27 Apr. (0.64) a 30 Sept. (0.85) 20 Oct. (0.85) 3 Nov. (0.86) 23 Nov. (0.91) 21 Dec. (0.60)			
Bermudagrass (2009)	9 Feb. (0.17) b 20 Mar. (0.32) 9 Apr. (0.63) ab 27 Apr. (0.59) ab 30 Sept. (0.69) 20 Oct. (0.66) 3 Nov. (0.70) 23 Nov. (0.58) 21 Dec. (0.45)			

Table A2 (continued). Summary of turfgrass species, K_c values, methodology used to determine K_c, and references.

Turfgrass Species	K_c	Study Period	Methodology and Water Availability	Reference and Location
St. Augustinegrass (2009)	9 Feb. (0.20) b 20 Mar. (0.32) 9 Apr. (0.40) b 27 Apr. (0.38) b 30 Sept. (0.82) 20 Oct. (0.76) 3 Nov. (0.83) 23 Nov. (0.84) 21 Dec. (0.65)	2008-2010	Turfgrasses monitored in PVC weight lysimeters (25 cm dia. × 33 cm deep) installed in the ground; well-watered conditions throughout the study. ET_c was gravimetrically determined twice monthly. ET_o was determined by the ASCE-EWRI standardized method (Allen et al., 2005a). $K_c = ET_c/ET_o$.	Wherley et al. (2015), central Florida
Zoysiagrass (2009)	9 Feb. (0.28) ab 20 Mar. (0.39) 9 Apr. (0.59) ab 27 Apr. (0.46) ab 30 Sept. (0.79) 20 Oct. (0.69) 3 Nov. (0.83) 23 Nov. (0.77) 21 Dec. (0.52)			
Bahiagrass (2010)	27 Apr. (0.77) a 11 May (0.89) a 25 May (0.95) a 8 June (0.87) 22 June (0.73) 6 July (0.94) 20 July (1.02) 3 Aug. (0.88)			
Bermudagrass (2010)	7 Apr. (0.66) b 11 May (0.79) ab 25 May (0.82) ab 8 June (0.75) 22 June (0.73) 6 July (0.88) 20 July (0.99) 3 Aug. (0.92)			
St. Augustinegrass (2010)	7 Apr. (0.52) c 11 May (0.69) b 25 May (0.75) b 8 June (0.76) 22 June (0.74) 6 July (0.78) 20 July (0.89) 3 Aug. (0.79)			
Zoysiagrass (2010)	7 Apr. (0.61) bc 11 May (0.72) b 25 May (0.78) b 8 June (0.78) 22 June (0.77) 6 July (0.92) 20 July (1.06) 3 Aug. (0.84)			
St. Augustinegrass		Mean K_L determined during 2007 and 2008. Observations grouped into early (days 78 to 153), middle (days 154 to 259), and late (days 260 to 335) season.	ET_{ref} predicted by modified Penman-Monteith equation. ET_a = changes in volumetric water content during two to five days of soil drying. K_L = actual ET / reference ET. K_L (landscape coefficient) for St. Augustinegrass treatment is equivalent to K_c in this study. Well-watered conditions.	Pannkuk et al. (2010), College Station and San Antonio, Texas
San Antonio location	0.52			
Seasonal mean: Early	0.44 c			
Middle	0.55 b			
Late	0.71 a			
College Station location	0.34			
Seasonal mean: Early	0.39 ns			
Middle	0.28 ns			
Late	0.24 ns			

Table A2 (continued). Summary of turfgrass species, K_c values, methodology used to determine K_c, and references.

Turfgrass Species	K_c	Study Period	Methodology and Water Availability	Reference and Location
Bahiagrass	Jan. (0.35) Feb. (0.35) Mar. (0.55) Apr. (0.80) May (0.90) June (0.75) July (0.70) Aug. (0.70) Sept. (0.75) Oct. (0.65) Nov. (0.60) Dec. (0.45)	July 2003 through December 2006.	ET_c = eddy correlation method. ET_{ref} = ASCE-EWRI equation (Allen et al., 2005a). $K_c = ET_c/ET_o$. Well-watered conditions.	Jia et al. (2009), central Florida
St. Augustinegrass and bermudagrass	Jan. (0.71) Feb. (0.79) Mar. (0.78) Apr. (0.86) May (0.99) June (0.86) July (0.86) Aug. (0.90) Sept. (0.87) Oct. (0.86) Nov. (0.84) Dec. (0.71)	Five years.	ET_c = data from Stewart and Mills, 1967 (five-year average monthly data). ET_{ref} = Hargreaves equation (Allen et al., 1998) using data for Miami.	Jia et al. (2009) using five-year average monthly ET_c data from Stewart and Mills (1967) for south Florida
Overseeded Froghair ryegrass in winter (Nov. to May; 3-year avg.). Tifway bermudagrass in summer (June to Sept.; 3-year avg.)	Nov. (0.82) Dec. (0.79) Jan. (0.78) Feb. (0.79) Mar. (0.86) Apr. (0.90) May (0.85) June (0.78) July (0.78) Aug. (0.82) Sept. (0.83)	November 1994 to September 1997.	ET_c = lysimeters (water balance). ET_o = simplified FAO Penman-Monteith equation (ASCE equation, Allen et al., 1994, 1998, 2005a). $K_c = ET_c/ET_o$. Well-watered conditions.	Brown et al. (2001), Tucson, Arizona
Bermudagrass and perennial rye	Jan. (0.44) Feb. (0.43) Mar. (0.67) Apr. (0.76) May (0.74) June (0.89) July (0.89) Aug. (0.82) Sept. (0.82)	1987 to 1989 (two golf course sites).	ET_a = lysimeters (water balance). ET_o = modified daily Penman combination equation (Jensen, 1973). $K_c = ET_c/ET_o$. Well-watered conditions	Devitt et al. (1992), Las Vegas, Nevada
Creeping bentgrass	Min.-Max.	Measurements from May to October (1987 and 1988) on mini-lysimeters installed in the field.	ET_a (actual) using water balance method. ET_p (potential) using Nebraska modified Penman equation. $K_c = ET_a/ET_p$. Well-watered conditions.	Salaiz et al. (1991), Mead, Nebraska
Seaside	1.02-1.31/0.79-1.26			
SR-1020	0.67-1.24/0.72-1.23			
Cobra	0.69-1.20/0.72-1.22			
Penncross	0.73-1.18/0.76-1.18			
Providence	0.71-1.16/0.72-1.18			
Penneagle	0.78-1.10/0.73-1.15			
Emerald	0.75-1.10/0.72-1.06			
Prominent	0.75-1.03/0.71-1.08			
National	0.60-1.0/0.70-0.98			
Pennlinks	0.60-0.98/0.68-0.98			
Kentucky bluegrass	July (1.03) Aug. (0.84) Sept. (1.0)	July to September (1984 and 1985).	ET_c = weighing lysimeters. ET_o = modified Penman equation (Burman et al., 1980). $K_c = ET_a/ET_o$. Well-watered conditions.	Aronson et al. (1987a), Kingston, Rhode Island
Red fescue	July (0.98) Aug. (0.83) Sept. (0.99)			
Perennial grass	July (1.05) Aug. (0.88) Sept.(1.02)			
Hard fescue	July (0.98) Aug. (0.80) Sept, (0.94)			

Table A2 (continued). Summary of turfgrass species, K_c values, methodology used to determine K_c, and references.

Turfgrass Species	K_c	Study Period	Methodology and Water Availability	Reference and Location
Cases under water-stressed conditions				
Cool-season (bluegrass, perennial ryegrass and tall fescue)	Mar. (0.05) Apr. (0.20) May (0.44) June (0.64) July (0.72) Aug. (0.69) Sept. (0.64) Oct. (0.61)	1998 to 2000.	ET_c = soil water balance equation. ET_o = Samani and Pessarakli (1986) equation. Field experiment. $K_c = f$(cumulative heat units).	Smeal et al. (2001), Farmington, New Mexico
Warm-season (bermudagrass, buffalograss and blue grama)	June (0.28) July (0.54) Aug. (0.60) Sept. (0.59)			
Kentucky bluegrass	0.60 to 0.80	1993 to 1994.	ET_r = Kimberly-Penman combination equation (Jensen et al., 1990). ET_a = 80% ETr. $K_c = ET_a/ET_r$.	Ervin and Koski (1998), Fort Collins, Colorado
Tall fescue	0.50 to 0.80			
Tifway bermudagrass	0.67		ET_c = soil moisture content (TDRs) during dry-down periods when no drainage occurred. ET_{ref} = FAO Penman equation (Doorenboos and Pruitt, 1984). $K_c = ET_c/ET_o$.	Carrow (1995), Griffin, Georgia
Common bermudagrass	0.68			
Meyer zoysiagrass	0.81			
Common centipedegrass	0.85			
Raleigh St. Augustinegrass	0.72			
Rebel II tall fescue	0.79			
Kentucky-31 tall fescue	0.82			
Hybrid and common bermudagrass:		1989 to 1991. K_c values are annual.	Water use determined by gravimetric method. ET_c = actual water use. ET_o = modified Penman equation (Doorenboos and Pruitt, 1977). $K_c = ET_c/ET_o$.	Garrot and Mancino (1994), Tucson, Arizona
Texturf-10	0.64			
Tifgreen	0.60			
Midiron	0.57			
Cool-season grasses	Jan. (0.61) Feb. (0.64) Mar. (0.75) Apr. (1.04) May (0.95) June (0.88) July (0.94) Aug. (0.86) Sept. (0.74) Oct. (0.75) Nov. (0.69) Dec. (0.60)	August 1981 to December 1983.	ET_c = actual applied water divided by the extra water factor (EWF90), which was 1.35 for this case. ET_o = modified Penman equation (Doorenboos and Pruit, 1977).	Meyer and Gibeault (1987), Riverside, California
Warm-season grasses	Jan. (0.55) Feb. (0.54) Mar. (0.76) Apr. (0.72) May (0.79) June (0.68) July (0.71) Aug. (0.71) Sept. (0.62) Oct. (0.54) Nov. (0.58) Dec. (0.55)	August 1981 to December 1983.	ET_c = actual applied water divided by extra water factor (EWF90), which was 1.35 in this case. ET_o = modified Penman equation (Doorenboos and Pruit, 1977). $K_c = ET_c/ET_o$.	Meyer and Gibeault (1987), Riverside, California