Turfgrass and Ornamental Plant Evapotranspiration and Crop Coefficient Literature Review

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February 23, 2009

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1. Executive summary

Landscapes have become an important crop in the U.S. in many ways. There are an estimated 50 million acres of maintained turfgrass on home lawns, golf courses, and other areas. Its use brings benefits to the environment but much concern has been created by the excessive use of both water and pesticides applied to landscapes. To preserve water it is important to select the correct turfgrass and landscape plants for any given climate. This report presents a detailed literature review related to turfgrass types, turf evapotranspiration rates (ETc) and crop coefficients (K_c). Turfgrass is the focus of this report since the majority of maintained landscaped area is in turfgrass. However, literature K_c values for ornamental plants are presented where they are available and the landscape coefficient method is introduced.

The results showed that warm-season turfgrasses are characterized by their lower ETc rates compared to cool-season turfgrasses. Warm-season turfgrasses ETc rates ranged from 0.03 in d^{-1} in bahiagrass to 0.37 in d^{-1} in Zoysiagrass, while cool-season turfgrasses showed ETc rates from 0.12 in d^{-1} in hard fescue to 0.49 in d^{-1} in Kentucky bluegrass. This high variability among species and intra-species were a response of the many factors, principally soil moisture conditions. The higher ETc rates were typically associated with well-watered conditions for the determination of both ETc and Kc values. Lower ETc rates were associated with water stress conditions. Variability was also observed in turfgrass crop coefficients, whose values changed substantially over the time period when measurements were conducted. Results were mixed, but it does appear that cool-season turfgrasses use more water than warm-season turfgrasses when water is non-limited. Maximum and minimum estimated monthly K_c values were 1.05 and 0.05, respectively, for cool-season grasses; for warm-season grasses monthly K_c values ranged from 0.99 to 0.28.

It is important to point out that K_c's are being incorporated into weather-based irrigation controllers; therefore, the selection of K_c values should be the most suitable for both the species and the location of interest. The most common methodology to measure crop evapotranspiration was the use of lysimeters (specifically minilysimeters for turfgrasses). Various Penman equations were the most common used to calculate reference evapotranspiration.

In addition to turfgrass, this report also deals with landscape plant water requirements. Relevant research-based data on ETc and K_c for ornamental plants is very limited. The landscape coefficient method is presented as a method to estimate irrigation requirements for landscapes (which includes turfgrasses and ornamental plants) based on landscape evapotranspiration (ET_L). ET_L is obtained by multiplying a landscape coefficient (K_L) by reference evapotranspiration (ETo). K_L replaces K_c because of important differences existing between a turfgrass system and landscape plantings. K_L is defined as the product of a species factor, a density factor, and a microclimate factor. A numeric value is assigned to each factor, which will depend on the knowledge and gained experience of the professional who will use this methodology, which makes the method quite subjective. We also make reference to the Water Use Classification of Landscape Species (WUCOLS) list, which is intended only as a guide to help landscape professionals because it provides irrigation water needs for over 1,900 plant species. In general, some subjectivity is found in this methodology.

The conclusions show that turfgrass water use is influenced by environmental factors such as weather (temperature, wind, solar radiation, relative humidity), soil type and soil moisture. It is also affected by species, genotype, and plant morphological characteristics, since all these factors affect both plant transpiration and soil evaporation. Concerning ornamental plants' water requirements, there is still a lack of information that leads us to look for a way to meet this need, like using the K_L approach. This approach is very subjective, so results might need some adjustments after they are calculated.

2. Introduction

Turfgrasses and ornamental plants are considered an integral part of landscape ecological systems worldwide which provide esthetic value (Roberts et al., 1992). 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 an excessive use of water and pesticides, resulting in an environmental pollution. Critics recommend the total replacement with what are termed 'native plants' (Fender, 2006). Although this could sound drastic for turfgrasses, its water requirements have been established by scientific study, which means that any application of water in amounts exceeding turf requirements can be attributed to human factors, not plant needs (Beard and Green, 1994).

Turfgrasses have been utilized by humans to enhance their environment for more than ten centuries and, for those individuals or group that debate the relative merits of any single landscape material, the complexity and comprehensiveness of these environmental benefits that improve our quality-of-life are just now being quantitatively documented through research (Beard and Green, 1994).

Turf has become an important U.S. crop based on the acreage covered. The most recent estimation of the turf area in the U.S. was presented by Milesi et al. (2005). They reported a total turfgrass area estimated as 100 million acres (+/- 21.9 million acres for the upper and lower 95% confidence interval bounds), 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 lower 95% confidence interval bound, that would represent 78 million acres and this estimate compares to the estimates of Morris (2003) who estimated 50 million of acres of turf in the U.S. on home lawns (66.7%), golf courses (20%), and sport fields, parks, playgrounds, cemeteries and highway roads (13.4%). The annual economic value of this turfgrass is estimated to be $40 billion. Florida has the second largest withdrawal of ground water for public supply in the U.S. (Solley et al., 1998) and some estimates indicate that 30-70% of publicly supplied drinking water use in Florida accounts for landscape water use (FDEP, 2002).

It is important to keep in mind that turfgrass water use varies among turfgrass species and within cultivars. However, cultural practices (like irrigation) can be manipulated to decrease a species' water use and enhance its drought resistance, playing an important role in water conservation (Shearman, 2008). Studies described next in sections 3.2.2 and 3.3 show the effects of applying different amounts of irrigation water on both turf evapotranspiration rates and Kc values. Well-watered conditions should be considered when turf evapotranspiration (ETc) is measured for crop coefficient development (Allen et al., 1998). Water stress will affect turf evapotranspiration rate, growth rate, and visual quality. Therefore, development of Kc values under water stress conditions has specific purposes [e.g. to be used by turf managers to determine on-site water use by both cool- and warm-season turfgrasses (Meyer and Gibeault, 1987)].

Reference evapotranspiration (ETo), turf evapotranspiration (ETc) and turf crop coefficients (K_c) can be used to schedule irrigation. The U.S. Environmental Protection Agency (EPA), through its sponsored partnership program named "WaterSense" (http://www.epa.gov/watersense/index.htm), support the need of using technologies with crop coefficients programmed into weather-based irrigation controllers for efficient irrigation. However, in cases, many controllers have been said to have 'generous' default crop coefficients, leading to an over-irrigation process, as settled in the "Notification of intent meeting summary" (EPA WaterSense, 2007).

Currently, Kc values for both turfgrasses and ornamental plants are considered important parameters for "landscape water budgets" as a way to increase the efficiency of irrigation systems. An example given in the Landscape Water Budget standards for the California Landscape Contractors Association - CLCA's Water Management Certification, which uses fixed parameters like crop coefficients (for warm-season, cool-season, native plants, ground cover/shrubs, and others) as key components to successfully completing the CLCA Water Management Certification (http://www.clca.us/water/memOnly/budget.html). In addition, the EPA Water Sense program has proposed a water budgeting procedure for new homes that used Kc's and KL's to computed required landscape irrigation (http://www.epa.gov/watersense/specs/homes.htm).

The objectives of this report are to present a literature review on both evapotranspiration and crop coefficients for turfgrasses in the U.S., and ETc values for ornamentals.

3. Literature review

3.1. Turfgrass overview

Turfgrasses are classified into two groups based on their climatic adaptation: warm-season grasses, 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. Cool season grasses, on the other hand, are generally more susceptible to moisture stress than warm season grasses (Duble, 2006). Buffalograss, for example, can survive long periods of severe moisture stress, whereas bluegrass would be killed by the same conditions. This difference in water use derives from changes in the photosynthetic process that occurred in grasses evolving under hot, dry conditions. These changes, which include modifications to biochemical reactions and internal leaf anatomy, greatly enhance the photysynthetic efficiency of warm-season species and help reduce water use. Increased photosynthetic efficiency means that plants can maintain high levels of carbohydrate production and continue to grow even when stomates are partially closed. This partial closure of the stomates slows the plant's water use. Cool-season grasses cannot maintain enough carbohydrate production to maintain growth unless their stomates are nearly wide open. When water is limited, transpiration rates are generally higher than those of warm-season grasses (Gibeault et al., 1989).

Some turfgrass species that are grown throughout the southeastern USA for home lawns, golf courses, athletic fields, right-of-ways, and various other applications are described below (Duble, 2008a; Kenna, 2006; Busey, 2002; Trenholm and Unruh, 2002; Ruppert and Black, 1997):

3.1.1. Warm-season turfgrasses

St. Augustinegrass [*Stenotaphrum secundatum* (Walt) Kuntze**]**: St. Augustinegrass is a warm-season grass which some authors believe is native from Africa (Kenna, 2006) or from both, the Gulf of Mexico and the Mediterranean (McCarty and Cisar, 1997). It grows vigorously during the warm (80 to 95 F) months of spring, summer, and early fall. Of all the warm season grasses, it is the least cold tolerant and has the coarsest leaf texture. It prefers well-drained, humid and fertile soils that are not exposed to long period of cold weather to produce an acceptable quality lawn. Like other warm-season grasses, it goes dormant and turns brown in the winter. It is very susceptible to winter injury and cannot be grown as far north as bermudagrass and Zoysiagrass.

<u>Disadvantages:</u> It recovers poorly from drought. There are shade tolerant cultivars existing (e.g. Seville, Delmar, Jade, and possibly Palmetto). It is susceptible to pest problems, like chinch bug, which is considered the major insect pest of this species. It wears poorly and some varieties are susceptible to cold damage.

Zoysiagrass (*Zoysia spp*.): Zoysiagrass is a warm-season turfgrass that spreads by rhizomes and stolons to produce a very dense, wear-resistant turf. These grasses have been developed and are adapted to a broader range of environmental conditions. It is believed that several species and varieties were introduced from the orient to the United States. There are three major species of zoysiagrass suitable for turf including japanese lawngrass (*Z. japonica*), mascarenegrass (*Z. tenuifolia*), and manilagrass (*Z. matrella*). Their slow growth makes them difficult to establish; however, this can be a maintenance advantage because mowing is needed less frequently compared to some other warm-season grasses. Zoysiagrass is adapted to a wide variety of soils, its primary advantage is its moderate tolerance to shade and salts, and provides a dense sod which reduces weed invasion. It is also stiff to the touch and offers more resistance than bermudagrass.

<u>Disadvantages:</u> Zoysiagrass is slow to establish because it must be propagated vegetatively. All zoysias form a heavy thatch which requires periodic renovation. There is a high fertility requirement and need for irrigation to maintain green color. These grasses are susceptible to nematodes, hunting billbugs and several diseases. It tends to be shallower rooting and is weakened when grown in soils low in potassium level.

Bahiagrass (*Paspalum notatum*): Bahiagrass is a warm-season grass that was introduced from Brazil in 1914 and used as a pasture grass on the poor sandy soils of the southeastern United States. The ability of bahiagrass to persist on infertile, dry soils and resistance to most pests has made it increasingly popular with homeowners and public entities like the Department of Transportation (DOT). It can be grown from seed which is abundant and relatively inexpensive. It develops an extensive root system which makes them one of the most drought tolerant lawngrasses and it has fewer pest problems than any other Florida lawngrass. It is easily recognized by the characteristic "Y" shape of its seedhead, as well as its stoloniferous growth habit.

<u>Disadvantages</u>**:** Due to the tough leaves and stems, it is difficult to mow. It can be a very competitive and unsightly weed in highly maintained turf. It is not well suited for alkaline and saline soils. It is intolerant to shade and to mole crickets.

Bermudagrass (*Cynodon dactylon*): Bermuda is a medium- to fine-textured warm-season turfgrass that spreads by rhizomes and stolons. Also called wiregrass, is planted throughout Florida primarily on golf courses, tennis courts and athletic fields. Extremely heat tolerant, but very intolerant of shade, bermudagrass is the dominant sunny lawn grass in the south and west of the U.S. It is one of the few warm-season grasses that can be taken north like Tennessee, North Carolina, Arkansas, and Oklahoma, as well as the Central Valley of California (Kenna, 2006). Bermudagrass is native to Africa where it thrived on fertile soils. It has excellent wear, drought and salt tolerance and is good choice for ocean front property, and it is competitive against weeds. Improvements in seed establishment as well as cold tolerance will help provide bermudagrass cultivars for the transition zone climates of the United States.

Disadvantages**:** Bermudagrass has a number of cultural and pest problems and therefore, will need a higher level of maintenance inputs than most other grasses. In central and north Florida, bermudagrasses become dormant in cold weather. Overseeding in fall with ryegrass is a common practice to maintain year-round green color. Bermudagrasses have very poor shade tolerance and should not be grown underneath tree canopies or building overhangs. It can also be a very invasive and hard to control weed in some turf settings.

Centipedegrass [*Eremochloa ophiuroides* (Munro) Hack**]:** Centipedegrass is a warm-season turf that is adapted for use in low maintenance situation. It was introduced into the United States from southeastern Asia. It has a slow growth pattern, so it is not very competitive against weeds. It is well adapted to sandy, acidic soils and tolerates low fertility, requiring little maintenance, compared to other turfgrasses. This grass is moderately shade-tolerant and requires infrequent mowing, and will survive mild cold temperatures.

Disadvantages**:** Centipedegrass is highly susceptible to damage from nematodes. It exhibits iron chlorosis and produces a heavy thatch if over fertilized. It does not tolerate traffic, compaction, high pH, high salinity, excessive thatch, drought, or heavy shade.

Seashore paspalum (*Paspalum vaginatum*): It is a warm-season grass that is native to tropical and sub-tropical regions world-wide. It was introduced into the United States around the world through maritime travel and it has since spread along coastal areas of the southeastern US, because seashore paspalum can survive high levels of salt in the salt-affected waters and environments of these areas. Breeding efforts to improve cold tolerance, color, density, and other turfgrass characteristics are well under way.

This grass produces a high quality turfgrass with relatively low fertility inputs. While it has initially been marketed for golf course and athletic field use, it has good potential for use in the home lawn market as well. The advantages for use of seashore paspalum in a home lawn situation include: excellent tolerance to saline water, excellent wear tolerance, good tolerance to reduced water input, relatively low fertility inputs needed to produce a dense, dark green lawn, few insect disease problems in most environments, tolerates a wide pH range, tolerates long periods of low light intensity and produces a dense root system.

Disadvantages: This grass has poor shade tolerance; it performs best when mowed at one to two inches; it is sensitive to many common herbicides and may be injured or killed by their use. Seashore paspalum tends to become thatchy, particularly when over fertilized and over-irrigated.

Buffalograss (*Buchloë dactyloides* (Nutt.) Engelm.): It is a native warm-season perennial grass that can be used for low-maintenance lawns and other turf areas. Buffalograss grows best in full sun, requiring at least 6 to 8 hours of direct sun daily, and under moderate rainfall (15 to 30 inches annually). Its tolerance to prolonged droughts and to extreme temperatures together with its seed producing characteristics enables buffalograss to survive extreme environmental conditions. It is one or the most uniform and attractive turf. Buffalograss is found throughout the Great Plains from Mexico to Montana (Duble, 2008a)

Disadvantages: It will not survive in sandy soils and it is only recommended for low maintenance, low use turfgrass areas. Over use or excessive traffic are the pressures that lead to the deterioration of a stand of buffalograss.

3.1.2. Cool-season turfgrasses

Note that cool-season grasses do not survive in Florida due to high temperatures and humidity; however, several are listed here since extensive water use research has been conducted on these grasses. Cool-season grasses, which are used in lawns, sports fields, golf courses, and roadsides include *Poa* L., *Lolium* L., *Festuca* L., and *Agrostis* L. (Beard, 1994).

Kentucky bluegrass (*Poa pratensis*): This grass is a general purpose turfgrass native to practically all of Europe, northern Asia and part of north of Africa. It is a long-lived perennial that is widely adapted throughout the cool-season growing areas. It also can be used in the cool semiarid and arid regions if irrigated. Bluegrass can survive several months without significant rainfall or irrigation. High nitrogen fertilization and frequent mowing greatly decrease root growth in this turfgrass (Kenna, 2006; Duble, 2008b).

Disadvantages: In alkaline soils Kentucky bluegrass often develops iron chlorosis. Root growth practically ceases at temperatures above 80^{o}F.

Perennial ryegrass (*Lolium perenne*): it is generally considered to be a short-lived perennial, but it can persist indefinitely if not subjected to extremes in high or low temperature. Ryegrass is a very competitive cool-season grass, best adapted to coastal regions that have moderate temperature throughout the year. However, it persists under cold winter conditions where it is protected by consistent snow cover. Because it germinates quickly, it is used to compliment Kentucky bluegrass in sunny lawn mixes in the cool-season zone; in the South, is the primary overseed grass (Kenna, 2006; UCDavies; 2004)

Disadvantages: It may suppress germination of other grasses in the mixture (allelopathy); it is drought sensitive and if seeded alone, becomes "steamy" after a couple of years. It also can become weedy when used to overseeded warm-season grasses.

Tall fescue (*Festuca spp*.): Introduced from Europe in the early 1800's, tall fescue can be found from the Pacific Northwest to the southern states in low-lying pastures. It grows best in moist environments, although tall fescue has good drought tolerance, surviving during dry periods in dormant conditions. It tolerates heat better than other cool-season species. Compared to bluegrass and perennial ryegrass, tall fescue tolerates shade conditions the most, but it is inferior to fine fescue in the shade (Kenna, 2006; Duble, 2008c).

Disadvantages: It should not be use where mowing heights are below 1.5 inches during summer months. Although its wear tolerance is considered good for cool season grasses, it is not nearly as wear tolerant as bermudagrass. Due to this, its use on golf courses and athletic fields in the South is limited.

Creeping bentgrass (*Agrostis stolonifera*): It is the grass cultivated exclusively on golf courses, especially on putting greens and fairways. Its name derives from the vigorous, creeping stolons than develop at the surface of the ground. The leaves on the bentgrass are long and slender. Due to its poor stress tolerance and high maintenance requirements, bentgrasses are not suitable for home lawns.

Disadvantages: When grown to normal height, this grass becomes shaggy. It does not tolerate hot, dry weather, or cold winters.

3.2 Evapotranspiration

3.2.1. Definition

Evapotranspiration (ET) represents the loss of water from the soil through the combined processes of evaporation (from soil and plant surfaces) and plant transpiration. Reference evapotranspiration (ETref) is the rate at which readily available soil water is vaporized from specified vegetated surfaces (Jensen et al., 1990). Reference evapotranspiration is defined as the ET rate from a uniform surface of dense, actively growing vegetation having specified height and surface resistance, not short of soil water, and representing and expanse of at least 328 ft. of the same or similar vegetation (Allen et al., 2005). Evapotranspiration is directly measured using lysimeters. Lysimeters are tanks filled with soil in which crops are grown under natural conditions to measure the amount of water lost by evaporation and transpiration. This method provides a direct measurement of ET and is frequently used to study climatic effects on ET and to evaluate estimating procedures. By the nature of its construction, a lysimeter prevents the natural vertical flow and distribution of water. Ideally, lysimeters must meet several requirements for the data to be representative of field conditions (Van Bavel, 1961; Miranda et al., 2006). Lysimeters can be grouped into three categories: (1) non-weighing, constant water-table type; (2) non-weighing, percolating-type; and (3) weighing types. Also, large and mini-lysimeters can be used for different applications. Large lysimeters are the standard instrument for measuring evapotranspiration (surface area > 6.6 ft^2) (Slatyer and McIlroy, 1961). To make good and reliable measurements, lysimeters need to meet some requirements:

- When lysimeter are used to measure actual evapotranspiration rates, it seems essential that they are either quite deep or fitted with a tensioning at the bottom, to allow a normal root growth;

- They should contain an undisturbed, representative profile. In a disturbed profile, moisture transmission, moisture retention, and root distribution is likely to be different from that of the original profile and measurements may not be representative;

- The vegetation inside and outside the lysimeter should be kept as similar as possible;

- Diminishing the effect of the lysimeter rim over ET measurements by reducing the lysimeter wall thickness, the gap between inner and outer walls, and the height of the lysimeter rim relative to soil surface;

- Reducing the oasis effect by providing sufficient distances of windward fetch of similar vegetation and soil moisture regimes.

Recently many researchers have used 'minilysimeters' in field studies (Grimmond et al., 1992). They have the advantage that minilysimeters (1) permit the measurement of the evaporative flux from smaller areas; (2) create less disturbance to the environment during installation; (3) are cheaper to install than the large ones. But there are a big number of potential sources of error associated when using lysimeters, either related with the mechanics or electronics of the lysimeter. In general, the effect of sources of error on the accuracy of evapotranspiration measurements is inversely related to the surface area of the lysimeter (Dugas and Bland, 1989).

A large number of empirical methods have been developed over the last 50 years to estimate evapotranspiration from different climatic variables. Some of these methods are derived from the now well-known **Penman equation** (Penman, 1948) to determine evaporation from open water, bare soil and grass (now called evapotranspiration) based on a "combination" of an energy balance and an aerodynamic formula, given as:

$$\lambda E = [\Delta(R_n - G)] + (\gamma\ \lambda\ E_a) / (\Delta + \gamma) \quad \textbf{(1)}$$

where λE is the evaporative latent heat flux in MJ m^{-2} d^{-1}, Δ is the slope of the saturated vapor pressure curve [$\delta e^o / \delta T$, where e^o is saturated vapor pressure in kPa and T is the temperature in ^oC, usually taken as the daily mean air temperature], Rn is net radiation flux in MJ m^{-2} d^{-1}, G is sensible heat flux into the soil in MJ m^{-2} d^{-1}, γ is the psychrometric constant in kPa $^oC^{-1}$, and E_a is the vapor transport of flux in mm d^{-1} [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:

$$\lambda ETo = \{[\Delta (R_n - G)] + [86{,}400\, \rho_a C_p (e_s^o - e_a)]/r_{av}\}/\ \Delta + \gamma\ (1 + r_s/r_{av}) \qquad \textbf{(2)}$$

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

As early as 1952, turfgrass crop-water requirement studies began in Florida (McCloud and Dunavin, 1954). Estimations of water use at Gainesville were underestimated according to the formulas of Blaney and Criddle (1950), Tabor (1931) and Thornthwaite (1948) when the mean temperature was above 70 F (McCloud, 1955). For this reason, an empirical formula (3) was developed for Gainesville, FL as follows:

$$\textbf{Potential daily water-use} = ETp = KW^{(T-32)} \qquad \textbf{(3)}$$

It was observed that formula fit the data best when K = 0.01, W = 1.07, and T = mean temperature in F. This formula was used to compute a predicted weekly water-use value, and both predicted and measured data were highly correlated (Mc Cloud, 1955). It is important to note that this equation is only relevant for Gainesville climatic conditions as explained by McCloud (1955).

An updated equation was recommended by FAO 56 (Allen et al. 1998) with the **FAO-56 Penman-Monteith Equation**. Allen et al. (1998) simplified equation (2) by utilizing some assumed constant parameters for a clipped grass reference crop that is 0.4 ft tall. In the context of this new standardization, reference evapotranspiration, it was assumed that the definition for the reference crop was “a hypothetical reference crop with an assumed crop height of 0.4 ft, a fixed surface resistance of 70 s m^{-1} and an albedo value of 0.23” (Smith et al., 1992). The new equation is:

$$ETo = \{[0.408\Delta (R_n - G)] + [\gamma\ 900/(T+273)\ U_2\ (e_s^o - e_a)]\}/\ \Delta + \gamma(\ 1 + 0.34\ U_2) \qquad \textbf{(4)}$$

where ETo is the reference evapotranspiration rate in mm d^{-1}, T is mean air temperature in ^{o}C, and U_2 is wind speed in m s^{-1} at 6.6 ft above the ground (and RH or dew point and air temperature are assumed to be measured at 6.6 ft above the ground level –or converted to that height- to ensure the integrity of computations). Equation 4 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}.

In 1999, the ASCE Environmental and Water Resources Institute Evapotranspiration in Irrigation and Hydrology Committee was asked by the Irrigation Association to propose one 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, ETos and another for a taller crop such as alfalfa, ETrs) were developed for daily (24 hr) and hourly time periods. **The ASCE-EWRI standardized reference ET equation (Allen et al., 2005)** based on the FAO-56 Penman-Monteith equation (4) for a hypothetical crop is given as,

$$\mathbf{ETsz = \{[0.408\ \Delta(R_n - G)] + [\gamma\ C_n /(T+273)\ U_2\ (e_s - e_a)]\}/\ \Delta + \gamma(1 + C_d\ U_2)} \qquad \mathbf{(5)}$$

where ETsz is the standardized reference evapotranspiration for a short reference crop (grass - ETos) or a tall reference crop (alfalfa - ETrs) in units based on the time step of mm d^{-1} for a 24-h day 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).

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

Calculation time step	Short reference crop ETos		Tall reference crop, ETrs		Units for ETos,ETrs	Units for R_n and G
	C_n	C_d	C_n	C_d		
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}

Reference evapotranspiration (ET) replaced the term potential ET. Reference evapotranspiration is defined as the ET rate from a uniform surface of dense, actively growing vegetation having specified height and surface resistance, not short of soil water, and representing an expanse of at least 328 ft of the same or similar vegetation (Allen et al., 2005). The crop evapotranspiration (ETc) under standard conditions is the evapotranspiration from disease-free, well fertilized crops, grown in large fields under optimum soil water conditions and achieving full production under the given climatic conditions (Allen et al., 1998).

3.2.2. Evapotranspiration of turfgrasses

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 referred to as evapotranspiration (Huang, 2006; Augustin, 2000). Most of the water transpired through the plant moves through openings in the leaves called stomates, whose primary benefit is the 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: 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 0.4 in of water per day in desert climates during summer months; whereas, in humid climates under similar temperature conditions, the daily losses may be only 0.2 in of water (Duble, 2006). The application of water to turfgrass in amounts exceeding its requirements can be attributed to human factors, not to plant needs (Beard and Green, 1994).

The most commonly used cool- and warm-season turfgrass species have been categorized for ETc rates (Beard and Kim, 1989) as shown in Table 2.

Table 2: Evapotranspiration rates of warm and cool-season turfgrasses commonly used in North America (after Beard and Kim, 1989).

Relative ranking	ET Rate (mm d^{-1})	ET Rate (in d^{-1})	Cool-season	Warm-season
Very low	< 6	< 0.24		Buffalo grass
Low	6 – 7	0.24 - 0.28		Bermudagrass hybrids Bluegrama Bermudagrass Centipedegrass Zoysiagrass
Medium	7 - 8.5	0.28 – 0.33	Hard fescue Chewings fescue Red fescue	Bahiagrass Seashore paspalum St. Augustinegrass Zoysiagrass
High	8.5 - 10	0.33 - 0.39	Perennial ryegrass	
Very high	> 10	> 0.39	Tall fescue Creeping bentgrass Annual bluegrass Kentucky bluegrass Italian ryegrass	

Many investigators have shown how turfgrass water use vary by species, genotypes, climatic conditions, plant density, water-table depth, water availability, plant morphological characteristics, etc. (Ekern, 1966; Stewart et al., 1967; Stewart et al., 1969; Tovey et al., 1969; Kneebone and Pepper, 1981; Aronson et al., 1987; Meyer and Gibeault, 1987; Kim and Beard, 1988; Green et al., 1990a; Green et al., 1990b; Atkins et al., 1991; Bowman and Macaulay, 1991; Green et al., 1991; Kneebone and Pepper, 1994; Brown, 2003). There are two common ways to determine the water loss due to evapotranspiration: measurement and estimation. Measurement methods include lysimeters, eddy correlation and soil water balance to name a few. Estimation methods include, energy balance, mass transfer, combination of energy and heat, mass transfer and crop coefficients. Next, summaries of research are presented based on direct measurement of evapotranspiration, specifically using both big and mini-lysimeters. Just keep in mind that potential errors in resolution can be found when using this methodology. As described in section

3.2.1, lysimeters need to meet some requirements to work adequately. This information is summarized in Table 3, and Table 4 shows the main methodologies used for ETc determination.

Kim and Beard (1988) conducted research on turfgrass evapotranspiration rates using 12 turfgrass species, including warm-season and cool-season grasses, growing under well-watered conditions, from 1982 to 1984. ET rates were determined by the water balance method. Black plastic minilysimeters were used. The ET rate differences among species were associated to morphological characteristics such as shoot density, number of leaves per unit area, leaf orientation, leaf width, and vertical leaf extension rate. St. Augustinegrass exhibited a medium low ET rate of 0.23 in d^{-1} due to a very low shoot density (low canopy resistance). Bahiagrass showed a medium ET rate of 0.25 in d^{-1} when growing under non-limiting soil moisture due to its high leaf area. In contrast, Adelayd seashore paspalum had a low ET rate of 0.21 in d^{-1} value associated with a very rapid vertical leaf extension rate but medium leaf width. Zoysiagrasses exhibited significant differences in ET rates, due to the vertical leaf orientation. The three bermudagrasses (Arizona common, tifgreen, and tifway) were in the low range due to a low leaf area. Centipedegrass low ET rates were related to a very slow vertical leaf extension rate.

Results reported by Atkins et al. (1991) showed variation in ET rates among 10-well watered St. Augustinegrass genotypes in the field and in a controlled-environment chamber in Texas. The experiment was carried out using black plastic minilysimeter pots. ETc rate estimations using a water-balance method were determined in Sept. 1985, July and Aug. 1986, and Sept. 1987. Averaged ETc rates were significantly lower in Sept. 1985 (0.21 in d^{-1}) than in Aug. 1986 and Sept. 1987 (0.51 and 0.56 in d^{-1}, respectively). The chamber study involved controlled conditions monitoring temperature, photoperiod, wind speed and solar radiation. The genotype effect was significant for ETc rates, probably due to the higher evaporative potential of the controlled-environment chamber. ‘Texas Common’ and ‘PI 410356’ ranked lowest for ETc rate at 0.26 and 0.29 in d^{-1}, respectively, while ‘TX 106’ and ‘TXSA 8218’ ranked highest, both at 0.32 in d^{-1}. St. Augustinegrass species seemed to have no significant intraspecies ETc rate variation when evaluated under well-watered field conditions. A similar study using minilysimeters under both field and controlled-environment conditions was carried out for eleven Zoysia genotypes under well-watered conditions, also in Texas (Green et al., 1991). Under field conditions, ETc rates were evaluated from 1985 to 1987, and the results showed genotype ‘KLS-11’ ranking highest for ET rate with 0.16 in d^{-1}, while genotype ‘Belair’ had the lowest rate with 0.15 in d^{-1}. ETc rates were higher under controlled conditions, with genotype 'KLS-11' showing the lowest rate (0.33 in d^{-1}) and genotype Emerald with the highest rate (0.41 in d^{-1}). The highest water consumption by Zoysia genotypes under controlled conditions was due to the higher evaporative potential demand of the environmental chamber.

Feldhake et al. (1983) used weighable bucket lysimeters to measure ET rates of different cool- and warm-season turfgrasses under the effects of mowing height, N fertilization, etc., in a study from 1979 to 1981 in Colorado. The study was performed under well-watered conditions. ET rates were 0.22 in d^{-1} for Kentucky bluegrass 'Merion', 0.23 in d^{-1} for tall fescue, and 0.18 in d^{-1} for both 'tifway' and 'common' bermudagrass. 'Merion' Kentucky bluegrass evapotranspiration rates varied according to the mowing height from 0.19 in d^{-1} (0.79 in mowing height + N) to 0.21 in d^{-1} (1.97 in mowing height + N). When Kentucky bluegrass was deficient in N, ET rate increased to 0.21 in d^{-1}. ET rate was influenced by the type of grass and by mowing height and fertility.

ET from four cool-season turfgrasses was compared under well-watered conditions under field conditions in Rhode Island (Aronson et al., 1987a) as follows: Kentucky bluegrass, perennial ryegrass, chewing red fescue and hard fescue. ET rates were measured by determining the mass loss of weighing lysimeters containing 0.5 ft deep sod soil cores. The lysimeters and the surrounding plots were sprinkler irrigated to saturation and drained to field capacity and then irrigated every 4 to 5 days in the absence of precipitation. The lysimeters were weighed at 24-h intervals to calculate water loss due to ET. The average ET rate for all turfgrasses for the two-year study (July through September) was 0.15 in d^{-1} for Kentucky bluegrass, 0.14 in d^{-1} for red fescue, 0.15 in d^{-1} for perennial ryegrass and 0.12 in d^{-1} for hard fescue. The same turfgrass species were tested in a similar experiment but under controlled conditions to test for responses to drought stress (Aronson et al., 1987b). Small 10-in diameter lysimeters were placed in a greenhouse and kept for 80 days under well-watered conditions before drought tests were begun. Adequate light and fertilizers were provided to each lysimeter. The grasses were exposed to two consecutive drought stress periods: the first one was continued until visible signs of stress were observed; second, the grasses were allowed to recuperate under well-watered conditions for 3 weeks until they recovered their initial turf quality scores. The second drought period was continued until plant death. ET was determined as previously described in this paragraph. Although no numerical results were published for water consumption, the most drought tolerant of the four grasses studied were the fescues. Both, the perennial ryegrass and Kentucky bluegrass were less drought tolerant and sustained substantial injury when the soil water potential declined to more than -125 centibars (cb). According to these results, the range between -50 to -80 cb may represent a threshold level of drought stress for cool-season grasses growing in this area, since characteristics like ET, quality score, leaf growth rate and leaf water potential showed marked changes under those soil water potentials. Tall fescue avoids drought better than Kentucky bluegrass because it can develop a deeper, more extensive root system, being more able to extract more deep soil moisture for continued transpiration, compared to Kentucky bluegrass (Ervin and Koski, 1998).

Another study using minilysimeters under controlled-environment conditions was carried out 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 at College Station, TX (Green et al.,1990a). ET rates were based on three sequential measurements from each minilysimeter made in 24 hr under non-limiting soil moisture conditions. The highest ET rates were exhibited by Kentucky bluegrasses (0.48 in d^{-1}) and the lowest by the fine-leafed fescues (0.30 in d^{-1}), results that agreed with those showed by Aronson et al. (1987b).

There are numerous studies measuring bermudagrass ET rates due to the prevalence of this grass on golf courses. Devitt et al. (1992) determined ET rates from lysimeters located on a park and on two golf course sites. The two-year average (1988-1989) ET rate at the golf course sites (one of them irrigated according to local management (control) and the other irrigated by input from an ETc feedback system) was 59 in y^{-1} (0.16 in d^{-1}). By contrast, the park site had a two year average ET rate of 42 in y^{-1} (0.11 in d^{-1}), which was 29% lower than the golf course sites. Differences were attributed to cultural management input. In Tucson, Arizona, a study carried out using percolating lysimeters and testing high and low management treatments (simulating a highly fertilized golf course fairways and commercial lawns in the Southwest in the former case, and equivalent to minimal home lawn management for the latter case) showed no significant differences among three bermudagrasses (Kneebone and Pepper, 1982). ‘Tifgreen’, ‘Santa Ana’ and ‘Seeded’ bermudagrasses showed an average ET rate of 0.18 in d^{-1} (65 in y^{-1}) under the high management treatment. Under the low management treatment, the average ET rate was 0.14 in d^{-1} (51 in y^{-1}) for the same bermudagrass species. Another study carried out in the same location by the same authors (Kneebone and Pepper, 1984), evaluated whether luxury water use of applied irrigation occurred, and what maximum ET rates might be when excessive water was available to bermudagrass. This trial was installed from Nov 26, 1979 to Oct 25, 1980 using percolation lysimeters. Three different sand-soil mixes were prepared in the following proportions: 19:1, 18:2, and 16:4, all of them providing good infiltration and drainage. Three irrigation levels (4.5, 9.6 and 14.3 in week^{-1}) applied in increments of 2.3, 4.8 and 7.2 in twice each week were used with each sand-soil mix. Results showed that increasing the availability of water whether by irrigation level or by water holding capacity of the sand-soil mix in most cases increased ET from bermudagrass. Average ET rates were 0.17, 0.28 and 0.30 in d^{-1} (1.22, 1.92 and 2.09 in week^{-1}) for 4.50, 10 and 14.33 in wk^{-1} application rates, respectively. Average ET rates were 0.20, 0.25 and 0.30 in d^{-1} (1.41, 1.73 and 2.09 in wk^{-1}) for 19:1, 18:2 and 16:4 sand-soil mixes. The data showed that ET rates from bermudagrass turf can exceed pan evaporation by a considerable amount.

Stewart et al. (1969) studied ET rate as a function of plant density and water table depth in South Florida using Tifway bermudagrass growing in non-weighing evapotranspirometers. Depth to water table was 24 in the first year, 36 in the second, and 12 in the third year during the 3-year study. Water replacement ranged from well-watered conditions at a 12 in water table to partial stress at a 36 in water table 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 water-table depths of 24 in (from 42 in y^{-1} (0.11 in d^{-1})-full sod- to 16 in y^{-1}(0.04 in d^{-1}) -no sod-), and 36 in (from 35 in y^{-1}(0.09 in d^{-1}) -full sod- to 19 in y^{-1}(0.05 in d^{-1}) -no sod-). ET rates decreased with cover for the water table depth of 12 in (from 42 in y^{-1}(0.11 in d^{-1}) -full sod- to 46 in y^{-1}(0.13 in d^{-1}) -no sod. Evaporation from bare soil (no sod, 46 in y^{-1} (0.13 in d^{-1})), with a 48 in water table was about 11% more than from full sod cover (42 in y^{-1} (0.11 in d^{-1})) in 1967. The ground surface of this treatment was moist continuously, indicating that the capillary fringe reached the soil surface. Similar results were shown in 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. The irrigation regime imposed moderate stress on the turfgrasses (water applied at 56% plant available soil water depletion). Average ET rate was 0.12 in d^{-1} (44 in y^{-1}). Compared to other reports, the results were lower. Reasons for this disparity 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 the previous report (Garrot and Mancino, 1994). This study carried out in Arizona, from 1989 to 1991, showed that bermudagrasses varieties 'texturf-10', 'tifgreen' and 'midiron' had mean ET rates of 0.10, 0.09 and 0.09 in d^{-1} (36, 34 and 33 in y^{-1}) respectively, under infrequent irrigation regime under fairway conditions. ET rate was derived from gravimetric samples and irrigation was applied only when turf showed symptoms of wilt. The conclusions remarked that bermudagrass growing in an arid environment can be maintained under fairway condition with 33 to 36 in of water annually.

Under low management (intended to be equivalent to minimal home lawn management) in a desert area of Arizona, and using 10.8 ft^2 lysimeter boxes, tall fescue and St. Augustinegrass used significantly more water than bermudagrass and zoysiagrass (72, 65 and 52 in y^{-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 even when under a high management the quality was improved, but was not as lush as many commercial lawns. Their data indicated that normal water use in Tucson might range from 51 to 67 in y^{-1} depending upon management. About 11 in of this amount was available from rainfall in this area.

A relatively new method to estimate crop evapotranspiration in Central Florida was used by Jia et al. (2007) from July 2003 through December 2006. Crop evapotranspiration (ETc) rates were estimated for bahiagrass using the eddy correlation method, and the study was conducted under well-watered conditions. This method overcomes the need to determine each component in the water balance by using the energy balance approach (Tanner and Greene, 1989). The results of this study showed that the highest average monthly ET rate (0.17 in d^{-1}) occurred in May. The lowest average monthly ET rate (0.03 in d^{-1}) occurred in January. Another study showed that bahiagrass used 11% more water than St. Augustinegrass under well watered conditions when UF/IFAS recommendations were followed (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 stress conditions, St. Augustinegrass may be more stressed beyond the point of recovery while Bahiagrass may recover when water becomes available (Zazueta et al., 2000).

Research over the last 30 years provides a much clear understanding of turfgrass water use rates throughout U.S. Warm-season species like hybrid bermudagrass, zoysiagrass, buffalograss, and centipedegrass consumed the lowest water use rates, ranging from 0.12 to 0.35 in day^{-1}. Cool-season species like the fine-leafed fescues ranked medium, whereas Kentucky bluegrass and creeping bentgrass showed very high water use rates, with 0.14 to 0.50 in day^{-1} (Kenna, 2008). However, several studies indicated that considerable inter- and intraspecies variation exists in ET rates (Green et al., 1990a).

Table 3: Summary table showing turfgrass species mean daily evapotranspiration rate (ETo), methodology used to determine ET, water availability, and respective references.

Turfgrass species	ET rate (in d^{-1})	Study period length	Methodology & water availability	Reference/ Location
Bahiagrass	Jan (0.03) Feb (0.03) Mar (0.08) Apr (0.14) May (0.17) Jun (0.13) Jul (0.12) Aug (0.11) Sep (0.09) Oct (0.07) Nov (0.06) Dec (0.03)	July 2003 through December 2006.	Eddy correlation method. Well-watered conditions.	Jia et al., 2007 Central Florida, FL.
Tifway bermudagrass Common bermudagrass Meyer zoysiagrass Common centipedegrass Raleigh St Augustinegrass Rebel II tall fescue Kentucky-31 tall fescue (K_c values are annual values)	0.19/0.17* 0.19/0.17* 0.18/0.17* 0.17/0.16* 0.20/0.17* 0.20/0.17* 0.17/0.18*	First season: from 26 June to 10 Oct 1989 (data on the left). *Second season: from 5/4/90 to 11/2/90 (data on the right).	TDR_s Water stress conditions.	Carrow, 1995. Griffin, GA.

Turfgrass species	ET rate (in d^{-1})	Study period length	Methodology & water availability	Reference/ Location
Bermudagrass overseeded with perennial ryegrass	0.15 to 0.18[a] 0.10 to 0.12[b]	2-yr study.	[a]Lysimeter irrigated using ET feedback system. [b]Lysimeter irrigated according to local management. Both, well-watered and water stress conditions.	Devitt et al., 1992, NV.
Bahiagrass Buffalograss Centipedegrass Bermudagrass (avg. 3 cultivars) Seashore paspalum St. Augustinegrass Tall fescue	0.25 0.17 to 0.21 0.18 to 0.22 0.16 to 0.23 0.18 to 0.24 0.19 to 0.25 0.20 to 0.28	From Aug. 1982 to Sept. 1984.	Water balance method (using black plastic minilysimeter pots). Well-watered conditions.	Kim and Beard, 1988. College Station, TX.
St. Augustinegrass (mean of ten genotypes)	0.19/0.30	Individual measurements in the field in Sept. 1985, July and Aug. 1986, and Sept. 1987(value on the left). Summer 1988 under controlled-environment conditions (value on the right).	Water balance method (using black plastic minilysimeter pots). Well-watered conditions.	Atkins et al., 1991. College Station, TX.
Zoysia (mean of 11 genotypes)	0.37/0.36	Fall 1985, Summer 1986 and Summer 1987. In the field from May to Oct (value on the left) and from Nov. to April under glasshouse conditions (value on the right).	Water balance method (using black plastic minilysimeters). Well-watered conditions.	Green et al, 1991. College Station, TX.
Kentucky bluegrass Red fescue Perennial grass Hard fescue	0.14 0.14 0.15 0.12	From July to September, 1984-1985.	Water balance method (using weighing minilysimeters).	Aronson et al., 1987a. Kingston, RI.

Turfgrass species	ET rate (in d^{-1})	Study period length	Methodology & water availability	Reference/ Location
Cool-season perennial grasses: Hard fescue Creeping bentgrass Sheep fescue Chewing fescue Creeping ann.bluegrs. Kentucky bluegrass Perennial ryegrass Tall fescue Rough bluegrass Kentucky bluegrass	 0.29 0.40 0.37 0.30 0.39 0.49 0.36 0.45 0.33 0.47	ET rate measured every 24-hour.	Water balance method (using black plastic minilysimeters under controlled environment). Well-watered conditions.	Green et al., 1990a. College Station, TX.
Bermudagrass	0.25	From 11/26/79 to 10/25/80.	Water balance (using $1m^2$ lysimeters). Well-watered conditions.	Kneebone and Pepper, 1984.
Bermudagrass Zoysiagrass	0.30 0.28	From 1977 to 1979.	Water balance (using $1m^2$ lysimeters). Both, well- and water stress conditions.	Kneebone and Pepper, 1982.
Merion Kentucky bluegrass Bermudagrass Bermudagrass Merion Kentucky bluegrass Rebel tall fescue Tifway bermudagrass Common buffalograss	0.19 (a) 0.21 (b) 0.14 0.19 0.22 0.23 0.18 0.18	First experiment: From 7/13/79 to 10/4/79. Second exp.: From 6/20/80 to 8/28/80. Third exp.: From 6/8/81 to 8/16/81.	Weighing lysimeter: [(a) 2 cm mowing height. (b) 5 cm mowing height]. Values are the average of two lysimeters. Well-watered conditions.	Feldhake et al., 1983. Ft. Collins, CO.
Tifway bermudagrass (original data in in y^{-1})	 0.11 0.09 0.11 0.09 0.09 0.12 0.07 0.07 0.12	Full sod treatment: 1965 1966 1967 2/3 sod treatmnt: 1965 1966 1967 1/3 sod treatmnt: 1965 1966 1967	Non-weighing evapo-transpirometers. Water stress conditions.	Stewart et al., 1969. Ft. Lauderdale, FL.

Turfgrass species	ET rate (in d^{-1})	Study period length	Methodology & water availability	Reference/ Location
Tifway bermudagrass		5-yr average (1963-67).	Non-weighing evapo-transpirometers.	Stewart et al., 1967.
	0.12	Depth to water table: 12 in	Water stress conditions.	Ft. Lauderdale, FL.
	0.11	Depth to water table: 24 in		
	0.11	Depth to water table: 36 in		

Table 4: List of most common methodologies used by the authors to determine ETc. Turfgrass type and maximum and minimum ETc values are shown too.

Methodology	Author	Turfgrass type	ETc range (in d^{-1}) min	max
Minilysimeters / water balance				
	Aronson et al., 1987.	Cool-season	0.09	0.16
	Kim and Beard, 1988.	Cool-season	0.20	0.28
	Green et al., 1990.	Cool-season	0.29	0.49
	Bowman and Macaulay, 1991.	Cool-season	0.18	0.51
	Aronson et al., 1987.	Warm-season	0.16	0.26
	Green et al., 1990b.	Warm-season	0.09	0.46
	Atkins et al., 1991.	Warm-season	0.15	0.23
	Green et al., 1991.	Warm-season	0.09	0.41
Large lysimeters / water balance				
	Stewart and Mills, 1967.	Warm-season	0.07	0.20
	Stewart et al., 1969.	Warm-season	0.09	0.11
	Kneebone and Pepper, 1982.	Warm-season	0.25	0.35
	Kneebone and Pepper, 1984.	Warm-season	0.15	0.35
	Devitt et al., 1992.	Warm-season	0.10	0.18
Eddy correlation				
	Jia et al., 2008.	Warm-season	0.02	0.20

3.3. Turf crop coefficients

A crop coefficient (K_c) is the ratio of the crop evapotranspiration (ETc) to the potential evapotranspiration (ETo) that varies in time based on growth and horticultural practices. Once such coefficients have been generated, only estimates of ETo are required to estimate actual ET needed for scheduling irrigation for a similar climate (Devitt and Morris, 2008). 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”. In the following paragraphs, several studies on crop coefficient determination for cool- and warm-season turfgrasses are presented and discussed. Table 5 shows a summary of crop coefficient values for these studies, and Table 6 shows a list of the most used methodologies to determine reference ETo.

K_c’s 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 crop coefficient 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). In specific cases were turf species and environment were previously studied, annual average K_c can be suggested, like the recommendations of Gibeault et al. (1989) using a K_c value of 0.8 for cool-season turfgrasses and 0.6 for warm-season turfgrasses.

In this literature review, K_c values for both warm-season and cool-season turfgrasses are described and discussed. K_c data for warm-season grasses includes common and hybrid bermudagrasses, St. Augustinegrass, bahiagrass, centipedegrass, zoysiagrass, and seashore paspalum. K_c values for cool-season turfgrasses includes Kentucky bluegrass, perennial ryegrass, tall fescue, mixed grasses, shortgrass and sagebrush.

One of the most comprehensive studies provided an estimate of Penman K_c’s for various grasses grown in southeastern U.S. was presented by Carrow (1995), including ‘Tifway’ bermudagrass, ‘common’ bermudagrass, ‘Meyer’ zoysiagrass, ‘common’ centipedegrass, ‘Raleigh’ St. Augustinegrass, and both, ‘Rebel II’ and ‘Kentucky-31’ tall fescue. The study was conducted in Georgia at plot level, 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 was determined by the FAO modified Penman equation, which is described by Doorenbos and Pruitt (1984) as:

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

where, ETope is reference evapotranspiration (mm), c is adjustment factor to compensate for the effect of day and night weather conditions, 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). Crop evapotranspiration (ETc) 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. The irrigation regime imposed moderate to moderately severe stress on the turfgrass but this would be representative of most home lawn irrigation regimes; however, this approach violates the "well-watered" conditions for crop coefficient development (Allen et al., 1998). ETc was determined by the soil-water balance method. Therefore, K_c was calculated dividing ETc 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 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. 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. Monthly crop coefficient data were developed in this experiment to evaluate responses of these species to 60% and 80% of replacement evapotranspiration for water conservation; under these stressed conditions, considerable error could exist in the K_c values. K_c values 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 by multiplying pan evaporation (E_{pan}) times annual crop coefficients, Kp, that were determined from previous research using applied water and evaporation pan data:

$$\mathbf{ETc = E_{pan} \times K_p}$$

Turfgrass crop coefficients were estimated by dividing ETc and ETo. The latter was calculated using the modified Penman equation (Doorenbos and Pruitt, 1977).

Another study comparing cool-season and warm-season turfgrasses was performed by Smeal et al. (2001) in New Mexico, from 1998 to 2000. One of the objectives was to formulate turfgrass crop coefficients. The warm-season species used were bermudagrass, buffalograss and blue gramma, while the cool-season species were bluegrass, perennial ryegrass and tall fescue seeded on individual plots. Sprinkler irrigation was applied to each plot, using catch-cans to collect and measure applied water after each irrigation. Soil moisture measurements were taken using a neutron probe in depth increments of 6 and 12 inches every 10 days during the active growing season. All plots were mowed weekly to a uniform height of 2.5 to 3.0 inches (3.5 to 4.0 inches for blue gramma and gramma/buffalograss mix). Appropriate fertilization and pest management techniques were used. For the purpose of this study, the water requirement was defined as the ET measured at the location farthest away from the line-source where turf quality was judged as still acceptable (i.e. not necessarily well-watered). Turf ET per period was calculated using a soil water balance equation. Although not directly mentioned in the paper, potential evapotranspiration was computed using the Samani and Pessarakly equation (http://weather.nmsu.edu/):

$$\mathbf{ETo = 0.0135\ (KT)(Ra)(TD)^{1/2}(TC+17.8)}$$

where TD is Tmax-Tmin (^oC), TC is average daily temperature (^oC) and Ra is extraterrestrial radiation (mm day^{-1}). K_c was calculated as the ratio between actual ET to ETo. Instead of monthly K_c values, the authors presented K_c's as a function of cumulative heat units or growing degree-days (GDD). This was done 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. K_c values ranged from both 0.3 to 0.72 and from 0.15 to 0.60 for cool-season and warm-season turfgrasses, respectively. In addition, two equations for K_c calculation based on GDD were presented:

$$\mathbf{K_c = (5.75 \times 10^{-4} GDD) - (1.425 \times 10^{-7}\ GDD^2) + (1.04 \times 10^{-11}\ GDD^3)}$$

for cool-season turfgrasses, and

$$\mathbf{K_c = (0.00127 \times GDD) - (8.399 \times 10^{-7}\ GDD^2) + (1.614 \times 10^{-10}\ GDD^3)}$$

for warm-season turfgrasses.

Based on these equations, and knowing, from the authors, that base temperatures for cool-season and warm-season turfgrasses are 40F and 60F, respectively, monthly K_c values were estimated using average monthly temperature from the area (http://www.weather.com). GDD were estimated. For cool-season turfgrasses, March was the month with the lowest K_c value (0.05) and July was the month with the highest value (0.72). Dormant conditions occurred from October to February. For warm-season turfgrasses, June showed the lowest K_c value (0.28) and August the highest (0.60). It seems that dormancy occurred from October to April.

Another study using bahiagrass '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 rates, under well-watered conditions. ETo was calculated using the standardized reference evapotranspiration equation. Monthly K_c values were low in the winter time because of the dormant grass status, and high in the summer time, although the K_c values also decreased in the summer time from peak values in May. The multiannual average K_c value was minimum in January (0.35) and maximum in May (0.90). Jia et al. (2007) also calculated turfgrass K_c values for southern Florida using Stewart and Mills (1967) Ft. Lauderdale, FL water use data for two warm-season grasses. Reference ET values were calculated using climate data for Miami, FL (USDC, 2007) where the daily average solar radiation values were estimated using Hargreaves' equation (Allen et al., 1998). The results showed that calculated K_c values for southern FL were higher than those in north Florida, especially in winter months. The reason of this difference is likely due to growing conditions persisting all year in the southern part of the state, with higher temperatures along the year compared to north Florida. The K_c value was maximum in May (0.99) and minimum in December (0.70). Another study in the southern area of Florida, the water budgets of a monoculture St. Augustinegrass 'Floratam' and an alternative ornamental landscape were compared (Park and Cisar, 2006). ETa was determined by a water balance equation and ETo was estimated using the McCloud method. Low Kc values were obtained, probably because the McCloud method was developed empirically for and not accurate outside the climatic conditions of Gainesville.

A study carried out in the humid northeast (Rhode Island) using Kentucky bluegrass (‘Baron’ and “Enmundi’ varieties), red fescue, perennial ryegrass and hard fescue under well-watered conditions during 1984 and 1985 showed that the mean crop coefficients ranged from 0.97 for hard fescue to 1.05 for ‘Baron’ Kentucky bluegrass (Aronson et al., 1987a). 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:

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

where ETo is reference crop evapotranspiration in J m^{-2} day^{-1}; Δ is the slope of the vapor pressure – temperature curve in kPa/^oC; γ is the psychometer constant in kPa/ ^oC; 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 overseeded with perennial ryegrass was presented by Devitt et al., 1992. Two vacuum-drained lysimeters were installed at two golf courses and at a park in Las Vegas, NV. Each site was equipped with an automated weather station. One lysimeter was irrigated according to local management and the other lysimeter irrigated by input from an ET feedback system. 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. 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 soil type and water quality were similar at each site, as well as mixed grasses, differences were attributed to cultural management input. The park turf was simply stressed due to less water received by irrigation, compared to the golf sites. As a consequence, ETc was much lower at the site park than the golf 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 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 ETc 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) as shown in equation 4 (section 3.2.1). Adequate plant nutrition and irrigation were provided to the turfgrasses. For warm-season overseeded bermudagrass, a minimum K_c occurred in June (0.78) and a maximum K_c in September (0.83). A constant K_c of 0.8 would be effective for estimating ETc during the summer months, but not for non-overseeded bermudagrass, which has extended periods of slow growth and lower ETc during the spring and fall. Monthly K_c's for cool-season overseeded 'Froghair' intermediate ryegrass varied from 0.78 (Jan) to 0.90 (Apr), which showed that winter K_c's were dependent upon temperature. Another study reporting K_c values for Tifgreen and Midiron hybrid bermudagrasses, and Texturf-10 common bermudagrass 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 conducted only when the turf showed symptoms of wilt. Time periods between irrigation events were referred to as soil dry down cycles (DDC). ET rate was determined using two methods: (i) through the determination of gravimetric soil moisture from soil cores (0 to 36 in depth, using 12 in 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, but average K_c values under their conditions 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. 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.

A similar experiment applying deficit irrigation but using cool-season turfgrasses was presented by Ervin and Koski (1998) in Colorado. Kentucky bluegrass (KBG) and tall fescue (TF) 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.

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, shortgrass, and sagebrush-grass. 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 in South Dakota, Wyoming and Idaho. The K_c values were relatively constant among the three study sites and over most of the growing season ranging from 0.75 to 0.90. 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.

Another factor contributing to the variation in K_c values is the differing computation procedures used by the various researchers to estimate ETo. Recently, the FAO and ASCE have identified this disparity in ETo computation procedures and have recommended using a standardized computation procedure based on the Penman-Monteith Equation to ensure uniform estimates of ETo (Allen et al., 1998).

Table 5: Summary chart showing turfgrass species, K_c, methodology used to determine K_c and respective references.

Turfgrass species	K_c	Study period length	Methodology & water availability	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. ETref: ASCE-EWRI equation (Allen et al.,2005) K_c: ETc/ETo. Well-watered conditions.	Jia et al., 2009. Central Florida, FL.

Turfgrass species	**K_c**	**Study period length**	**Methodology & water availability**	**Reference/ Location**
St. Augustinegrass + Bermudagrass	Jan (0.71) Feb (0.79) Mar (0.78) Apr (0.86) May (0.99) Jun (0.86) Jul (0.86) Aug (0.90) Sep (0.87) Oct (0.86) Nov (0.84) Dec (0.71)	5 years.	ETc: data from Stewart and Mills, 1967 (5-yr average montly data). ETref: Hargreaves equation (Allen et al., 1998) using data for Miami. Water stress conditions.	Jia et al., 2009 (using 5-yr average monthly ETc data from Stewart and Mills, 1967 for South Florida.
Overseeded froghair ryegrass (Nov-May) – Winter (3-yr avg.) Tifway bermudagrass (Jun-Sept) – Summer (3-yr avg.)	Nov (0.82) Dec (0.79) Jan (0.78) Feb(0.79) Mar (0.86) Apr (0.90) May (0.85) Jun(0.78) Jul (0.78) Aug (0.82) Sep (0.83)	Nov. 1994 to Sept. 1997.	ETc: lysimeters (water balance) ETo: simplified FAO Penman-Monteith equation (ASCE equation., Allen et al., 1994, 1998, 2005). K_c: ETc/ETo. Well-watered conditions.	Brown et al., 2001. Tucson, AZ.
Cool-season (bluegrass, perennial ryegrass and tall fescue) Warm-season (bermudagrass, buffalograss and blue grama)	Mar (0.05) Apr (0.20) May (0.44) Jun (0.64) Jul (0.72) Aug (0.69) Sep (0.64) Oct (0.61) Jun (0.28) Jul (0.54) Aug (0.60) Sep (0.59)	1998 to 2000.	ETc: soil water balance equation ETo: Samani and Pessarakli (1986) equation. Field experiment K_c: ETc/ETo. Water stress conditions.	Smeal et al., 2001. Farmington, NM.
Kentucky Bluegrass Tall fescue	0.60 to 0.80 0.50 to 0.80	1993 to 1994.	ETr: (Kimberly-Penman combination eq.(Jensen et al., 90). Eta: 80% ETr K_c: ETa/ETr Water stress conditions.	Ervin and Koski, 1998. Fort Collins, CO.

Turfgrass species	K_c	Study period length	Methodology & water availability	Reference/ Location
Tifway bermudagrass Common bermudagrass Meyer zoysiagrass Common centipedegrass Raleigh St Augustinegrass Rebel II tall fescue Kentucky-31 tall fescue K_c values are annual	0.67 0.68 0.81 0.85 0.72 0.79 0.82	First season: from 26 June to 10 Oct 1989 (data on the left). Second season: from 5/4/90 to 11/2/90 (data on the right).	ETc: soil moisture content (TDR_s) during dry-down periods when no drainage occurred. ETref: FAO Penman equation (Doorenboos and Pruitt, 1984). K_c = ETc/ETo Water stress conditions.	Carrow, 1995. Griffin, GA.
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: Modified daily Penman combination equation (Jensen, 1973). K_c = ETc/ETo. Both, well-watered and water stress conditions.	Devitt et al., 1992. Las Vegas, NV.
Hybrid and common Bermudagrass: Texturf-10 Tifgreen Midiron	 0.64 0.60 0.57	1989 to 1991. These are annual K_cs.	Water use determined by gravimetric method. ETc=actual water use ETo=(mod. Penman, Doorenboos and Pruitt, 1977). K_c = ETc/ETo. Water stress conditions.	Garrot and Mancino, 1994. Tucson, AZ.
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 (Jensen and Haise, 1963).Well-watered conditions.	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. ETo: Modified Penman equation (Burman et al., 1980). K_c: ETa/ETo. Well-watered conditions.	Aronson et al., 1987a. 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.	ETc: 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 (Doorenboos and Pruit, 1977). Water stress conditions.	Meyer et al., 1985. 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)	Aug. 1981 to Dec. 1983.	ETc: 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 (Doorenboos and Pruit, 1977). K_c: ETc/ETo. Water stress conditions.	Meyer et al., 1985. Riverside, CA.

Table 6: List of common methodologies used by the authors to determine reference ET. K_c range Turfgrass type and maximum and minimum ETc values are shown too.

Equation used	Author	Turfgrass type	K_c range min	K_c range max
ASCE equation				
	Jia et al., 2009 (North FL).	Warm-season	0.35	0.90
	Jia et al., 2009 (using data from Stewart and Mills, 1967, South FL).	Warm-season	0.70	0.99
	Brown et al., 2001.	Warm-season	0.78	0.82
		Cool-season	0.78	0.90
Penman /Modified Penman				
	Erwin and Koski, 1998.	Cool-season	0.50	0.80
	Carrow, 1995.	Cool-season	0.79	0.82
	Aronson et al., 1987a.	Cool-season	0.72	1.23
	Meyer and Gibeault, 1987.	Cool-season	0.60	1.04
	Carrow, 1995.	Warm-season	0.67	0.85
	Garrot and Mancino, 1994.	Warm-season	0.57	0.64
	Devitt et al., 1992.	Warm-season	0.43	0.89
Samani and Pessarakli				
	Smeal et al., 2001.	Cool-season	0.05	0.72

3.4. Water use affected by turfgrass characteristics and environmental factors

Turfgrass ET rates vary among species and cultivars within species. Inter- and intra-specific variations in ET 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 increased emphasis on developing new varieties which require less water, are more tolerant to heat, cold, or salinity stresses or improved disease or insect resistance (Kenna, 2006).

Some of the 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). Other studies also recommend the use of infrequent irrigation for better turfgrass quality (Bennett and Doss, 1960; Zazueta et al., 2000), because excessive irrigation, which keeps the root system saturated with water, can be harmful to the lawn (Trenholm et al., 2001).

Both, turfgrass quality and resistance to drought is of primary interest to turfgrass managers as a result of irrigation practices. In a study using warm-season grasses common bermudagrass, centipedegrass, zoysiagrass and seashore paspalum, Huang et al. (1997) tested four soil moisture treatments: (i) a control, water content in the entire soil profile kept at field capacity; (ii) upper 8 in soil drying while the lower 16 in segment was maintained at field capacity, (iii) upper 16 in soil drying, while the lower 8 in segment was kept at field capacity and (iv) a rewatering treatment. AP14 and PI 299042 paspalum (the former a Floridian ecotype), and TifBlair centipedegrass produced higher total root length (TRL) in the entire soil profile. Rewatering caused further shoot growth recovery of the three previous ecotypes, but only partial recovery was observed for Zoysiagrass, bermudagrass and Adalayd paspalum. TRL declined significantly with the soil drying treatments for zoysiagrass and bermudagrass, but paspalum ecotypes were not affected by the treatments. Drought resistance of PI 509018 paspalum was equal to tifblair Centipedegrass but higher than AP14. The least resistant were Zoysiagrass, followed by bermudagrass and Adalayd paspalum. Youngner et al. (1981) showed in two consecutive studies set up in California, the first one for two warm-season grasses (St. Augustinegrass and common bermudagrass) and, the second one using two cool-season grasses (‘Alta’ tall fescue and ‘Merion’ Kentucky bluegrass), the effect of five irrigation treatments: (i) a control based on common practice; (ii) irrigation based on evapotranspiration from a pan, and (iii) three automatic irrigations activated by tensiometers at different settings, with the objective to develop guidelines for turfgrass irrigation practices. The field study, consisting of 20-by-20-ft plots containing two turf varieties, had four replications and subjected to sprinkler irrigation. St. Augustinegrass quality was good under all treatments, as well as bermudagrass. Mean maximum root depth across all treatments were higher for bermudagrass than for St. Augustinegrass, but no differences among the treatments for either species. Kentucky bluegrass used less water than tall fescue. The studies showed that tensiometers and evaporation pans were effective irrigation guides, saving significant amount of water as a result. Variation in turf quality occurred frequently but was difficult to relate each to a specific irrigation treatment.

Increased mowing height and amount of top growth can be expected to increase evapotranspiration by increasing the roughness of the plant canopy surface, by increasing the capacity for absorbing advective heat and by increasing root growth, which results in a greater soil water source to exploit (Kneebone et al., 1992). Most data on mowing height effect is observed with cool-season grasses. Within warm-season grasses, zoysiagrass, buffalograss and centipedegrass showed increased ETc rates at optimum heights of cut (Kim and Beard, 1984). Also, any cultural practice that increases leaf surface area, internode length and leaf extension (i.e. nitrogen [N] fertilization), is expected to increase water use. Feldhake et al., (1983) reported a 13% higher ETc rate for Kentucky bluegrass in Colorado when 8.8 lb/1196 yd^2 of N was applied each month during spring and summer compared with only one application for the season, applied in spring. Also, soil compaction may affect ETc more than N source or N rates, since it may not allow the root system to function adequately due to the poor soil aeration, platy massive soil structure and low infiltration rates, which results in reduced water holding capacity of the soil (Huang, 2006).

3.5. Ornamental plants water needs overview

Reliable research-based data on landscape plants water requirements is very limited, with few sources of information offering quantitative estimates (Pittenger and Shaw, 2005), including the widely-referenced publication, Water Use Classification of Landscape Plants –WUCOLS- (Costello and Jones, 1999) which is not based on scientific field research. One of the main reasons why there is little availability of scientific information is the large number of plant species, and the substantial resources needed to identify the water requirements of an individual species. WUCOLS is a list intended as a guide to help landscape professional identify irrigation water needs of landscape species or for selecting species and to assist in developing irrigation schedules for existing landscapes. This guide provides irrigation water needs evaluation for over 1,900 species used in California landscapes, based on the observations and field experience of 41 landscape horticulturists in California. Water needs categories assigned for each species were determined by consensus of the committee. These categories are: high (70-90% ETo), moderate (40 -60% ETo), low (10-30% ETo) and very low (<10% ETo). Assignments were made for each of six regions in California: region 1: North-Central coast; region 2: central valleys; region 3: south coastal; region 4: south inland valleys and foot hills; region 5: high and intermediate desert; region 6: low desert. All of these regions are based on different climate zones in California. Each plant of the species list falls into one or more of the following vegetation types: trees (T), shrub (S), groundcovers (Gc), vines (V), perennial (P) and biennals (Bi). Cultivars with some exceptions are not mentioned. Turfgrasses were not evaluated by the committee, although WUCOLS includes a list of irrigation requirements for turfgrasses from the University of California ANR public 24191: Turfgrass ET map, central coast of California. However, this list has some limitations. It is also subjective (based on field observations rather than scientific data);

it is a partial list since not all landscape species are included, and last, not all regions of California are included in the evaluations.

3.5.1. Ornamental plants evapotranspiration in Florida

Erickson et al. (2001), carried out an study in Florida, comparing nitrogen runoff and leaching between a turfgrass landscape (St. Augustinegrass) and an alternative residential landscape which included twelve different ornamental ground covers, shrubs, and trees (50% native from Florida). The ornamental species used were the same as those used in the two studies previously described. ETc was determined for each landscape treatment based on rainfall, irrigation, and percolate data measured during the experiment. The mean dry season ETc was estimated to be 1.72 and 0.83 in month^{-1} for both St. Augustinegrass and mixed-species, respectively, while the mean wet season ETc was 4.11 in mo^{-1} and 3.82 in mo^{-1} for the same landscapes. With these data, the estimated total annual ETc for the turfgrass landscape would be 35 in y^{-1} and for the ornamental landscape 28 in y^{-1}.

ETc and K_c values of *Viburnum odoratissimum* (Ker.-gawl) grown in white and black multi-pot box system (MPBS) were measured in Florida during summer and fall (Irmak, 2005). From a previous study (Irmak et al., 2004) it was reported that the plants grown in the white MPBS had significantly higher growth rates and plant biomass production, since the black MPBS had heat induced stress caused by high root-zone temperatures. In summer, the measured ETc ranged from 12.12 to 13.15 in for the black and white MPBS plants, respectively; in fall, it ranged from 13.62 to 13.81 in for the black and white MPBS plants, respectively. K_c values of plants growing in the black and white MPBS ranged from 0.64 to 1.29, respectively, during the summer and K_c values ranged from 0.55 to 1.68 for the black and white MPBS, respectively, during the fall. For both seasons, the highest K_c values were obtained at the end of the growing season.

A study carried out in Florida using *Viburnum odoratissimum* (Ker.-gawl), *Ligustrum japonicum* Thunb., and *Rhaphiolepsis indica* Lindl. growing into 3 gal containers for 6 months were irrigated under different irrigation regimes consisting of an 0.7 in daily control and irrigation to saturation based on 20%, 40%, 60% and 80% deficits in plant available water (management allowed deficits – MAD) (Beeson, 2006). The results recommended 20%, 20% and 40% MAD for the previously mentioned woody ornamentals, respectively, for commercial production. The actual evapotranspiration for these results were 25% lower than the control conditions for *Viburnum odoratissimum* (Ker.-gawl) (33 vs 43 gal); 28.9% higher than the control conditions for *Ligustrum japonicum* Thunb. (36 vs 28 gal) and 10.4% higher than the control conditions for *Rhaphiolepsis indica* Lindl. (23 vs 20 gal).

4. Estimating water needs for landscape plantings

The irrigation requirements are well established for agricultural crops; however, in urban landscapes, irrigation requirements have been determined for many turfgrasses but not for most landscape species. Landscape irrigation increases dramatically during summer months and contributes substantially to peak demand placed on municipal water supplies, and outdoor water use may account for 40 to 60% of residential water consumption (White et al., 2004). Estimates of landscape water needs are important to preserve water resources, to keep the landscape quality and to save money. Water is a limited natural resource that needs to be supplied according to the plant needs and so money can be saved since water costs continue to increase. The potential for plant injury caused by water deficits or excess can be minimized by identifying plant water needs (Costello et al., 2000).

The prediction of water use in landscapes with multiple plant species is still incipient and has just started (Havlak, 2003). There is a system of estimating irrigation water needs of landscapes, based on reference evapotranspiration (ETo) and a landscape coefficient (K_L) which is a function of a species factor (k_s), microclimate factor (k_m) and a density factor (k_d) which has been developed and is currently being updated in California (Costello et al., 2000). However, this method includes information that is based on research and on field experience (observation) and readers are advised for some subjectivity in the method, and estimations of water needs are not exact values. Another methodology has been proposed by Eching and Snyder (2005) where the landscape coefficient (K_L) estimation considers a species (K_s), microclimate (K_{mc}), vegetation (K_v), stress (K_s) and an evaporation (K_e) factors. This method includes a computerized program called LIMP.XLS which is able to calculate ETo rates, determine landscape coefficient (K_L) values, estimate landscape evapotranspiration (ET_L) and determine irrigation schedules at daily basis. Finally, White et al. (2004) proposed to find a relationship between ETc and ETo for a multiple plant species landscape to calculate a landscape coefficient for use in the development of residential water budgets.

4.1 The Landscape Coefficient Method

The Landscape Coefficient Method (LCM) describes a method of estimating irrigation needs of landscape plantings in California on a monthly basis. It is intended as a guide for landscape professionals. The assignment of species coefficients was done by asking members of a committee to place the species under different water use categories and no actual field measurements support the values given in the study (Garcia-Navarro et al., 2004). Readers are advised that LCM calculations give estimates of water needs, not exact values, and adjustments to irrigation amounts may be needed in the field (Costello et al., 2000). Water needs of landscape plantings can be estimated using the landscape evapotranspiration formula:

$$\mathbf{ET_L = (K_L)\,(ETo)} \tag{4}$$

where landscape evapotranspiration (ET_L) is equal to the landscape coefficient (K_L) times reference evapotranspiration (ETo). The ET_L formula differs from the ETc formula since the crop coefficient (K_c) has been substituted for the landscape coefficient (K_L). This change is necessary because of important differences which exist between crop or turfgrass systems and landscape plantings.

4.1.1. The landscape coefficient formula

Costello et al. (2000) pointed out the reasons why there must be a landscape coefficient: 1) because landscape plantings are typically composed of more than one species, 2) because vegetation density varies in landscapes and 3) because many landscapes include a range of microclimates. These factors make landscape plantings quite different from agricultural crops and turfgrasses and they need to be taken into account when making water loss estimates for landscapes. The landscape coefficient estimates water loss from landscape plantings and functions as the crop coefficient but not determined in the same way. Species, density and microclimate factors are used to calculate K_L.

$$\mathbf{K_L = (k_S)\,(k_d)\,(k_{mc})} \tag{5}$$

By assigning numeric values to each factor, a value of K_L can be determined. The selection of each numeric value will depend on the knowledge and gained experience of the landscape professional, which make the method largely subjective.

4.1.2. The landscape coefficient factors

The species coefficient (k_s): This factor ranges from 0.1 to 0.9 and are divided into 4 categories, very low, low, moderate and high. These species factor ranges apply regardless of vegetation type (tree, shrub, herbaceous) and are based on water use studies, and from agricultural crops. Relative water need requirements for plants have been completed for over 1800 sp (see the water use classifications of landscape species -WUCOLS III- list).

The density coefficient (k_d): This factor is used in the landscape coefficient formula to account for differences in vegetation density among landscape plantings. This factor is separated into three categories: low (0.5–0.9), average (1.0) and high (1.1–1.3). Immature and sparsely planted landscapes, with less leaf area, are assigned a low category k_d value. Planting with mixtures of trees, shrubs and groundcovers are assigned a density factor value in the high category. Plantings which are full but are predominantly of one vegetation type are assigned to the average category.

The microclimate coefficient (k_{mc}): This factor ranges from 0.5 to 1.4 and is divided into three categories: low (0.5–0.9), average (1.0) and high (1.1–1.4). An 'average' microclimate condition is equivalent to reference ET conditions: open-field setting without extraordinary winds or heat inputs atypical for the location. In a 'high' microclimate condition, site features increase evaporative conditions (e.g. planting near streets medians, parking lots). 'Low' microclimate condition is common when plantings are shaded for a substantial part of the day or are protected from strong winds.

4.1.3. Irrigation efficiency and calculating the total amount of water to apply

The ET_L formula calculates the amount of irrigation water need to meet the needs of plants; however, this is not the total amount of water needed to apply. The landscape will require water in excess of that estimated by ET_L since every irrigation system is inefficient to some degree. The total amount or water needed for a landscape planting is calculated using the following formula, in spite of the method use to determine irrigation efficiency:

$$\mathbf{TWA = ET_L/IE} \tag{6}$$

Where TWA = Total Water Applied, ET_L = Landscape Evapotranspiration and IE = Irrigation Efficiency. Just note that the IE factor needs to be addressed carefully when planning and managing landscapes.

5. Discussion and Conclusions

As a group, warm-season turfgrasses have lower ETc rates than cool-season turfgrasses. Within warm-season grasses, species ETc rates ranged from 0.07 to 0.30 in d^{-1} (bermudagrass), 0.03 to 0.25 in d^{-1}in d^{-1} (bahiagrass), 0.16 to 0.22 in d^{-1} (centipedegrass), 0.17 to 0.21 in d^{-1} (buffalograss), 0.17 to 0.30 in d^{-1} (St. Augustinegrass), 0.18 to 0.24 in d^{-1} (seashore paspalum) and 0.17 to 0.37 in d^{-1} (Zoysiagrass). Kentucky bluegrass exhibited very high water use rates (as high as 0.49 in d^{-1}), followed by tall fescue (0.14 to 0.45 in d^{-1}), bentgrass (max. of 0.40 in d^{-1}), and hard fescue (0.12 to 0.37 in d^{-1}). However, it is difficult to establish and recommend a minimum and maximum rate for a specific species since the results are mixed due to climatic and methodology differences in water use determination. However, it does appear that in general cool-season turfgrasses use more water than warm-season but that in some cases warm-season grass water use may approach cool-season water use rates under non-limiting water conditions. Results from Jia et al. (2009), Brown et al., (2001), Devitt et al. (1992), Atkins et al. (1991), Green et al. (1991) and Kneebone and Pepper (1982) showed high ETc values for warm-season turfgrasses; these experiments were set under well watered conditions or under high management treatment (high fertilization rates and non-limiting soil moisture), which makes the results reliable since the plants had no water stress at all.

Differences in reference evapotranspiration estimation impact many of the reviewed K_c values; however, the Penman methods will likely agree the closest. A number of studies used slightly stressed turfgrass, due to either dormancy or water stress, conditions for K_c development and these values should be avoided. For example, Jia et al. (2009) showed monthly K_c values varying from very low in December (0.35) to high in summer (0.90). This difference was because K_c was estimated over dormant as well as growing turfgrass. Compared to other results where turf K_c values were estimated during growing periods, these K_c values looked too low for a turfgrass K_c. However, the annual range of values given by Jia et al. (2009) are appropriate for estimation of annual water needs.

Minimum and maximum K_c values ranged between 0.05 to 1.23. As for ETc, K_c values were higher for cool-season grasses. However, under well watered conditions, warm-season grasses showed high Kc values that did approach those shown by cool-season grasses. In general, all turfgrasses had substantial changes in crop coefficient values over the time 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.

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.

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 impacted the K_c values.

In contrast to turfgrasses, ornamental water requirements data are very scarce and most of the available data is not direct water use determination studies. The landscape coefficient method is presented here as a methodology to estimate a landscape coefficient (K_L). K_L multiplied by a reference evapotranspiration (ETo) could give an estimate of the water requirement for a specific group of plants in a determined location. However, this methodology is very subjective.

6. Acknowledgements

The authors want to thank the South West Florida Water Management District for funding the development of this review.

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