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# Efficient Irrigation for Recreational Turfgrass in New England: Evapotranspiration and Crop Coefficients

James W. Poro
*University of Massachusetts Amherst*

# EFFICIENT IRRIGATION FOR RECREATIONAL TURFGRASS IN NEW ENGLAND: EVAPOTRANSPIRATION AND CROP COEFFICIENTS

A Thesis Presented

By

JAMES W. PORO

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Approved as to style and content by:

J. Scott Ebdon, Chair

Michelle DaCosta, Member

Paul Brown, Member

Geunhwa Jung, Graduate Program Director

# DEDICATION

I would like to dedicate this thesis to my supportive girlfriend Allie, and her cat Pringle. You are the most supportive person I know. Without your temperance and genuine belief in my capabilities, I would not have finished this body of work nor continually strive to better myself.

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## ABSTRACT

## EFFICIENT IRRIGATION FOR RECREATIONAL TURFGRASS IN NEW ENGLAND: EVAPOTRANSPIRATION AND CROP COEFFICIENTS

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JAMES PORO, B.S., UNIVERSITY OF MASSACHUSETTS AMHERST

M.S., UNIVERSITY OF MASSACHUSETTS AMHERST

Directed by: Dr. J. Scott Ebdon

As water demand increases it will become more imperative for golf course superintendents, landscape managers, and other industry professionals to improve water use efficiency in the management of recreational turfgrass. Scheduling irrigation according to actual turfgrass evapotranspiration rates ($ET_T$) is an integral component of efficient irrigation practices. Impracticality of field derived $ET_T$ for industry use, however, directs the need of weather station derived reference (predicted) evapotranspiration ($ET_0$). To accurately predict (estimate) $ET_T$ of turf and other crops, scientifically derived landscape (crop) coefficients ($K_c$ values) are used in conjunction with mathematical models that incorporate local meteorological data. Research is limited, however, in identifying $K_c$ values and subsequent $ET_0$ for turfgrass species selected and maintained under high intensity recreational practices congruent of golf courses and sports fields in the cool-humid northeast climate. Therefore, objectives of this study were to (i) observe and record $ET_T$ of three commonly selected recreational turfgrass species; 'Exacta' Perennial ryegrass (*Lollium perenne* L.), 'Touchdown' Kentucky bluegrass (*Poa pratensis* L.), and 'Memorial' Creeping bentgrass (*Agrostis stolinifera* L.) maintained as

golf and sports turf, (ii) analyze the impact various management practices (nitrogen fertility and height of cut) have on $ET_T$, (iii) develop accurate $K_c$ values appropriate for use with the recommended FAO 56 Penman-Monteith mathematical model for accurate $ET_0$ of recreational turf maintained in the cool-humid northeast.

Four heights of cut (HOC) and two nitrogen fertility rates (N) were evaluated to determine their impact on turfgrass growth and subsequent water use and $ET_T$ of three recreational turfgrass species. Golf turf (creeping bentgrass) maintained at a lower height of cut than sports turf exhibited a smaller leaf area component and a significantly lower (20%) $ET_T$. N applied as slow release (82%) throughout the growing season increased $ET_T$ by 5%, particularly with perennial ryegrass sports turf. Taller HOC also increased $ET_T$ by 10% due to increased leaf area indices and subsequent decreased resistance to ET. Predicted $ET_0$ according to FAO 56 for all three years of the study (79 observations) captured 71% of $ET_T$. Yearly and monthly calculations suggest less variable (cloudy) weather yielded more accurate $ET_0$. Crop coefficient ($K_c$) values established in conjunction with FAO 56 $ET_0$ ranged from 0.90 to 1.00 for shorter golf course turf (creeping bentgrass), and 1.15 to 1.25 for taller sports turf (Kentucky bluegrass and perennial ryegrass). Results indicate shorter grass exhibits a lower $ET_T$ than taller grass due to various factors, and in the case of industry application, FAO 56 $ET_0$ can accurately estimate $ET_T$ of recreational turf in the cool-humid northeast when fitted with appropriate $K_c$ values.

## TABLE OF CONTENTS

Page

## LIST OF TABLES

Tables Page

## LIST OF FIGURES

Figures Page

# CHAPTER 1

# LITERATURE REVIEW

## Introduction

Water use will continue to be a fundamental concern of turfgrass managers as availability and restrictions further limit recreational and residential water use. Recreational turfgrass including golf courses and sports fields, as well as manicured landscapes comprise large areas of land and can require significant amounts of water to maintain acceptable quality, function, and overall survival and persistence. Both sports facilities and golf courses provide numerous economic and environmental advantages to their local communities including employment, physical activity, community aesthetics, and local revenues. Golf courses alone account for over 44% of the turfgrass industry (Haydu et al., 2008), and are directly responsible for nearly half a million jobs in the United States. Managing such facilities, however, demands extensive inputs, particularly water.

According to the United States Environmental Protection Agency (EPA) over 26 billion liters of water (approximately 30% of total national water use) is for outdoor use, specifically in the maintenance of landscapes. Golf courses alone account for over 607,500 million hectares of irrigated turfgrass in the United States (Environmental Institute for Golf, 2009). Maintaining greens, tees and fairways requires extensive inputs throughout the growing season, specifically high volumes of water. To remain economically competitive while simultaneously preserving and maximizing water use efficiency, turfgrass facilities need to develop and implement effective irrigation practices. Recreational turfgrass managers will continue to see water use limitations and restrictions as drought conditions continue to expand in both frequency and geographically throughout the United States. As of September 2012, the National Oceanic and Atmospheric Administration (NOAA) reported that 64% of the contiguous United States was still experiencing drought conditions. These areas persist into the northeast where turfgrass managers are becoming more familiar with chronic drought conditions and limiting water availability.

Irrigation is one of the largest and most costly inputs associated with turfgrass systems, identified as a primary expenditure of golf course maintenance budgets, including associated materials, labor, maintenance, and implementation (Carrow, 2005). It is estimated golf courses in the United States require in excess of seven billion liters of water per day to maintain (Environmental Institute for Golf, 2009). Many golf courses and municipalities rely on local and state water supplies for their irrigation needs, which can come at high price, specifically in areas where water availability may be limited. Minimizing wasteful water use is of both an environmental and financial interest to turfgrass managers.

## Evapotranspiration (ET)

Water conservation is a growing concern among the public community, with recreational water use identified as a major proponent of waste and as a means to lower overall water consumption (Sass and Horgan, 2006). Improving water conservation practices while maintaining acceptable turfgrass quality and economic viability will continue to be a driving factor in the turfgrass industry (Carrow, 2005). Quantifying the water needs of recreational turfgrass is a major objective of an industry effort to reduce overall water consumption. Incorporating accurate measurements of the simultaneous water loss through plant transpiration and soil evaporation (collectively termed evapotranspiration) into an irrigation program is an essential part of a successful, more efficient irrigation program. In a crop such as turfgrass, where the turf's canopy covers the soil surface, water loss as transpiration is the dominant process in ET because of high leaf area and 100% shading of the soil surface; leaf area index (LAI) for mowed turf (3.1 cm height of cut) ranges from 3 to 5 for Kentucky bluegrass (*Poa pratensis* L.) and perennial ryegrass (*Lolium perenn*e L.) (Brede and Duich, 1986). Similar ranges in LAI have been reported for mowed warm-season turfgrass such as zoysiagrass (*Zoysia japonica* Steud.) (Erickson and Kenworthy, 2011).

Scheduling irrigation according to actual turfgrass water use rates reduces waste by replacing only the amount of water lost from the rootzone to turfgrass use. Adequate irrigation amounts are vital to maintaining the function and vigor of recreational turf. The detrimental effects of over-irrigating and under-irrigating are a major concern with maintaining the economic viability of golf courses, sports fields and manicured landscapes. Excessive irrigation of turfgrass in greater quantity and frequency, has been associated with increased leaching of nutrients (Petrovic, 1990), susceptibility to disease such as dollar spot (*Sclerotinia homoeocarpa*) (Jiang et al., 1998; Qian and Engelke, 1999), reduced root growth (Madison and Hagen, 1962; Qian and Fry, 1996; Lanier et al., 2012) as well as the loss in wear tolerance (Beard, 1973), vigor, and overall health (Jordan et al., 2003). Conditions such as excessive soil compaction and thatch development that promote irrigation runoff and practices including a closer height of cut

(HOC) and higher N that inhibit root growth and soil water acquisition complicate irrigation practices and increase irrigation requirements. These conditions and practices, which are generally associated with recreational turf, promote inefficient irrigation and plant water use (Fry and Huang, 2004).

## Factors Affecting Turfgrass Evapotranspiration ($ET_T$)

Golf courses and sports fields consist of highly maintained grassy areas that exhibit a growth habit and morphological appearance different from less intensely managed lawns and parks. Golf and sport grass require higher shoot density and verdure (green biomass) for all important cushioning and associated protection that is afforded to the plant and athlete are under foot and vehicular traffic. As such, when compared to lawn grass, optimal vigor and function for recreational turf requires (i) higher uniformity and density provided by shorter HOC and frequent mowing, (ii) higher N for sustained leaf turn-over, and (iii) higher irrigation amounts maintained near or at field capacity (non-limiting soil moisture) for sustained growth (and ET) for optimal wear tolerance and recovery. Deficit irrigation practices (irrigating at less than 100% of ET replacement) have practical water conservation benefits for many turf uses with water savings ranging from 20 to 40% in lawn turf (Meyer et al., 1985; Feldhake et al., 1984) and golf course fairway turf (DaCosta and Huang, 2006) to as high as 80% water savings (Fu et al., 2007). However, deficit irrigation replacement levels (moisture limiting conditions) can impact on wear tolerance and recovery of recreational turf by reducing shoot growth and ET. The reduction in ET and associated loss in transpirational cooling has been shown to be equivalent to a 1.7 °C rise in leaf temperature for each 10% decrease in irrigation (Feldhake et al., 1984), and therefore can diminish turf function under traffic.

Evapotranspiration from the plant and leaf surface to the bulk air can be expressed in its simplest form according to Ohm's Law analogy as:

$$ET = \frac{-(e_s - e_a)}{r_t} \quad \text{[Equation 1]}$$

where ET is evapotranspiration, $e_s$ and $e_a$ represent the vapor pressure (g $m^{-3}$) of air in the interior leaf and air above the canopy, respectively, and their difference representing the vapor pressure deficit (VPD) of air. The total of all resistances along the pathway from leaf-to-air is denoted as $r_t$ and is expressed as sec $m^{-1}$. Total resistance ($r_t$) along the pathway can be expressed in different forms, as discussed below, but the fundamental process is critical to understanding the rate of water loss from the turfgrass systems and how species and cultivars as well as cultural practices such as fertility, HOC and irrigation influences actual ET loss from turf. Furthermore, these same fundamental resistances and VPD controlling actual ET from turf are the basis of mathematical models [net solar radiation ($R_n$) plus aerodynamic (resistance, $r_a$) components or combination equations] used to predict actual turf ET using meteorological (climatic) data. Weighing lysimeters (i.e., water balance method; Sharma, 1985), however, is the most reliable method for estimating the actual ET of the crop ($ET_T$).

Lysimetry is the basis of developing reliable research results and for determining true (measured) estimates of water use in agricultural systems. While lysimetry is the measure of the crops true ET ($ET_T$) for establishing efficient irrigation practices, lysimetry is labor intensive and not very practical for scheduling irrigation events in the field. To that end, and as discussed below, meteorological data (solar radiation, air temperature, relative humidity, wind speed) is used to measure atmospheric demand, which is expressed as a standardized crop such as alfalfa or tall grass (0.12 m tall) and referred to as reference crop evapotranspiration ($ET_0$). Unlike reference $ET_0$ that is based solely on evaporative demand, turf $ET_T$ is affected by numerous other factors in addition to climatic factors.

Turf ET is affected by numerous plant factors including leaf area components and canopy architecture (i.e., canopy resistance, denoted as $r_c$ by Johns et al., 1983). In addition, bulk surface resistance ($r_s$) defined by Allen et al. (1998) as the diffusivity of water vapor from leaf-to-air through stomata and is derived from the crops leaf area index as $r_s = r_l/LAI$ [Equation 2] where $r_l$ is the leaf stomatal resistance (s $m^{-1}$). Under non-limiting soil moisture where stomatal resistance ($r_l$) is small (i.e., open stomata), $r_s$ decreases with increase leaf area index [Equation 2] and according to Equation 1 ET increases. Unlike Johns et al. (1983) expression of surface resistance, Allen et al. (1998) do not identify $r_c$ (canopy resistance) in the bulk surface resistance expression but rather $r_c$ is bulked along with $r_l$ in their $r_s$ expression. Johns et al. (1983), however, expresses $r_s$ as $r_c + r_l$ separately and considers stomatal resistance ($r_l$) as internal to the leaf and $r_c$ as an external leaf resistance to ET.

Johns et al. (1983) and Allen et al. (1998) include turbulent exchange resistance or aerodynamic resistance to ET ($r_a$) as another resistance that is external to the leaf. Aerodynamic resistance is the resistance to the transfer of heat and water vapor from the evaporating surface into the bulk air above the canopy. The aerodynamic resistance term is known to decrease with increasing wind speed in a curvilinear trend until some constant $r_a$ is achieved (Monteith, 1965). Martin et al. (1994) found Penncross creeping bentgrass (*Agrostis palustris* Huds.) $r_a$ at 9.5 cm HOC to decrease by four fold from 122 to 32 s $m^{-1}$ as wind speed increased from 0.5 to 8 m $s^{-1}$. Johns et al. (1983) reported the external leaf resistance ($r_a$ and $r_c$) to be 2 to 4 times larger than stomatal leaf resistance ($r_l$) under non-limiting soil moisture. As such, the authors concluded that external leaf resistances such as resistance to water vapor and heat flux from the turf canopy to the atmosphere ($r_a$) and resistance to water vapor exchange within the canopy ($r_c$) influenced ET more than the contribution of stomatal resistance to ET under non-limiting soil moisture. Accordingly, correlation between turfgrass ET rates using mini-lysimeters and stomatal density has been statistically non-significant (Shearman, 1986; Green et al., 1990; Atkins et al., 1991; Green et al., 1991). Conversely, leaf area components such as leaf extension rates have been positively correlated with ET rates (Shearman, 1986, 1989; Bowman and Macaulay, 1991; Ebdon and Petrovic, 1998).

Recreational areas are maintained at a lower HOC than lawn grass, often as low as 3.2 mm representative of golf greens and 9.5 mm at fairway HOC. Turfgrass maintained at lower HOC typically exhibit lower $ET_T$ rates (Madison and Hagan, 1962; Shearman and Beard, 1973; Biran et al., 1981; Feldhake et al., 1983; Brown and Kopec, 2000). According to Equations 1 and 2, this decrease in $ET_T$ under lower HOC is the result of decreased transpirational leaf surface area, lower LAI and higher $r_l$ (and $r_s$). Variable ET rates due to differential HOC and associated effects on resistances will influence water needs and must be accounted for in estimating irrigation amounts that are derived from ET estimates. According to the 1/3 rule of mowing frequency (Turgeon, 2002), lower HOC increases mowing frequency and in turn promotes minimal leaf surface area to accumulate between mowing events; thus reducing LAI and $r_s$. Additionally, frequent mowing at a shorter HOC may decrease turbulent flow (wind speed, u, m $s^{-1}$) across an evaporating surface when compared to taller grass where $r_a$ increases and ET decreases under shorter grass due to lower wind speed at lower height (Allen et al., 1998). Furthermore, regular mowing with shorter HOC reduces surface roughness (z) and the transfer of heat and water vapor from the canopy to bulk air, which increases aerodynamic resistance ($r_a$). Clearly, short grass such as golf green and fairway turf are associated with greater aerodynamic resistance ($r_a$) and surface resistance ($r_s$) to ET than taller grass such as sports and lawn grass.

Height of cut can also influence canopy resistance to ET because of the influence of HOC on aerial shoot (tiller) density, leaf density and leaf orientation. Tiller and leaf density along with a decumbent (horizontal) growth habit is promoted by decreasing HOC (Madison and Hagan, 1962; Sheffer et al., 1978). Kim and Beard (1988) observed lower $ET_T$ among 12 warm-season turfgrass species with higher shoot and leaf density and with a substantial decumbent leaf orientation. They proposed that a decumbent growth habit and high density can be significant physical barriers (resistance) to water vapor flux from transpiring leaves within the turf canopy sufficient to increase vapor density and lower VPD (and ET). In cool-season turfgrass, Ebdon and Petrovic (1998) showed similar relationships among cultivars of Kentucky bluegrass (*Poa pratensis* L.) in canopy resistance components. They reported that horizontal leaf orientation, high shoot (tiller) density and high verdure were associated with lower ET, which they attributed to higher canopy resistance to ET.

Similar to the results reported by Kim and Beard (1988) and Biran et al. (1981), Ebdon and Petrovic (1998) reported low leaf area components including slower vertical leaf extension rates and narrow leaf width were strongly correlated with promoting lower

ET. Shearman (1986) also reported a similar relationship between low leaf area and high canopy resistance in promoting lower ET. Specifically, Shearman observed negative correlations in Kentucky bluegrass cultivars between ET and verdure and shoot density and a positive correlation between ET and vertical leaf extension rates. Similar results between mini-lysimeter derived ET and canopy resistance components (verdure and shoot density) and leaf area (leaf extension rates) were also reported in perennial ryegrass (*Lolium perenne* L.) cultivars by Shearman (1989).

Cool-season $C_3$ turfgrass species managed under similar evaporative and cultural conditions typically exhibits a higher ET rate than $C_4$ turfgrass (Biran et al., 1981; Feldhake et al., 1983). This is due to differences between the $C_3$ and $C_4$ pathways with $C_4$ turfgrass exhibiting higher water use efficiency (g dry wt-to-g $H_2O$ ratio) over $C_3$ turfgrass (Biran et al., 1981). Numerous studies have been conducted to measure $ET_T$ of species (Youngner et al., 1981; Aronson et al., 1987; Kim and Beard, 1988; Fry and Butler, 1989) and within cultivars of the same species (Kopec et al., 1988; Shearman, 1986, 1989; Salaiz et al., 1991; Ebdon and Petrovic, 1998). Interspecies and interspecies differences in ET can be explained in large part by variation in leaf area and canopy resistance components when turf is maintained under non-limiting soil moisture. Under favorable soil moisture, internal leaf (stomatal) conductance (g) is fully expressed and leaf resistance ($r_l + r_s$) is small and in turn external leaf resistances ($r_c + r_a$) are dominant over surface resistance ($r_l + r_s$) (Johns et al., 1983). Alternatively, under soil moisture deficits such as deficit irrigation replacement and wilt base irrigation (irrigation applied at mild dehydration), stomatal resistance increases (Perdomo et al., 1996; Huang and Gao, 1999; Ebdon and Kopp, 2004; Lanier et al., 2012) and $r_l$ and $r_s$ exceed external resistances ($r_c + r_a$). As such, turfgrass $ET_T$ determined under non-limiting soil moisture is uncorrelated with $ET_T$ under progressive water stress (Kopec et al., 1988; Fernandez and Love, 1993; Ebdon and Kopp, 2004).

Nitrogen fertilization has been shown to have a significant influence on leaf growth and ET rates especially for $C_3$ and $C_4$ species used as golf and sports grass. Higher N is known to promote faster leaf extension rates and higher $ET_T$ (Feldhake et al., 1983; Ebdon et al., 1999; Barton et al., 2009; Erickson and Kenworthy, 2011; McGroary et al., 2011). Similar to species and cultivar genetic effects of leaf area on ET, in these N fertility studies leaf growth rates are positively correlated with turf $ET_T$. Nitrogen promotes higher LAI (Barton et al., 2009) and in turn reduces surface resistance ($r_s$, Equation 2) and increases ET (Equation 1). In addition, and similar to taller HOC, taller grass due to faster leaf growth from higher N can reduce aerodynamic resistance ($r_a$) by increasing surface roughness (z). As a water conservation measure in turfgrass, the need to reduce N and LAI and thereby reduce ET rates needs to be carefully balanced with function such as wear tolerance. For example, Hoffman et al. (2010) under simulated traffic reported optimal N rates to be between 147 and 245 kg N $ha^{-1}$ $yr^{-1}$ for maximum wear tolerance and recovery in perennial ryegrass. These N rates, however, may not be optimal for using the least amount of water.

Comparing the effects of environmental and cultural preconditioning on ET rate, Shearman and Beard (1973) showed that N rate, HOC (0.7, 2.5, and 12.5 cm), and light intensity (full sun versus low light) promoted the greatest effect on ET while irrigation (wilt irrigation versus non-limiting) and mowing frequency were intermediate and temperature (10, 20, 33 °C) had the least effect on ET. The relative effects of light intensity and culture (HOC and N) on ET were correlated with leaf area. Under controlled environments, however, Ebdon et al. (1998) reported almost 90% of the effect on cultivar $ET_T$ was due to climatic conditions (evaporative demand, temperature) while cultivar (genetic) effect was secondary in its influence on Kentucky bluegrass $ET_T$. Turfgrass maintenance is not a single factor program. Multiple practices in combination are more relevant to turf function; however, such research is limited to the work of Shearman and Beard (1973), Biran et al. (1981) and Feldhake et al. (1983) in understanding multifactor effects on ET.

Evaluation of differential mowing heights can be problematic in the measurement of $ET_T$ because of the effects of differential HOC may have on aerodynamic and surface resistances. For reliable estimates of crop $ET_T$ a lysimeter should be surrounded by a buffer (fetch) of the same crop, stage of development and density. Aboukhaled et al. (1982) suggested a buffer area that followed a 400-to-1 buffer area-to-lysimeter area ratio. In addition, Rosenburg et al. (1983) suggested in order to minimize the border (oasis) and boundary effect that the crop height relative to the fetch should follow a 1-to-100 ratio. Fetch requirements are more important for arid environments. Mather (1959) and Fougerouze (1966) suggested the fetch requirements are smaller for humid environments such as the cool-humid New England region. Feldhake et al. (1983) in Colorado used a 6.25 $m^2$ plot area with a 0.0491 $m^2$ lysimeter area for a 127-to-1 buffer area-to-lysimeter area ratio. Similarly, the HOC-to-fetch ratio for the 5 cm HOC (1-to-25) and 2 cm (1-to-62.5) used by Feldhake did not follow the 1-to-100 ratio suggested by Rosenburg. However, Feldhake et al. (1983) believed that the oasis effect of the taller grass $ET_T$ (5 cm HOC) growing in the shorter grass (2 cm HOC) was not a dominant factor on ET. Similarly in Arizona, Brown et al. (2001) did not believe a 2 cm differential in HOC to be a major problem.

## Reference Evapotranspiration ($ET_0$)

The general approach for estimating actual ET is to compute a reference evapotranspiration ($ET_0$) for a standard surface based on climatic conditions. Most mathematical models (reference $ET_0$) used to predict ET of turf ($ET_T$) are based on climatic (evaporative demand) data combining solar radiation, aerodynamic resistance ($r_a$) with wind speed (u) components such as the Penman equation (Penman, 1948). Monteith (1965) proposed a modification of the Penman equation, in which bulk surface resistance terms ($r_s$) were incorporated into the wind component. This computation is often referred to as the Penman-Monteith equation.

Like some agricultural crops, turfgrass systems can be viewed as a single leaf because of its high uniformity and dense cover. Therefore a single layer or "big-leaf" model, described below, is appropriate. These single layer models include the Penman (Penman, 1948), modified Penman (Burman et al., 1982; Wright, 1982) and its numerous variations, the Penman-Monteith equation (Monteith, 1965) and its inclusion of a well-defined surface (leaf) resistance ($r_l$) component, and the FAO 56 equation (Allen et al., 1998). The Food and Agriculture Organization of the United Nations (FAO-56 Paper, Allen et al., 1998) simplified the Penman-Monteith equation by making some assumptions regarding the reference crop. Specifically, FAO 56 assumes the reference crop to be "*a hypothetical reference crop with an assumed crop height of 0.12 m, a fixed surface resistance of 70 s $m^{-1}$ and an albedo of 0.23*." The assumption for albedo (radiant energy reflection) of 0.23 and bulk surface (leaf-canopy) resistance of 70 s $m^{-1}$ may be appropriate for well maintained, dense, green crops such as turfgrass. Other FAO 56 assumptions, however, especially the crop height of 0.12 m, may not correlate with some crops such as turf. Typical HOC of 0.032 to 0.095 m for golf and 0.32 to 0.64 m for sports grass are major departures from the FAO 56 model assumptions for crop height, however, adjustments can be made. To that end, the predicted (hypothetical) reference crop ET ($ET_0$) may need to be experimentally adjusted by comparing reference ET values with ET values derived from lysimetry under conditions (evaporative demand and culture) representative of the crop and location of interest. To that end, crop coefficients ($K_c$) can be determined experimentally to adjust reference $ET_0$ to match the crop $ET_T$.

Other assumptions of FAO 56 and single layer combination equations used to estimate reference $ET_0$ is that the crop is assumed to be (i) well watered (non-limiting soil moisture) and therefore not short of water and (ii) with uniform green cover and therefore free of disease. Accordingly, these reference ET models have been referred to as Potential Evapotranspiration (PET) but in recent years the term reference ET has been adopted. Clearly, the model assumptions for surface resistance of 70 s $m^{-1}$ may be violated under (i) soil moisture deficits (deficit irrigation replacement and wilt based ET), and higher $r_s$ caused by higher $r_l$ and (ii) lower HOC, and higher $r_s$ (and $r_c$) due to lower LAI and decumbent growth. Such departures from the model's assumptions due to HOC can be adjusted using an experimentally derived $K_c$.

The implementation of ET base irrigation in order to apply the proper amounts of water is complicated by the numerous combination equations available to predict turf $ET_T$. Brown et al. (1998) showed that under similar evaporative demand environments, reference $ET_0$ models (modified Penman and Penman-Monteith FAO 56) may range by as much as 30% in their estimate of $ET_0$. The use of a single model such as the FAO 56 Penman-Monteith equation (Allen et al., 1998) as the standard model may help to reduce the confusion that is associated with the numerous models that offer different solutions in estimating $ET_0$. These models may introduce as much variation in their estimate of reference $ET_0$ equal to the variation caused by species and cultural factors have on turf $ET_T$. Brown et al. (2001) observed in bermudagrass (*Cynodon dactylon* L. × *C. transvaalinsis* Davy) that the modified Penman $ET_0$ can be 10 to 15% higher than the Penman-Monteith reference $ET_0$ in the desert southwest and recommended caution when comparing among different reference $ET_0$. Others have found the prediction between measured $ET_T$ and reference $ET_0$ in well watered crops was superior with the Penman-Monteith equation while Penman predictions over-estimated measured $ET_T$ by 20 to 40% (Allen, 1986; Steiner et al., 1991). Hence, the recommendation by the United Nations Food and Agricultural Organization for Penman-Monteith (FAO 56, Allen et al., 1998) for computing reference $ET_0$ values.

## Crop Coefficients ($K_c$)

Measured $ET_T$ of the turfgrass system and reference $ET_0$ are affected by evaporative demand measured by $R_n$ and the aerodynamic and surface resistances that are representative of the transport (heat and water vapor) properties of the crop surface. To insure that the reference $ET_0$ is a match of the true water loss and irrigation requirements of the turfgrass system additional research is often needed to validate the reliability of the reference $ET_0$ for predicting turf $ET_T$. To that end, crop coefficients are used to adjust the reference $ET_0$ value to match turf $ET_T$. Crop coefficients are a simple ratio of actual $ET_T$-to-reference $ET_0$ ($K_c = ET_T/ET_0$). Once a reliable $K_c$ value has been determined experimentally the $K_c$ value can then be used with reference $ET_0$ values from on-site weather stations to estimate actual $ET_T$ as $ET_T = ET_0 \times K_c$. If the reference $ET_0$ model is a perfect fit for actual $ET_T$ then the $K_c$ value approaches 1. Alternatively, overestimation by $ET_0$ ($K_c < 1$) or underestimation by $ET_0$ ($K_c > 1$) allows for adjustments to be made to correct for aerodynamic and surface resistances and associated departures between the crop's $ET_T$ and reference $ET_0$ model.

Most of the $K_c$ values that have been determined are from areas outside the cool-humid northeast including semi-arid and arid climates (Meyer et al., 1985; Devitt et al., 1992; Ervin and Koski, 1998; Brown et al., 2001), warm-humid southeast (Carrow, 1995), and mid-west (Kopec et al., 1988; Salaiz et al., 1991). Evapotranspiration and $K_c$ values for cool-humid environments have been limited to the research of Aronson et al. (1987) in Rhode Island on lawn grass and more recently in Minnesota on golf course greens (Sass and Horgan, 2006). Since $K_c$ values are derived directly from turf $ET_T$, any one of the numerous factors discussed previously that can alter $ET_T$ including species-cultivars, HOC, irrigation level (plant stress) and N fertility can alter $K_c$ values for which the weather station reference $ET_0$ does not measure. For example, as soil moisture deficits and drought stress progress with soil drying, $ET_T$ and $K_c$ values decline (Kopec et al., 1988).

Among $C_3$ species maintained as lawn turf (mowed at 50 mm HOC), $K_c$ values from the Aronson study in Rhode Island ranged from 0.88 (hard fescue, *Festuca ovina*) to 1.09 (Kentucky bluegrass) based on the modified Penman $ET_0$. As previously discussed, the modified Penman can be 10 to 15% higher for turf than FAO 56 $ET_0$ (Brown et al., 2001) and even greater for other crops (Allen, 1986, Steiner et al., 1991). These $K_c$ values from Rhode Island may need to be adjusted up from 0.88 to 1.09 for Penman $ET_0$ derived $K_c$ to 0.98 to 1.24 for FAO 56 $ET_0$ derived $K_c$. Aronson et al. (1987) recommended a $K_c$ value of 1.0 for $C_3$ lawn grass species using the Penman equation but these $K_c$ values may be closer to 1.1 to 1.15 if FAO 56 was used to calculate reference $ET_0$. Sass and Horgan (2006) in Minnesota recommended a $K_c$ value of 0.98 for short grass golf turf (5 mm) using FAO 56 and they observed a similar range as reported by Aronson et al. (1987) for tall grass lawn turf (50 mm HOC). These results are problematic because of the theoretically different LAI, and aerodynamic ($r_a$) and surface ($r_s$) resistances offered by 50 mm and 5 mm HOC turf reported in the Rhode Island and Minnesota studies, respectively. In theory, greater resistances associated with short grass golf turf are expected to exhibit lower $K_c$ values than tall grass lawn turf. The $K_c$ range of 0.85 to 1.05 for golf green HOC in Minnesota does not correlate with Rhode Island data unless Rhode Island $K_c$ values are corrected and adjusted up to 1.1 to 1.15 to account for the higher modified Penman $ET_0$ compared to FAO 56 $ET_0$. Conversely, if no adjustments are made to account for the variation introduced by different reference $ET_0$ models, golf green HOC (5 mm) and lawn grass HOC (50 mm) would have similar $K_c$ values under non-limiting soil moisture despite theoretically different LAI, and aerodynamic ($r_a$) and surface ($r_s$) resistances.

Salaiz et al. (1991) reported $K_c$ values ranging from 0.86 to 1.15 for 10 creeping bentgrass cultivars maintained in Nebraska at 12.5 mm HOC and derived from the (Nebraska) modified Penman equation. Comparing $K_c$ values between different climatic regions is difficult because $K_c$ values are known to be lower under more arid environments (Carrow, 1995). Under similar evaporative demand, however, higher LAI due to higher N can promote $K_c$ values up when comparing well fertilized golf course sites with park sites (Devitt et al., 1992). In Kansas, Penman-Monteith was shown to over-estimate turf $ET_T$ under low evaporative demand (low $ET_0$, i.e., cool-cloudy, calm days, low $R_s$-to-$R_{so}$ ratio, low u) but under-estimated turf $ET_T$ under high evaporative demand (high $ET_0$, i.e., hot-clear sky, windy, high $R_n$, high $R_s$-to-$R_{so}$ ratio, high u) (Qian et al., 1996). The authors also noted that the correlation between $C_4$ turfgrass $ET_T$ and reference $ET_0$ were generally lower than those observed in arid regions.

Measured ET and reference $ET_0$ will vary monthly with evaporative demand during periods when supplemental irrigation may be required. Aronson et al. (1987) reported biweekly $K_c$ values from early July to Late Sept that were variable from period to period and year to year. Specifically, they found Penman $ET_0$ under-predicting ($K_c >$ 1) and over-predicting ($K_c < 1$) turf $ET_T$ depending on the month and year. Crop coefficients in the cool-humid region of Rhode Island ranged from 0.80 to 1.23 and therefore Aronson et al. (1987) recommend a seasonal $K_c$ average of 1.0 across the five species they evaluated. In their study the authors used a simple daily $ET_T$-to-$ET_0$ ratio averaged over periods and years to estimate $K_c$. New England is characterized as having highly variable summer temperatures, humidity, cloudiness (low $R_n$) and therefore variable evaporative demand. Ebdon and Petrovic (1998) reported the relative ranking of cultivar $ET_T$ in Kentucky bluegrass can change significantly with evaporative demand, which in turn can alter $K_c$ of the turf. These highly variable climatic conditions can make targeting $K_c$ values to the specific month unreliable for the New England region. Additionally, significant year-to-year variation requires multiple years of testing to develop reliable $K_c$ values, which typically have been tested over a 2 to 3 year period

(Aronson et al., 1987; Salaiz et al., 1991; Devitt et al., 1992; Carrow, 1995; Brown et al., 2001).

Brown et al. (2001) report consistent $K_c$ values of 0.78 to 0.83 for bermudagrass in the semi-arid desert southwest from June to Sept. Furthermore, they concluded that $K_c$ values are less reliable during periods of cloudy weather. They found when the ratio of measured solar radiation ($R_s$) to theoretical clear sky solar radiation ($R_{so}$) increased, the coefficient of variation of $K_c$ for bermudagrass decreased. Accordingly, the repeatability (reliability) of $K_c$ values increased with clear sky radiation (higher $R_s/R_{so}$ ratio). The authors also reported computations of $K_c$ using different methods in addition to the method used by Aronson et al. (1987). Brown et al. (2001) estimated $K_c$ using least square regression with $ET_0$ and $ET_T$ as the independent and dependent variables, respectively. However, the practical application of $K_c$ derived from least square regression requires the intercept to be statistically equally to “0.” As such, the least square equation and $ET_T$ are dependent on the slope (*b*) only and in this special case the slope is assumed to be $K_c$ ($ET_T$-to-$ET_0$ ratio). They found no serious bias introduced by the various methods used to calculate $K_c$.

## Research Justification

Crop coefficients for irrigating recreational turf under New England climatic conditions is critically needed for the following reasons (i) as a matter of turf function trafficked areas are maintained under conditions where water is not growth limiting and ET based irrigation is a priority (ii) the assumptions of single layer reference $ET_0$ models correlate nicely with the dense vegetative cover of recreational turf where transpiration is the dominant process over evaporation (iii) multifactor studies are needed to understand the effects on $K_c$ for a full range of cultural practices representative of recreational areas (iv) $K_c$ values from other $C_3$ turf growing regions do not necessarily transfer to New England (v) $K_c$ values for New England need to be re-calculated using the recommended FAO 56 Penman-Monteith equation to estimate reference $ET_0$ and (vi) other water conservation techniques that are variations on ET replacement ($ET_T = ET_0 \times K_c$) such as wilt-irrigation and deficit irrigation replacement cannot be effectively implement until reliable $K_c$ values have been developed and tested over multiple years.

## Research Objectives

The objective of this research is to develop monthly and seasonal crop coefficients adjusted according to measured $ET_T$ for species and turf culture representative of golf and sports grass when $ET_0$ is computed using the FAO 56 Penman-Monteith equation.

## Materials and Methods

Studies were conducted at the Joseph Troll Turf Research and Education Center in South Deerfield, MA. Three species were selected to represent commonly used recreational turfgrass species of the New England region. On 14 August 2009 the following grasses were established on a native Hadley silt-loam soil (coarse-silty, mixed, superactive, nonacid, mesic, Typic Udifluents), (i) 'Memorial' creeping bentgrass was planted as a representative of golf course turf, and (ii) 'Touchdown' Kentucky bluegrass and 'Exacta' perennial ryegrass were planted as pure stands as representative of sports grass. Each of the three species were arranged as a complete factorial with two N rates corresponding to 98 and 196 kg N $ha^{-1}$ $yr^{-1}$ for a 3 by 2 species by N rate treatment combination. Low N rate plots followed a May and September fertilizer schedule with N applied at 49 kg N $ha^{-1}$ per application. The high N rate also included a summer fertilizer treatment (July) and late fall treatment (November) using the same N rate of 49 kg N $ha^{-1}$. Granular N fertilizer applied in summer contained 82% of the total N in a slow-release form while fertilizer N applied during other times of the year contained approximately 40% of the total N as slow release.

The six species-N rate combinations were established as 3.12 by 1.56 m main plots. Each main plot was split to represent 1.56 by 1.56 m sub-plots to account for differential HOC representative of golf and sports grass. The sports grass main plots were split as 3.2 and 6.4 cm HOC while creeping bentgrass was cut at 0.32 and 0.95 cm (greens and fairway heights, respectively). Daily mowing was required for green HOC whereas fairway HOC (0.95 cm) and high maintenance sports grass (3.2 cm HOC) followed the same 3 day mowing schedule while tall sports grass (6.4 cm HOC) was mowed once per week. The HOC and N rates chosen allowed for a full range of favorable (high maintenance) and unfavorable (low maintenance) conditions for the sports and golf turf to be evaluated.

Mini-lysimeters were installed into the center of each of the sub-plots. Approximately one month prior to the initiation of ET measurements (21 May, 2010), cores including intact plants and soils (10 cm diameter and 20 cm deep to include a majority of the root system) were removed from established sub-plots using a cup cutter and placed into polyvinyl chloride (PVC) tubes of the same size as the cores to form mini-lysimeters. Nylon mesh screen was be taped to the bottom of each PVC tube in order to maintain the plant and soil column intact while allowing for water drainage out of the mini-lysimeters. Mini-lysimeters received the same management as the surrounding plot (buffer) area. The buffer area-to-lysimeter area ratio followed a 310-to-1 ratio while the short grass HOC for green (0.32 cm) and the tall grass HOC of sport grass (6.4 cm) corresponded to a HOC-to-fetch ratio of 1-to-250 and 1-to-12, respectively. Main plots were separated by border areas (1.56 m) that were maintained at greens HOC (0.32 cm) in order to ease the mowing of short grass plots within the mixed fetch of taller grass. Main plots were arranged as a randomized complete block design with four replicates.

Evapotranspiration rates within individual sub-plots were measured using the gravimetric mass balance method. Mini-lysimeters allow for direct calculation of mass changes due to plant water uptake and soil evaporation and have been utilized in several investigations on turfgrass ET (Feldhake et al., 1983; Aronson et al., 1987; Qian and Fry, 1996; DaCosta and Huang, 2006). Measurement of $ET_T$ based on weighing lysimeters is distinguished from $ET_0$, where $ET_0$ is estimated by means of an empirical model based on climatic data. Evapotranspiration is measured daily using lysimetry during periods of no rainfall according to the water balance equation:

$ET_T = I + P - \Delta S - D$ (Equation 3)

where $I$ is irrigation, and $P$ is precipitation, which are additions into the system (+ values), while $\Delta S$ is the change is soil moisture storage and $D$ is drainage, which are losses out of the system (– values). Under the conditions of this study $ET_T$ reduces to weight loss difference ($\Delta S$) where the difference in mass over a 24 h period is assumed to be $ET_T$.

Mini-lysimeters are weighed at 24 hour intervals with a balance providing accuracy to the nearest gram. Daily $ET_T$ is calculated based on the difference in the weight of mini-lysimeters at 24-hour intervals. To maintain non-limiting soil moisture only 3 days of consecutive daily ET measurements are allowed before irrigation is initiated to reestablish container capacity of the lysimeters. Except for greens HOC, growth during the ET measurement period is allowed to occur continually and uninterrupted by mowing. Conversely, mowing and defoliation of lysimeters installed into green HOC sub-plots is practiced daily with clippings removed. Clipping removal was shown to have no significant effect on weight loss and ET measurements for greens HOC. Clippings were collected following mowing for all treatments at the start of a new ET measurement cycle (1 to 3 days depending on rainfall). Daily ET measurements were conducted during the summer months (Late June, July, August, and early Sept.) from 2011 through 2013.

Vertical leaf extension rates were measured daily to the nearest mm during ET measurements by subtracting the difference between the total plant height from the previous day. Total shoot density and leaf width were made in early July and late August of each season from two 1.72 cm diameter samples taken from each sub-plot. Leaf width was measured to the nearest mm at mid-point from the 2nd sub-tending leaf (Ebdon and Petrovic, 1998). Leaf width and vertical leaf extension rate are leaf area components while turf shoot density is a canopy resistance component in both $C_4$ and $C_3$ turfgrass (Kim and Beard, 1988; Ebdon and Petrovic, 1998). Additionally, rooting potential was determined at the time of sampling for shoot density by sampling to a soil depth of 65 cm. Root samples were partitioned into 0 to 10 cm, 10 to 25 cm, 25 to 45 cm and 45 to 65 cm depths. Roots were washed and oven dried for 72 hrs at 70 °C.

The FAO 56 Penman-Monteith equation was used as the predictive model for turf $ET_T$. In areas where significant changes in wind speed, dew point or cloudiness occur during the day, calculation of the reference $ET_0$ using hourly time steps is better than using 24-hour calculation time steps. Allen et al. (1998) describe the exact form of the FAO 56 Penman-Monteith equation for hourly time steps that was used:

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma\frac{37}{T_{hr}+273}u_2(e^o(T_{hr}) - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \qquad \text{Equation 4}$$

where

$ET_0$ reference evapotranspiration [mm $h^{-1}$],

$R_n$ net radiation at the grass surface [MJ $m^{-2}$ $h^{-1}$],

G soil heat flux density [MJ $m^{-2}$ $h^{-1}$],

$T_{hr}$ mean hourly air temperature [°C],

$\Delta$ saturation slope vapor pressure curve at $T_{hr}$ [kPa °C$^{-1}$],

$\lambda$ psychrometric constant [kPa °C$^{-1}$],

$e°(T_{hr})$ saturation vapor pressure at air temperature $T_{hr}$ [kPa],

$e_a$ average hourly actual vapor pressure [kPa],

$u_2$ average hourly wind speed at 2 m height [m s$^{-1}$].

In Equation 4 all units cancel (i.e., multiplier 408) so $ET_0$ reduces to mm h$^{-1}$. Reference ET measurements were made with an on-site weather station (Campbell Scientific Inc., Logan, UT, model ET 106), which is located on 7.5 cm tall grass at least 100 m in all directions from non-grassy surfaces and 150 m from where $ET_T$ was measured using lysimeters. All sensors (air temperature, anemometer, pyranometer, rainfall, relative humidity) were recalibrated by Campbell Scientific Inc. during June 2011 before the start of the 2011 season. Wind speed and direction were measured at a 2 m height as were other measurements. The constant of 0.34 for wind speed of the standard $ET_0$ equation (Equation 4) measured at 2 m height will deviate slightly from actual wind speed measured at heights different from the 2 m standard. However, this recommended 2 m height for the measurement of wind speed at 2 m ($u_2$) was followed in computing a standard reference $ET_0$. Daily reference $ET_0$ was calculated by an hourly time step and summation of predicted $ET_0$ from each hourly time step. A working crop coefficient of 1.0 was selected and used throughout the study. Turf $ET_T$ and reference $ET_0$ were measured according to a 24 h period from 900 h to 900 h. For a thorough discussion of $R_n$ and $u_2$ computations of the standard reference $ET_0$ for Equation 4 see Allen et al. (1998).

Crop coefficients were computed on a biweekly and seasonal basis for the irrigation season (late June to early Sept) derived daily as a simple arithmetic $ET_T$-to-$ET_0$ ratio and then averaged over biweekly and seasonal periods. The computation of biweekly $K_c$ averages can be problematic in the cool-humid New England region due to the potential for spot showers during the summer period (Aronson et al., 1987) making turf $ET_T$ difficult to measure and $K_c$ values difficult to calculate without the use of a rainout shelter. Secondly, and as discussed previously (Aronson et al., 1987), $K_c$ values are highly variable on a biweekly basis suggesting the need to compute averages over the entire irrigation season, which may be more repeatable and have more practical application in the implementation of ET based irrigation in the cool-humid region (Sass and Horgan, 2006).

Brown et al. (2001) used regression (least square regression) with $ET_T$ as the response variable (dependent) and reference $ET_0$ as the predictor (independent variable) in the computation of $K_c$ values for bermudagrass in the desert south west. Specifically, the intercept of the least square equation if statistically equal to zero can be omitted from the least square equation and therefore the slope ($b$) is assumed to be $K_c$. Brown et al. (2001) reported that the arithmetic ratio and least square regression estimates of monthly $K_c$ values to be similar under this special zero intercept case when the linear regression line is forced through zero.

Under the unpredictable rainfall conditions of New England, the biweekly or monthly estimates using the least square regression method may not be appropriate to achieve sufficient daily observations and degrees of freedom (≈20 df) for reliable estimates of $K_c$ and second-order statistics (variance) with the least square regression approach (Gauch et al., 2003). As such, the least square approach may be more appropriate for estimating $K_c$ over the season and year using as many daily $ET_T$ and $ET_0$ observations as possible. To that end, least square regression to estimate $K_c$ will be computed by regressing the $ET_T$ for each species, HOC and N rate on reference $ET_0$. These least square $K_c$ estimates can then be compared with the simple ratio estimate of $K_c$ averaged over the summer period for creeping bentgrass, perennial ryegrass, Kentucky bluegrass, 98 and 196 kg N $ha^{-1}$ $yr^{-1}$, and short and tall HOC.

The data was analyzed as a 3 by 2 factorial of species and N rate as main plots with HOC as the sub-plot arranged as a randomized complete block design. Single degree of freedom (df) orthogonal contrasts were computed to compare golf turf (green and fairway) with sports grass (Kentucky bluegrass and perennial ryegrass). The short cut golf and tall grass sports turf share similar surface and aerodynamic resistances within their respective group while exhibiting distinctly different theoretical resistances, as well as leaf area and canopy resistance components between the groups. Orthogonal contrasts comparing Kentucky bluegrass with perennial ryegrass were also performed. Single df contrasts to partition the species main effects were then crossed with N rate and HOC to further partition the various 2- and 3-way interactions.

# CHAPTER 2

# FAO 56 PENMAN-MONTEITH CROP COEFFICIENTS FOR THE COOL-HUMID REGION


## Abstract

Scheduling irrigation applied to turf using actual turf evapotranspiration ($ET_T$) is one of many strategies available to conserve water. Turf $ET_T$ measured with weighing lysimeters can be estimated using reference ET ($ET_0$) from meteorological data corrected using crop coefficients ($K_c$). Crop coefficients must be determined experimentally for the local climatic and cultural conditions. Previous studies for the region have calculated $K_c$ values for tall grass species only (sports and lawn) using reference $ET_0$ equations that are no longer recommended. The objectives of this research were (i) develop reliable $K_c$ values for irrigating turf for the New England region when $ET_0$ is computed using the FAO 56 Penman-Monteith equation and (ii) evaluate the effects of two heights of cut (HOC), two N rates, and three species on $K_c$ values. 'Memorial' creeping bentgrass (CB; *Agrostis stolonifera* L.) was planted as a representative of golf course turf, with 'Touchdown' Kentucky bluegrass (KB; *Poa pratensis* L) and 'Exacta' perennial ryegrass (PR; *Lolium perenn*e L.) planted as pure stands as representatives of sports and lawn grass. The three species were arranged as a complete factorial with two N rates corresponding to 98 and 196 kg N $ha^{-1}$ $yr^{-1}$. The six (3 × 2) main plots (3.12 by 1.56 m) were split according to HOC with tall grass (KB and PR) mowed at 3.125 and 6.25 cm HOC and short grass CB at 0.3125 and 0.9375 cm HOC. Crop coefficients were calculated as daily $ET_T$-to-$ET_0$ ratio and using linear regression slope estimates ($ET_T$ vs.

$ET_0$) derived from 79 measurements including the months of July and August from 2011 to 2013. Both methods that were used to estimate $K_c$ were in agreement (0.00 to 0.02) according to the effects of species, HOC, and N on $K_c$ values. FAO 56 $ET_0$ accounted for 67% (n=79, $P \leq 0.001$) of the total variation in actual turf $ET_T$ (from lysimetry) but in some years (2012) the $r^2$ was as high as 0.84 (n=30, $P \leq 0.001$). Short grass CB exhibited 20% lower turf $ET_T$ and $K_c$ values, ½ the leaf growth rates, 5-fold greater shoot density, and 67% less rooting at the 25 to 45 cm soil depth than tall grass KB and PR. Turf $ET_T$ and $K_c$ values were correlated with leaf growth rates (r=0.66, n=48, $P \leq 0.001$) and shoot density (r=–0.67, n=48, $P \leq 0.001$). Greater bulk surface resistance ($r_s$) and aerodynamic resistance ($r_a$) along with lower leaf area of short grass CB can account for golf green and fairway HOC lower turf $ET_T$ and $K_c$ values. Crop coefficients increased by approximately 5% with N applied in summer and by 10% with the higher HOC. Linear regression slope derived $K_c$ values ranged from 0.90 to 1.00 for short grass CB while tall grass KB and PR $K_c$ values ranged from 1.15 to 1.25. Cultural practices promoting greater leaf area and that diminish resistance to $ET_T$ will need to use higher $K_c$ values.

## Introduction

The culture of turfgrass even for those growing in the cool-humid New England region must be targeted at efficient irrigation. To that end, irrigating turf according to evapotranspiration (ET) can prevent over watering and leaching and in turn reduce the cost of maintenance and preserve water quality. Irrigation is one of the most costly inputs identified as a primary expenditure of golf course maintenance budgets (Carrow, 2005). Drought concerns continually persist for turf managers. For example, the National Oceanic and Atmospheric Administration (NOAA) reported that 64% of the contiguous United States was still experiencing drought conditions as of September 2012. Such areas persist into the northeast where turfgrass managers are becoming more familiar with chronic drought conditions and limiting water availability. Irrigating turf using ET replacement is one of several strategies available for conserving water applied to turf.

Golf courses and sports fields consist of highly maintained grassy areas that exhibit a growth habit and morphological appearance different from less intensely managed lawns and parks. Intensely trafficked golf and sport grass require higher amounts of irrigation for optimal shoot density and verdure (green biomass) for proper cushioning and protection for the athlete and turfgrass plant under traffic stress (Murphy and Ebdon, 2013). In such turf where the canopy covers the soil surface, water loss as transpiration is the dominant process in ET because of high leaf area and 100% shading of the soil surface. Higher leaf area index (LAI) increases ET and LAI has been reported to range from 3 to 5 for Kentucky bluegrass (*Poa pratensis* L.) and perennial ryegrass (*Lolium perenn*e L.) turf mowed at 3.1 cm height of cut (Brede and Duich, 1986). Many local, state, and federal agencies have developed guidelines for water conservation and the Commonwealth of Massachusetts is amending their current water conservation standards for all turf (Massachusetts Water Commission, 2012).

Incorporating ET into an irrigation program to replace water loss through plant transpiration and soil evaporation is an essential part of a successful, more efficient irrigation program. The general approach for estimating actual ET is to compute a reference evapotranspiration ($ET_0$) for a standard surface based on climatic conditions. Earlier mathematical models (reference $ET_0$) used to predict ET of turf ($ET_T$) were based on climatic (evaporative demand) data combining solar radiation, bulk air above the canopy described as aerodynamic resistance ($r_a$) using wind speed (u) components (Penman, 1948). The only reported research conducted in New England (Rhode Island) to compare actual $ET_T$ with reference $ET_0$ (Aronson et al., 1987) was based on $ET_0$ derived using the modified Penman equation (Burman et al., 1980). More recent equations such as the Penman-Monteith reference $ET_0$ (Allen et al., 1989) were developed that added a surface resistance ($r_s$) component to represent the canopy resistance to vapor flux from plant leaf stomates into the bulk atmosphere. Surface resistance measured as canopy resistance in mowed turf by Johns et al. (1981) can be significant and greater than stomatal resistance when turf is grown under non-limiting soil moisture. The addition of bulk surface resistance can offer improvements in estimating ET over earlier reference $ET_0$ equations such as the Penman equation and its variations (Allen et al., 1989). Allen et al. (1998) recommend the Penman-Monteith $ET_0$ as the single equation for crop irrigation in their report (paper 56) to the Food and Agriculture Organization of the United Nations; designated as FAO 56 $ET_0$. Brown et al. (2001) recommended the use of

FAO 56 Penman-Monteith $ET_0$ to avoid confusion that results with different reference equations in estimating turf ET for irrigation.

Daily $ET_0$ values to predict turf ET are readily available to the turf manager using on-site weather stations and to the general public from weather networks such as those developed in Arizona (Brown et al., 1988) and California (Snyder et el., 1985). However, the reliability of reference $ET_0$ is dependent on the reference equation used to compute reference $ET_0$ values and on the actual ET rate of the turf ($ET_T$). Aronson et al. (1987) reported seasonal averages of the modified Penman $ET_0$ values in summer for Rhode Island for Kentucky bluegrass and perennial ryegrass that were approximately equal to actual turf $ET_T$ measured using weighed lysimeters. Crookston and Hattendorf (2010), however, found FAO 56 $ET_0$ estimates under-estimated Kentucky bluegrass and perennial ryegrass turf ET by 12 to 14%, respectively, in summer in Colorado. Brown et al. (1998, 2001) also observed FAO 56 $ET_0$ to generate 10 to 15% lower reference $ET_0$ values than the modified Penman equation for warm-season turf in the desert southwest. The Penman $ET_0$ equation used in the Rhode Island study offers no calculation for surface resistance ($r_s$) that is afforded by the Penman-Monteith equation. As such, FAO 56 $ET_0$ estimates can be lower due to more resistance (surface resistance, $r_s$) in addition to aerodynamic resistance ($r_a$) that are identified with FAO 56 $ET_0$ estimates compared to Penman $ET_0$ estimates. Under wet (saturated) conditions the $r_s$ component is zero and the Penman-Monteith $ET_0$ equation reduces to the Penman equation. In order to maintain healthy turf, such (saturated) conditions are avoided especially in summer when ET based irrigation is practiced.

Ebdon et al. (1998) reported that 87% of the total variation in Kentucky bluegrass cultivar $ET_T$ (using mini-lysimeters) was accounted for by evaporative demand ($ET_0$) with genotype accounting for 8% and interaction (evaporative demand by genotype) accounting for 5% of $ET_T$. When the crop is not short of water, evaporative demand drives $ET_T$ and irrigation requirements. However, the ability to modify $ET_T$ exists by altering species (Youngner et al., 1981; Aronson et al., 1987; Kim and Beard, 1988; Fry and Butler, 1989; DaCosta and Huang, 2006) and cultivar (Shearman, 1986, 1989; Kopec et al., 1988; Salaiz et al., 1991; Ebdon and Petrovic, 1998). In addition to genetic variation, $ET_T$ decreases with (i) lower mowing height of cut (HOC) and increase mowing frequency (Shearman and Beard, 1973; Biran et al., 1981; Feldhake et al., 1983; Brown and Kopec, 2000), (ii) lower N fertilization rate (Shearman and Beard, 1973; Feldhake et al., 1983; Ebdon et al., 1999; Barton et al., 2009; Erickson and Kenworthy, 2011; McGroary et al., 2011), (iii) progressive soil drying with reduced stomatal conductance (Perdomo et al., 1996; Huang and Gao, 1999; Ebdon and Kopp, 2004; Lanier et al., 2012), (iv) narrow leaf width (Kim and Beard, 1988; Ebdon and Petrovic, 1998;), (v) slower vertical leaf extension rates (Biran et al., 1981; Shearman, 1986, 1989; Kim and Beard, 1988; Bowman and Macaulay, 1991; Ebdon and Petrovic, 1998), and (vi) higher turf shoot density (Shearman, 1986, 1989; Kim and Beard, 1988; Ebdon and Petrovic, 1998).

Due to the numerous factors that affect turf $ET_T$, which are independent of evaporative (climatic) factors measured by reference $ET_0$, a correction or transfer factor known as a crop coefficient ($K_c$) is needed. Crop coefficients are calculated as a simple $ET_T$-to-$ET_0$ ratio and are used to adjust reference $ET_0$ values computed by weather stations to better fit actual turf $ET_T$ for the local climatic and cultural conditions. The numerous factors that increase turf $ET_T$ such as higher N and taller HOC will increase $K_c$ values and in turn will increase water amounts (ET replacement) applied as irrigation; calculated as $ET_T = K_c \times ET_0$. Like turf $ET_T$, calculated $K_c$ values ($ET_T/ET_0$) are also affected by reference $ET_0$. For the same crop grown under the same evaporative environment, Penman $ET_0$ is expected to be 10 to 15% higher than FAO 56 $ET_0$ producing $K_c$ values in summer that are 10 to 15% lower than FAO 56 $ET_0$ derived $K_c$ values. Brown et al. (2001) recommended Penman $ET_0$ derived Kc values need to be increased by 10 to 15% for use with the Penman-Monteith equation. This is necessary because greater resistance (i.e., bulk surface resistance, $r_s$, hence lower $ET_0$) is accounted for using the Penman-Monteith reference equation when compared with the Penman reference equation.

Most of the $K_c$ values that have been determined are from areas outside the cool-humid northeast including the semi-arid and arid climates (Meyer et al., 1985; Devitt et al., 1992; Ervin and Koski, 1998; Brown et al., 2001), warm-humid southeast (Carrow, 1995), and mid-west (Kopec et al., 1988; Salaiz et al., 1991). Evapotranspiration and $K_c$ values for the cool-humid environments have been limited to research in Rhode Island by Aronson et al. (1987) on lawn grass and more recently in Minnesota on golf course greens (Sass and Horgan, 2006). Using the modified Penman equation Aronson et al. (1987) recommended a $K_c$ value (average) of 1.0 for lawn turf (mowed at 5 cm HOC); $K_c$ values ranged from 0.88 (hard fescue, *Festuca longifolia* Thuill) to 1.09 (Kentucky bluegrass). Sass and Horgan (2006) in Minnesota recommended a $K_c$ value of 0.98 for short grass golf turf (0.5 cm) using FAO 56. Both Minnesota and Rhode Island studies reported similar solar radiation, air temperatures, relative humidity, and wind speed. The short grass canopies of golf turf used in the Minnesota study would be expected to exhibit lower $K_c$ values (lower $ET_T$) due to the greater canopy resistance ($r_c$) as suggested by Johns et al. (1981), greater bulk surface resistance ($r_s$), and greater aerodynamic resistance ($r_a$) typical of shorter grass canopies. Following the adjustments recommended by Brown et al. (2001) the Rhode Island lawn grass $K_c$ values should average 1.10 to 1.15 for use with the FAO 56 Penman-Monteith equation, however, this needs to be validated using lysimeters to measure $ET_T$ and FAO 56 $ET_0$ procedures to measure $ET_0$. In a Colorado study evaluating Kentucky bluegrass and perennial ryegrass Crookston and Hattendorf (2012) reported $K_c$ values in this range (1.12 to 1.14) using FAO 56 $ET_0$.

Salaiz et al. (1991) reported $K_c$ values ranging from 0.86 to 1.15 (0.98 $K_c$ average) for 10 creeping bentgrass (*Agrostis stolonifera* L.) cultivars maintained in Nebraska at 1.25 cm HOC, fertilized with 294 kg N $ha^{-1}$ $yr^{-1}$, and derived using the modified Penman equation. Sass and Horgan (2006) in Minnesota recommended a $K_c$ value of 0.98 for short grass golf turf mowed at 0.5 cm, fertilized with 220 kg N $ha^{-1}$ $yr^{-1}$, using FAO 56 $ET_0$. These observed $K_c$ values for short grass turf are similar in range as reported by Aronson et al. (1987) for tall grass lawn turf (5.0 cm HOC) using the modified Penman equation. These three studies that report similar $K_c$ values demonstrate the confusion in the selection and use $K_c$ values for turf grown under different meteorological conditions using different reference $ET_0$ procedures. Furthermore, these studies utilized different species, HOC, and N fertility practices with known effects on turf $ET_T$, and in turn, $K_c$ values.

## Objectives

Allen et al. (1998) recommended $K_c$ values of 0.90 to 0.95 for cool-season turfgrass when using FAO 56 Penman-Monteith $ET_0$ and where the HOC is 6 to 8 cm. Brown et al. (2001), however, question the author's recommendation because they do not offer any direct research evidence for their recommendation. Additional research is needed using the recommended FAO 56 Penman-Monteith equation, which is just one of many factor affecting $K_c$ values. The objectives of this research were (i) develop reliable $K_c$ values for irrigating turf using ET replacement for the New England region when $ET_0$ is computed using the FAO 56 Penman-Monteith equation and (ii) evaluate the effects of two HOC, N rates, and three species on $K_c$ values.

## Materials and Methods

### Field Treatments

Field plot studies were conducted at the Joseph Troll Turf Research and Education Center in South Deerfield, MA. The latitude and longitude of the site are 42.49°N and 72.59°W, respectively, located at 86.9 m elevation above sea level. Three species were selected to represent commonly used recreational and lawn turf species for the cool-humid region. On 14 August 2009 the following grasses were established on a native Hadley silt-loam soil (coarse-silty, mixed, superactive, nonacid, mesic, Typic Udifluents), (i) 'Memorial' creeping bentgrass was planted as a representative of golf course turf, and (ii) 'Touchdown' Kentucky bluegrass and 'Exacta' perennial ryegrass were planted as pure stands as representative of sports and lawn grass.

Each of the three species were arranged as a complete factorial with two N rates corresponding to 98 and 196 kg N $ha^{-1}$ $yr^{-1}$ for a 3 by 2 species by N rate treatment combination. Low N rate plots followed a May and September fertilizer schedule with N applied at 49 kg N $ha^{-1}$ per application. The high N rate also included a summer fertilizer treatment (July) and late fall treatment (November) using the same N rate of 49 kg N $ha^{-1}$. Granular N fertilizer applied in summer contained 82% of the total N in a slow-release N (SRN) form (as methylene urea) while fertilizer N applied during other times of the year contained approximately 40% of the total N as slow release. All plots were treated uniformly with preventative fungicides, insecticides, and herbicides to maintain actively growing grass in order to satisfy the criteria for standard conditions according to FAO 56 $ET_0$ (Allen et al., 1998) that the crop ET is the ET from disease free, well fertilized and growing under optimum soil water conditions.

The six species-N rate combinations were established as 3.12 by 1.56 m main plots. Main plots were arranged as a randomized complete block design with four replicates. Each main plot was split to represent 1.56 by 1.56 m sub-plots to account for differential HOC representative of golf and sports-lawn grass. The sports-lawn grass main plots, hereafter referred to as tall grass, were split as 3.125 and 6.25 cm HOC while creeping bentgrass, hereafter referred to as short grass, was cut at 0.3125 and 0.9375 cm (greens and fairway heights, respectively). Daily mowing was required for green HOC whereas fairway HOC (0.9375 cm) and high maintenance sports grass (3.125 cm HOC) followed the same 3 day mowing schedule while tall sports(lawn) grass (6.25 cm HOC) was mowed once per week. The HOC and N rates chosen allowed for a full range of favorable (high maintenance) and unfavorable (low maintenance) conditions for the sports and golf turf to be evaluated.

### Turf $ET_T$

Mini-lysimeters were installed into the center of each of the sub-plots. Approximately one month prior to the initiation of ET measurements (21 May, 2011), cores including intact plants and soils (10 cm diameter and 20 cm deep to include a majority of the root system) were removed from established sub-plots using a cup cutter and placed into polyvinyl chloride (PVC) tubes of the same size as the cores to form mini-lysimeters. Nylon mesh screen was taped to the bottom of each PVC tube in order to maintain the plant and soil column intact while allowing for water drainage out of the mini-lysimeters. Mini-lysimeters received the same management as the surrounding plot (buffer) area. The buffer area-to-lysimeter area ratio followed a 310-to-1 ratio while the short grass HOC for green (0.3125 cm) and the tall grass HOC of sport grass (6.25 cm) corresponded to a HOC-to-fetch ratio of 1-to-250 and 1-to-12, respectively. Main plots were separated by border areas (1.56 m) that were maintained at greens HOC (0.3125 cm) in order to ease the mowing of short grass plots within the mixed fetch of taller grass.

Evapotranspiration rates within individual sub-plots were measured using the gravimetric mass balance method. Mini-lysimeters allow for direct calculation of mass changes due to plant water uptake and soil evaporation and have been utilized in several investigations on turfgrass ET (Feldhake et al., 1983; Aronson et al., 1987; Qian and Fry, 1996; DaCosta and Huang, 2006). Measurement of $ET_T$ based on weighing lysimeters is distinguished from $ET_0$, where $ET_0$ is estimated by means of an empirical model based on climatic data. Evapotranspiration is measured daily using lysimetry during periods of no rainfall according to the water balance equation:

$$ET_T = I + P - \Delta S - D$$

where $I$ is irrigation, and $P$ is precipitation, which are additions into the system (+ values), while $\Delta S$ is the change is soil moisture storage and $D$ is drainage, which are losses out of the system (– values). Under the conditions of this study $ET_T$ reduces to weight loss difference ($\Delta S$) where the difference in mass over a 24 h period is assumed to be $ET_T$.

Mini-lysimeters were weighed at 24 hour intervals with a balance providing accuracy to the nearest gram. Daily $ET_T$ is calculated based on the difference in the weight of mini-lysimeters at 24-hour intervals. To maintain non-limiting soil water only 3 days of consecutive daily ET measurements were allowed before irrigation was initiated to reestablish container capacity of the lysimeters. Except for greens HOC, growth during the ET measurement period was allowed to occur continually and uninterrupted by mowing. Conversely, mowing and defoliation of lysimeters installed into green HOC sub-plots was practiced daily with clippings removed. Clipping removal was shown to have no significant effect on weight loss and ET measurements for greens HOC. Clippings were collected following mowing for all treatments at the start of a new ET measurement cycle (1 to 3 days depending on rainfall). Daily ET measurements were conducted during the summer months (July and August) from 2011 through 2013. There were 23, 30, and 26 daily $ET_T$ events in 2011, 2012, and 2013, respectively.

## Plant Characteristics

Vertical leaf extension rates were measured daily to the nearest mm during ET measurements by subtracting the difference between the total plant height from the previous day. Total shoot density and leaf width were made in early July and late August of each year from two 1.72 cm diameter samples taken from each sub-plot. Leaf width was measured to the nearest mm at mid-point from the 2$^{nd}$ sub-tending leaf (Ebdon and Petrovic, 1998). Leaf width and vertical leaf extension rate were leaf area components while turf shoot density was a canopy resistance component (Kim and Beard, 1988; Ebdon and Petrovic, 1998). Additionally, rooting potential was determined at the time of sampling for shoot density by sampling to a soil depth of 65 cm. Root samples were partitioned into 0 to 10 cm, 10 to 25 cm, 25 to 45 cm and 45 to 65 cm depths. Roots were washed and oven dried for 72 hrs at 70 °C.

## Reference (Predicted) $ET_0$

The FAO 56 Penman-Monteith equation was used as the predictive model for turf $ET_T$. In areas where significant changes in wind speed, dew point or cloudiness occur during the day, calculation of the reference $ET_0$ using hourly time steps is better than using 24-hour calculation time steps. The hourly values are stored in memory and summed to give daily reference $ET_0$ value. Allen et al. (1998) describe the exact form of the FAO 56 Penman-Monteith equation for hourly time steps that was used:

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{37}{T_{hr} + 273} u_2 (e^o(T_{hr}) - e_a)}{\Delta + \gamma(1 + 0.34u_2)}$$

where

$ET_0$ reference evapotranspiration [mm $h^{-1}$],

$R_n$ net radiation at the grass surface [MJ $m^{-2}$ $h^{-1}$],

G soil heat flux density [MJ $m^{-2}$ $h^{-1}$],

$T_{hr}$ mean hourly air temperature [°C],

$\Delta$ saturation slope vapor pressure curve at $T_{hr}$ [kPa °$C^{-1}$],

$\lambda$ psychrometric constant [kPa °$C^{-1}$],

$e°(T_{hr})$ saturation vapor pressure at air temperature $T_{hr}$ [kPa],

$e_a$ average hourly actual vapor pressure [kPa],

$u_2$ average hourly wind speed at 2 m height [m $s^{-1}$].

In the above reference $ET_0$ equation all units cancel (i.e., multiplier 408) so $ET_0$ reduces to mm $h^{-1}$. Reference ET measurements were made with an on-site weather station (Campbell Scientific Inc., Logan, UT, model ET 106), which is located on 7.5 cm well-watered tall grass at least 100 m in all directions from non-grassy surfaces and 150 m from where turf $ET_T$ was measured using lysimeters. All sensors (air temperature, anemometer, pyranometer, rainfall, and relative humidity) were recalibrated yearly by Campbell Scientific Inc. Wind speed and directional sensors (034A-LC6, Met One Inc., Grants Pass, OR) were measured at a 2 m height as were all other meteorological measurements. The constant of 0.34 for wind speed of the standard $ET_0$ equation measured at 2 m height will deviate slightly from actual wind speed measured at heights different from the 2 m standard. However, this recommended 2 m height for the measurement of wind speed at 2 m ($u_2$) was followed in computing a standard reference $ET_0$. Solar radiation was measured using LI200X-LC5 solar radiation sensor (LICOR, Inc., Lincoln, NE), air temperature and relative humidity were measured using the CS500-LC5 sensor (Vaisala, Inc., Woburn, MA), and rainfall amounts was measured using the TE525LC5 tipping bucket rain gauge (Texas Electronics Inc., Dallas, TX). For a thorough discussion of $R_n$ and $u_2$ computations of the standard reference $ET_0$ see Allen et al. (1998).

**Crop Coefficients ($K_c$) Values**

Daily reference $ET_0$ was calculated by an hourly time step and summation of predicted $ET_0$ from each hourly time step. A working crop coefficient of 1.0 was selected and used throughout the study. Turf $ET_T$ and reference $ET_0$ were measured according to a 24 h period from 900 h to 900 h. Crop coefficients were computed on a seasonal basis for the irrigation season (July through August) from daily $ET_T$-to-$ET_0$ ratio and then averaged. The computation of biweekly and monthly $K_c$ averages can be problematic in the cool-humid New England region due to the potential for spot showers during the summer period (Aronson et al., 1987) making turf $ET_T$ difficult to measure and $K_c$ values difficult to calculate without the use of a rainout shelter. Secondly, and as discussed by Aronson et al. (1987), $K_c$ values are highly variable on a biweekly and monthly basis suggesting the need to compute averages over the entire irrigation season, which may be more repeatable and have more practical application in the implementation of ET based irrigation for the cool-humid region (Sass and Horgan, 2006).

Brown et al. (2001) used regression (least square regression) with $ET_T$ as the response variable (dependent) and reference $ET_0$ as the predictor (independent variable) in the computation of $K_c$ values for warm-season turfgrass in the desert south west.

Specifically, if the intercept is statistically equal to zero the intercept of the least square equation can be omitted and the slope (*b*) is assumed to be $K_c$. Brown et al. (2001) reported that the arithmetic ratio and least square regression estimates of $K_c$ values to be similar under this special (zero intercept) case when the linear regression line is forced through zero.

Under the unpredictable rainfall conditions of New England, the biweekly or monthly estimates using the least square regression method may not be appropriate to achieve sufficient daily observations and degrees of freedom (≈20 df) for reliable estimates of $K_c$ and second-order statistics (variance) with the least square regression approach (Gauch et al., 2003). As such, the least square approach was more appropriate for estimating $K_c$ over the season and year using as many daily $ET_T$ and $ET_0$ observations as possible. To that end, least square regression to estimate $K_c$ were computed by regressing the $ET_T$ for each species, HOC and N rate on reference $ET_0$. These least square $K_c$ estimates were compared with the simple ratio estimate of $K_c$ averaged over the summer period for creeping bentgrass (CB), perennial ryegrass (PR), Kentucky bluegrass (KB), 98 and 196 kg N $ha^{-1}$ $yr^{-1}$, and short and tall HOC.

### Statistical Analysis

Data for $ET_T$ and $ET_0$ are reported as mm $d^{-1}$ while their ratios as $K_c$ values are reported without units. There were 23, 30, and 26 daily turf $ET_T$ measurement events made in 2011, 2012, and 2013, respectively, along with $ET_0$ and $K_c$ values reported for those same years. Leaf width and shoot density data were averaged across sampling periods (early July and late August) with leaf width reported as mm and shoot density as shoots per square decimeter (no. $dm^{-2}$). Daily leaf growth rate were averaged across the daily July and August measurement period and are reported as mm $d^{-1}$. Root dry weights were averaged over the same measurement periods (early July and late August) and are reported as mg dry weight per $cm^{-3}$.

All data was analyzed by ANOVA (MINITAB, State College, PA) as a 3 by 2 factorial of species and N rate as main plots with HOC as the sub-plot. Because treatments (fixed effects) were applied to the same respective plots in 2011, 2012, and 2013, years were treated as the repeated measure. The short cut golf and tall grass sports turf share similar surface ($r_s$) and aerodynamic ($r_a$) resistances within their respective group while potentially exhibiting different theoretical resistances, as well as leaf area (LAI) and canopy resistance ($r_c$) components, between the groups. As such, single degree of freedom (df) orthogonal contrasts were computed to compare golf turf (green and fairway) with sport-lawn grass (Kentucky bluegrass and perennial ryegrass). Orthogonal contrasts comparing Kentucky bluegrass with perennial ryegrass were also performed. Single df contrasts to partition the species main effects were crossed with N rate and HOC to further partition the various 2- and 3-way interactions. Fischer's protected least significant difference (LSD) values at the 0.05 level were used for comparisons between treatments and main effects. Confidence intervals (95%) are reported for regression (slope) estimates for $K_c$ values for main effects (species, HOC, and N rate) for comparing with $ET_T$-to-$ET_0$ arithmetic ratio estimates of $K_c$ values.

## Results and Discussion

### Turf $ET_T$

Previous research raised concerns regarding the effect of differential HOC on mini-lysimeter measured ET. Feldhake et al. (1983) in Colorado observed no temperature gradient from within 0.36 m of the edge in the transition from 2 to 5 cm HOC. They believed any border effect was secondary to the effect of short grass versus tall grass canopies and their effect on measured ET of the turf. In our study, the mowed plot area where lysimeters were installed in the center of plots was smaller (24,336 $cm^2$) than the Feldhake et al. (1983) study in Colorado (62,500 $cm^2$). However, our smaller lysimeter area (81 $cm^2$) compared to the Feldhake study (491 $cm^2$) created a less favorable (oasis) edge effect because of our 1-to-300 (lysimeter area-to-plot area "fetch area" ratio) compared to 1-to-127 for the Colorado study. Aboukhaled et al. (1982) suggested a buffer area that followed a 1-to-400 lysimeter area-to-plot area ratio. In addition, fetch requirements are more important for arid environments. Mather (1959) and Fougerouze (1966) suggested the fetch requirements are smaller for humid environments such as the cool-humid New England region. While turf ET may be affected by the oasis effect, like Feldhake et al. (1983), this was not a dominant factor.

The short grass canopy of CB (0.3125 and 0.9375 cm HOC) was associated with significantly lower $ET_T$ compared to tall grass (3.125 and 6.25 cm) KB and PR (Tables 1 and 2). Short cut CB (average of green and fairway HOC) was approximately 20% lower in $ET_T$ (4.11 mm $d^{-1}$) compared to the combined mean of KB and PR (5.08 mm $d^{-1}$, Table 2). The single df contrast comparing CB versus All (KB and PR) (Table 1) accounted for

98% of the effect of Species (S) and S accounted for 48% of the total treatment variation (data not shown). The CB $ET_T$ rates are similar to those reported by Sass and Horgan (2006) in July and August for Minnesota but are substantially lower by almost 90% compared to the CB $ET_T$ rates in July and August observed in Nebraska by Salaiz et al. (1991).

No difference in turf $ET_T$ was observed between the two tall grass species (KB and PR) (Tables 1 and 2). Tall grass species turf ET for July and August across all years averaged 5.08 mm $d^{-1}$ (Table 2). Kentucky bluegrass ranged from 4.88 (low N and low HOC) to 5.58 mm $d^{-1}$ (high N and high HOC) while PR ranged from 4.50 (low N and low HOC) to 5.89 mm $d^{-1}$ (high N and high HOC) (data not shown). These turf $ET_T$ rates in summer are approximately 25% higher than reported by Aronson et al. (1987) in Rhode Island for the same species but 15% lower for KB and PR in Colorado (Crookston and Hattendorf, 2010). In the Aronson study turf $ET_T$ was the average of July, August, and the full month of September for 2 years. Progressively shorter days and lower solar radiation in September can diminish turf $ET_T$.

Nitrogen applied in summer as SRN significantly increased turf $ET_T$, however, the increase in turf $ET_T$ when compared to non-fertilized plots was only 5% according to main effects for N (Tables 1 and 2). A significant CB vs. All (KB and PR) × N interaction was observed (Table 1) that showed PR in summer fertilized with 49 kg N $ha^{-1}$ promoted a significant (15%) increase in $ET_T$ compared to non-fertilized plots under irrigation in summer (Table 2). Neither CB nor KB showed any effect of N fertilization on $ET_T$. The fertilizer N used in our study in summer was approximately 82% as SRN from methylene urea, which was not sufficient to cause an increase in $ET_T$ in either CB or

KB $ET_T$ (Table 2). Ebdon et al. (1999) reported that KB leaf growth in response to N was curvilinear with diminishing return as N increased while Ebdon et al. (2013) and Hoffman et al. (2010) found PR to be linear in its leaf growth in response to N. As stated previously, there was a 2-fold increase (1.39 mm $d^{-1}$ increase) in turf $ET_T$ with PR compared to only 0.7 mm $d^{-1}$ increase in $ET_T$ with KB by fertilizing in summer as HOC increased.

Perennial ryegrass exhibited significantly higher leaf growth rates (2.11 mm $d^{-1}$) than KB (1.91 mm $d^{-1}$) with CB exhibiting ½ the leaf growth rate (0.96 mm $d^{-1}$) of KB and PR. Leaf area is a significant factor affecting turf $ET_T$, which promotes greater LAI and $ET_T$ (Shearman and Beard, 1973; Feldhake et al., 1983; Ebdon et al., 1999; Barton et al., 2009; Erickson and Kenworthy, 2011; McGroary et al., 2011). Turf $ET_T$ in our study was highly correlated with leaf growth rates (r=0.66, n=48, $P \leq 0.001$) suggesting any practice that diminishes leaf area will reduce turf $ET_T$. Plots fertilized with SRN in summer when compared to non-fertilized plots promoted either greater leaf growth rates or turf $ET_T$ in all species except for CB (Table 2).

The main effect of HOC on $ET_T$ was significant (Table 1) with taller HOC promoting a 10% higher $ET_T$ (Table 2) than the short grass HOC. No interaction between S and HOC was detected (Table 1) in turf $ET_T$ indicating species and HOC effects on turf $ET_T$ were independent. These results suggest that the taller HOC significantly promoted an increase in $ET_T$ in all species compared to the shorter HOC (i.e., CB: 0.9375 vs. 0.3125 cm HOC; KB and PR: 6.25 vs. 3.125 cm HOC). The short grass canopy of CB was the major factor in this species 20% lower turf $ET_T$ compared tall grass KB and PR as reported above. Clearly, the 2-fold (for KB and PR) and 3-fold (for CB) higher HOC differential was sufficient to cause higher $ET_T$ in these species under the conditions of this study. As stated previously, the main effect of taller HOC caused a 10% increase in turf $ET_T$, which was similar to the 15% increase in turf $ET_T$ with taller HOC (from 2 to 5cm) reported by Feldhake et al. (1983) in Colorado. Golf green and fairway HOC (0.3125 and 0.9375 cm, respectively) exhibited the lowest $ET_T$ rate because of their lower LAI and frequent mowing; greens HOC CB exhibited the lowest $ET_T$ (4.01 mm $d^{-1}$ ) followed by fairway HOC CB (4.22 mm $d^{-1}$) (data not shown).

A significant interaction was detected between the effect of N and HOC on $ET_T$ (Table 1). No significant difference was observed in $ET_T$ between the fertilized and non-fertilized plots when mowed at the low HOC, which averaged 4.49 and 4.56 mm $d^{-1}$, respectively (data not shown). The effect of fertilizer N on increasing $ET_T$ in summer was only observed at the tall HOC where plots fertilized with 49 kg N $ha^{-1}$ were significantly higher in $ET_T$ (5.24 mm $d^{-1}$) compared to non-fertilized plots (4.73 mm $d^{-1}$). Regardless of the species, the data suggest that fertilizing in summer with SRN when the turf is not short of water can have a significantly greater effect on increasing turf $ET_T$ when mowed at the high end of the HOC. No 3-way interaction (S × N × HOC) among the main effects was observed on $ET_T$ in this study (Table 1).

As discussed previously, the effect of species accounted for most (48%) of the total treatment variation on $ET_T$, which was followed by HOC (12%), and N (3%) with the random effect of year-to-year variation accounting for 2% (data not shown). While the effect of year-to-year variation on $ET_T$ was significant (Table 1), this effect is not under the control of the turf practitioner and therefore will not be discussed in detail. However, year 2013 was associated with the lowest turf $ET_T$ (4.63 mm $d^{-1}$) and lowest leaf growth rates (1.28 mm $d^{-1}$) (Table 2). A significant Y × S interaction (Table 1) indicated that year-to-year variation had no effect on $ET_T$ of short grass CB while KB $ET_T$ was lowest in year 2013 when PR exhibited the highest $ET_T$ in that same year (Table 2). A significant HOC by Y interaction was also detected in $ET_T$ that indicated turf $ET_T$ did not vary significantly between years at the taller HOC while at the lower HOC turf $ET_T$ in 2013 was lowest compared to years' 2011 and 2012 (data not shown). There were six significant 2-way, 3-way and 4-way interactions between fixed effects (S, HOC, and N) and year detected with leaf growth rate (Table 1), however, these interactions accounted for less than 10% of the total treatment variation. Conversely, the two 2-way interactions (Y × S and Y × HOC) discussed above accounted for 16% of the total treatment variation in turf $ET_T$.

The effect of species on shoot density accounted for 94% of the total treatment variation, which was due to the variation accounted for by the single df contrast comparing short grass CB versus tall grass KB and PR (Table 1) that accounted for 99% of the effect of species (data not shown). Short grass CB exhibited more than a 5-fold greater shoot density (1239 shoot $dm^{-2}$) compared to tall grass species (KB and PR), which averaged approximately 240 shoot $dm^{-2}$ (Table 2). No difference between tall grass species (KB and PR) was observed (Tables1 and 2). The main effect of HOC accounted for less than 1% of the treatment variation in shoot density but the effect was significant (Table 1). The lower HOC increased shoot density (Table 2) and no interactions between HOC with other fixed effects (S and N) were observed; indicating the closer HOC increased aerial shoot density in all species regardless of N rate. No effect on shoot density was observed due to the effect of N (Table 1). The data indicates that N affected turf $ET_T$ through its affects on leaf growth rates but not density while HOC affected shoot density but not leaf growth rates.

Higher shoot density has been proposed as a morphological characteristic that increases canopy resistance ($r_c$) to water vapor flux in mowed turfgrass (Shearman, 1986, 1989; Kim and Beard, 1988, Ebdon and Petrovic, 1998). Greater canopy resistance to ET has been shown to be 2 to 4 times larger as a resistance to water vapor flux than stomatal resistance when turfgrasses are maintained under non-limiting soil water (Johns et al., 1981). Shoot density has been shown to be negatively correlated with measured $ET_T$ (Shearman, 1986, 1989; Kim and Beard, 1988, Ebdon and Petrovic, 1998). We found a strong negative correlation between turf $ET_T$ and shoot density ($r=-0.67$, $n=48$, $P\leq0.001$). These results suggest that greater aerial shoot and leaf density was sufficient resistance to water vapor flux to increase vapor pressure density within the canopy to lower turf $ET_T$ (and vapor pressure deficit) as suggested by Johns et al. (1981).

Canopy resistance as described by Johns et al. (1981) is a component of the bulk surface resistance ($r_s$) described by Allen et al. (1998). The 20% lower turf $ET_T$ of closely mowed CB maintained as green and fairway HOC is most likely due to the lower LAI and greater surface resistance ($r_s$) (Allen et al., 1994). In addition, the significantly slower vertical leaf growth rates of short grass CB, which is ½ that of tall grass species (Table 2) can also reduce LAI and in turn, increase surface resistance, $r_s$ (Allen et al., 1994; Brown et al., 2001). Also, leaf width for short grass CB was approximately ½ the leaf width of tall grass KB and PR (Table 2), which may further lower LAI in this species and HOC. Accounting for additional resistances to lower CB turf to $ET_T$, slower leaf extension rates and daily mowing associated with CB greens HOC can reduce the accumulation of leaf area above the canopy surface that can increase aerodynamic resistance ($r_a$) of the bulk air above the canopy (Johns et al. 1981; Kim and Beard, 1988). Aerodynamic and surface resistances usually increase with decreasing HOC.

Pinter et al. (1979) found that when plants exhibited lower transpiration (i.e., lower turf $ET_T$) their leaf temperatures' increased. We recorded turf canopy temperatures from 1300 h to 1400 h on 30 August 2011 using an infrared thermometer (OMEGA Engineering Inc., Stamford CT, model 0S51). Five canopy temperature measurements per plot were recorded at a distance of 0.5 m above the turf canopy integrating an area of 31 $cm^2$. Averaged solar radiation ($R_n$) under clear sky was 692 $Wm^{-2}$, with an air temperature average of 27.1 °C, and average wind speed of 1.65 m $s^{-1}$ during the measurement period. Canopy temperature average for short grass CB was 26.1 °C, which was significantly higher ($P \leq 0.001$) than tall grass KB and PR, which averaged 24.3 and 24.2 °C, respectively. Feldhake et al. (1983) also reported that short grass (2 cm HOC) exhibited higher leaf temperatures (30 °C) than 5 cm HOC turf (29 °C). Under the conditions of our study where plants were not short of water, the greater resistance ($r_a$ and $r_s$) of short grass CB canopies was sufficient to lower turf $ET_T$ by reducing water vapor transfer, which also reduced latent heat flux transfer causing higher turf canopy temperatures in this species.

### FAO 56 Predicted $ET_0$

Mean, minimum, and maximum reference $ET_0$ calculated using the FAO 56 Penman-Monteith equation are reported in Table 3 for July and August months for all three years of the experimental period. Although mean reference $ET_0$ (evaporative demand) like turf $ET_T$ was lower in 2013 than 2011 and 2012, according to 95% confidence intervals, no statistical difference between yearly averages in FAO 56 $ET_0$ were observed. July averages for FAO 56 $ET_0$ were higher than the month of August in 2011 and 2012, however, no difference existed in 2013 between July and August estimates for reference $ET_0$. Calculated reference $ET_0$ using FAO 56 was more reliable (repeatable) in August based on lower coefficient of variation (CV, 11.7%) for this month, especially in 2012 (10.7%) and 2013 (10.9%).

Brown et al. (2001) reported that CVs generally decreased with decreasing cloudiness. Estimated solar radiation ($R_n$) may be less reliable during cloudy conditions. In our study, reference $ET_0$ calculated by the FAO 56 Penman-Monteith equation was highly correlated with solar radiation(r=0.88) accounting for as much as 77% of the variation in mean daily $ET_0$ (Table 4, showing year 2012 with the highest daily reporting dates). Cloudy skies are one factor contributing to less reliable reference $ET_0$ estimates and $K_c$ values. Brown et al. (2001) used the ratio of measured $R_n$ to theoretical clear sky radiation ($R_{so}$) as an indication of cloudy conditions and the reliability of estimating $ET_0$ and $K_c$ values. They found as the $R_n$-to-$R_{so}$ ratio increased (with more clear sky conditions), CVs decreased especially with the approach of clear sky conditions ($R_n$-to-$R_{so}$ > 0.90). We expressed mean daily solar radiation (MJ $m^{-2}$ $d^{-1}$) relative to the maximum measured $R_n$ (not $R_{so}$) for the 2012 reporting period ($R_n$-to-$R_{n\ max.}$, Table 4) and the corresponding CV. The CV for the August 2012 reporting period for $R_n$-to-$R_{n\ max.}$ was approximately ½ the CV for the July 2012 period, 9.1 and 19.3%, respectively. This data suggests less variable cloud cover day-to-day in August than July for year 2012;

hence, more repeatable reference $ET_0$ estimates (lower CV) in August of 2012 as reported in Table 3.

Predicted $ET_0$ according to FAO 56 captured 61% (2011), 84% (2012) and 68% (2013) of measured $ET_T$ based on lysimetry (Fig. 1). There were 23, 30, and 26 daily $ET_T$ events in 2011, 2012, and 2013, respectively. The general regression (all reporting dates for three years, n=79) FAO 56 $ET_0$ captured 67% of the total variation in turf $ET_T$. The slope estimates for year 2013 ($b$=0.76) was statistically lower ($P \leq 0.05$) than year 2011 ($b$=1.45) and 2012 ($b$=1.29) (Fig. 1). Figure 2 shows the same data ($ET_T$ versus $ET_0$) for all years (2011, 2012, and 2013) where the linear regression intercept (line) is forced through zero and the linear regression slope ($b$) is the estimate for the $K_c$ for those years. The assumption of linear regression derived slope estimates for $K_c$ (Table 5) is that the fitted line passes through zero (the origin, Fig. 2). In all cases for main effects reported in Table 5 for the general regression using all data (n=79) to estimate $K_c$ using the regression slope indicated that the intercept was not significantly different from zero; allowing the intercept not to be included in the final regression equation. Including the intercept reduces the practical usefulness of slope derived $K_c$ estimates because in those cases turf $ET_T$ is dependent on the intercept and $ET_0$.

The 1-to-1 line (Fig. 2) represents a crop coefficient of “1”. Regression lines for any year above the 1-to-1 line represents $K_c$ values greater than 1 while regression lines below the 1-to-1 line corresponding to $K_c$ values less than 1. For years 2011, 2012, and 2013, all $K_c$ values all are greater than “1” with year 2011, 2012, and 2013 slope estimates corresponding to 1.13, 1.14, and 1.07, respectively. These slope derived $K_c$ values for the three years correspond closely with the simple ratio method ($ET_T$-to-$ET_0$,

Table 2) reported as 1.13, 1.13, and 1.09 for year 2011, 2012, and 2013, respectively. Year 2011 and 2012 were statistical different from year 2013 according to ANOVA of the simple ratio method (Table 2). Unlike the simple ratio method (Table 2), 95% confidence intervals for slope estimates ($K_c$ values) shown in Table 5 indicated no statistical difference between years. All regression slope derived $K_c$ values for all years were within the 95% confidence interval for the general regression slope estimate of 1.12 (Table 5), which was the same $K_c$ value as the simple ratio method average of all three years (Table 2).

## Crop Coefficients ($K_c$ values)

There was strong agreement between the two methods (Table 2, simple ratio method; Table 5, slope estimates) used to estimate $K_c$ values using FAO 56 Penman-Monteith for the main effects of species, HOC, and N. In all cases, the general regression for all years (n=79, Table 5) was an effective average of individual years (2011, 2012, and 2013) for fixed main effects (S, N, HOC) and year; specifically, 95% confidence intervals indicated no difference between the three years. The one exception was KB in 2013, which exhibited a 95% confidence interval for regression slope derived $K_c$ values that was lower ($K_c$ = 1.05) than the general regression interval for all years ($K_c$ = 1.23) (Table 5). Crop coefficients reported in Table 2 ($ET_T$-to-$ET_0$ ratio) and Table 5 (slope derived $K_c$) were within 0.01 of each methods' respective $K_c$ estimate with the exception of KB and year 2013, which were within 0.02 (Tables 2 and 5). Brown et al. (2001) also reported the same range in difference between the two methods.

According to 95% confidence intervals, $ET_T$-to-$ET_0$ ratio derived $K_c$ values reported by month and year (Table 3) were statistically similar for July and August. Seasonal CVs for $K_c$ values (Table 3) ranged from 15.7 (July 2011) to 20.7% (July 2013) while those reported by Aronson et al. (1987) in Rhode Island ranged from 15 to 30%. Coefficient of variation for $K_c$ values observed by Brown et al. (2001) in the desert south west for fairway HOC bermudagrass (*Cynodon dactylon* L. × *C. transvaalinsis* Davy) in summer ranged from 5.7 to 18.5%. The lower CVs for $K_c$ values reported by Brown et al. (2001) using FAO 56 $ET_0$ are approximately 50% more accurate than our estimates of $K_c$ using FAO 56 $ET_0$ and 85% more accurate than the Rhode Island study reported $K_c$ estimates derived using the modified Penman equation. This variability reflects the more unsettled (cloudy) weather, higher humidity, and precipitation of the cool-humid New England region as well as the use of the less reliable modified Penman equation in the case of Rhode Island study.

Aronson et al. (1987) found that the lack trends and inconsistent data from month-to-month and year-to-year in New England made it necessary to average $K_c$ values. In our study the use of a constant $K_c$ for estimating turf $ET_T$ in summer is appropriate based on the statistically similar $K_c$ values for the $ET_T$-to-$ET_0$ ratio by month and year (Table 3, Fig. 4) and yearly slope estimates reported in Table 5. However, these $K_c$ values will vary with the species, HOC, and N rate applied (Tables 2 and 5).

Crop coefficients derived using the simple ratio method (Table 2) and linear regression (Table 5) indicated that short grass CB exhibited significantly lower $K_c$ values (0.96, Table 2; 0.97 Table 5) compared to tall species (KB and PR), which averaged 1.20. The approximately 20% lower $K_c$ values for short cut CB reflects the 20% lower turf $ET_T$

for this species reported earlier (Table 2). It follows that any practice that affects turf $ET_T$ such as HOC and N fertilization discussed previously will in turn affect $K_c$. As such, like turf $ET_T$, $K_c$ values increased with increasing leaf growth rates (Fig. 3) with leaf growth accounting for 43% of the total variation in $K_c$ values. Brown et al. (2001) reported a similar relationship between crop coefficients and growth rate in bermudagrass during summer in Arizona. Furthermore, as shoot density increased in our study, $K_c$ values decreased, r=–0.67, $P \leq 0.001$). We found lower HOC to significantly lower $K_c$ values based on both the $ET_T$-to-$ET_0$ ratio method (Table 2) and $K_c$ calculated using regression slope estimates, especially for year 2012 and 2013 (Table 5). Fertilizing in summer with SRN at 49 kg N $ha^{-1}$ significantly increased $K_c$ values according to the ratio method (Table 2) but no difference in $K_c$ values were observed based on regression slope estimates (Table 5).

All reported $K_c$ estimates for main effects are greater than 1 with the exception of short cut CB (Tables 2 and 5), which was less than 1. According to 95% confidence intervals for slope estimates of $K_c$ values (Table 5), short grass CB ranged from 0.92 to 1.00. These $K_c$ values for CB maintained at greens and fairway HOC (0.3125 and 0.9375 cm) were similar to those reported by Sass and Horgan (2006) using FAO 56 $ET_0$ in Minnesota for CB maintained at 0.5 cm HOC. These authors reported a range for FAO 56 $ET_0$ derived $K_c$ of 0.85 to 1.05 with a recommended (average) $K_c$ of 0.98 for short cut CB. Salaiz et al. (1991) using the modified Penman equation to estimate $ET_0$ in Nebraska reported a range of 0.87 to 1.13 for 10 CB cultivars mowed at 1.25 cm HOC. Allen et al. (1998) recommends for cool-season turfgrass a working coefficient for $K_c$ of 0.95 and HOC of 6 to 10 cm but they do not provide any direct research in support of their recommendation. Our reported range for short grass CB (0.3125 to 0.9375 cm HOC) of approximately 0.90 to 1.00 (Table 5) and that of Sass and Horgan (2006) follows closely with the recommendation of Allen et al. (1998) for a $K_c$ value less than 1.0 that is intended, however, for significantly taller grass (6 to 10 cm). The lower $K_c$ values for short grass CB are consistent with this species HOC and its greater resistance to $ET_T$ discussed previously including the potential for greater surface resistance ($r_s$, higher shoot densities), greater aerodynamic resistance ($r_a$, short HOC, slower leaf growth rate) and lower LAI (narrow leaf texture and slower vertical leaf extension rates).

No difference was observed between tall grass KB and PR $K_c$ values according to both methods of calculating crop coefficients (Tables 2 and 5). The average $K_c$ value (1.20) for tall grass (KB and PR) and 95% confidence interval (1.17 to 1.25) are significantly greater than 1.0 (Table 5). Aronson et al. (1987) reported and recommended an average $K_c$ of 1.0 for irrigating cool-season turfgrass in the cool-humid northeast. In the Aronson study, $K_c$ values were derived using the modified Penman equation and not the FAO 56 Penman-Monteith equation. We made adjustments in computing $K_c$ values following the recommendation of Brown et al. (1998, 2001) in cases where different reference $ET_0$ procedures are used and $K_c$ values can differ by as much as 25% in estimating $ET_0$ under similar climatic (evaporative) conditions. The modified Penman equation used by Aronson et al. (1987) will over-estimate $ET_0$ relative to FAO 56 Penman-Monteith $ET_0$ because the modified Penman equation does not account for the significant surface resistance ($r_s$ and $r_c$) of turf, especially in the shorter (3.125 cm HOC) tall grass. Adjusting Rhode Island $K_c$ values up by 10 to 15% (Brown et al., 2001) and as high as 25% (Brown et al., 1998) for use with the FAO 56 Penman-Monteith $ET_0$ would give ranges similar to $K_c$ values reported in Table 5 using FAO 56 $ET_0$ for tall grass KB and PR.

Similar to the results reported with turf $ET_T$, we observed a significant S × N interaction effect on $K_c$ values with crop coefficients increasing significantly on tall grass PR in response to fertilization with 49 kg N $ha^{-1}$ (Table 2). Alternatively, CB and KB exhibited no response to fertilizer applied as 82% SRN in summer. Accordingly, spoon-feeding with low N rates (0.5 to 1.0 g $m^{-2}$) of water soluble N (WSN) would not be expected to cause any significant increase in turf $ET_T$. It is likely that applying greater percentages of WSN in summer at the same N rate (49 kg N $ha^{-1}$) would cause significant increases in leaf growth and turf $ET_T$. Like turf $ET_T$, the effect of species and HOC on $K_c$ did not interact (Table 1) suggesting that the effect of species and HOC were independent in their effect on $K_c$ values. However, there was a significant interaction between HOC and N on $K_c$ (Table 1). Specifically, like turf $ET_T$, no difference was observed between fertilized and non-fertilized plots in summer at the low HOC while significant increases in $K_c$ with N was observed with the taller HOC regardless of the species; no significant S × HOC × N interaction was observed (Table 1). Crop coefficients increased with N from 1.11 to 1.23 under the taller HOC while at the lower HOC $K_c$ values were statistically similar between non-fertilized and fertilized turf, 1.07 and 1.06, respectively (data not shown).

The data indicates that fertilizing taller CB (i.e., fairway, 0.9375 cm HOC) and taller PR and KB turf (6.25 cm HOC) in summer with 82% SRN may promote higher turf $ET_T$ and therefore, higher crop coefficients (irrigation amounts) may be needed to compensate for the higher $ET_T$. The higher $K_c$ in summer with N fertilization compared to non-fertilized turf represents approximately a 0.10 increase in $K_c$ for the taller HOC. According to regression slope estimates, the recommended range for $K_c$ values in summer for tall grass species (KB and PR) is 1.15 to 1.25 (Table 5). The higher $K_c$ value of 1.25 may be appropriate for taller HOC KB and PR (6.25 cm HOC) under fertilization in summer while the lower $K_c$ value of 1.15 would be recommended for non-fertilized KB and PR at the shorter HOC (3.125 cm). The lower $K_c$ value of 1.15 with tall grass species (KB and PR) correlate with practices such as low HOC and low N that lower turf $ET_T$ (Table 2 and 5). Conversely, the higher $K_c$ value of 1.25 correlate with the effects associated with higher HOC and higher N that increase $ET_T$ (Tables 2 and 5). The average $K_c$ value of 1.20 (Tables 2 and 5) for tall grass KB and PR is recommended where competing effects from two or more cultural practices that increase and decrease turf $ET_T$ in summer, such as low HOC and high N or high HOC and low N, are followed.

For short HOC CB, the range in summer for $K_c$ values is 0.90 to 1.00 (Table 5). The lower $K_c$ of 0.90 may be more appropriate for conditions promoting lower turf $ET_T$ such as greens HOC (0.3125 cm) under low N (spoon-feeding) while a summer $K_c$ value of 1.0 may be recommended where higher $ET_T$ is expected due to the effects of taller HOC (0.9375 cm) under fertilization (Tables 2 and 5). As described for tall grass species, the average $K_c$ value for short grass CB ($K_c$ =0.95, Tables 2 and 5) may be appropriate where turf maintenance is implemented that include cultural practices with opposite and competing effects on turf $ET_T$. In addition to fertilizer and HOC, Kneebone et al. (1992) and more recently Kopp and Jiang (2013) and Leinauer and Devitt (2013) describe numerous other cultural factors affecting water use in turf including soil compaction and cultivation, growth regulators, and species and cultivars.

## Rooting

Rooting differences (mg dry weight $cm^{-3}$) were detected among treatments at all soil depths with the exception of the deepest portion of the soil profile (45 to 65 cm, Table 6). The effect of treatment was due principally to the effect of species (Table 6). The effect of species accounted for 72, 41, and 26% of the total treatment variation at the 0 to 10, 10 to 25, and 25 to 45 cm soil depth, respectively, while other fixed main effects were less than 3% of the treatment variation in rooting. Additionally, single df contrasts comparing CB versus All (KB and PR) was significant at the 0 to 10, 10 to 25, and 25 to 45 cm depth indicating differences between the short grass CB and tall grass KB and PR.

Rooting at soil depths from 0 to 45 cm for short grass CB was significantly less than tall grass KB and PR (Table 7). Rooting dry weights per $cm^3$ for short grass CB was approximately 45% less than tall grass KB and PR at the 0 to 25 cm soil depth but CB rooting declined further to approximately 64% of the rooting of tall grass species at the 25 to 45 cm soil depth (Table 7). The effect of short grass HOC (0.3125 and 0.9375 cm) significantly reduced rooting especially in the deepest portion of the rooting profile when compared to the taller 3.125 and 6.25 cm HOC. No significant main effect due to HOC was observed indicating that the effect of HOC (tall vs. short grass) was not significant (Tables 6 and 7); suggesting no difference in rooting between green and fairway HOC (0.3125 vs. 0.9375 cm) and tall grass species HOC (3.125 vs. 6.25 cm). The effect of HOC, however, was observed to influence rooting through its interaction with species, which is discussed below.

The effect of fertilization with N on rooting was secondary to the effect of species but significant differences were observed at the 10 to 25 and 25 to 45 cm soil depths (Table 6). Rooting dry weights decreased with higher N by approximately 18 and 33% at the 10 to 25 and 25 to 45 cm soil depths, respectively (Table 7). No interactions between N with either species and HOC were observed, however, a significant S × HOC interaction was detected at the 10 to 25 and 25 to 45 cm soil depths (Table 6). Specifically, KB rooting at the 10 to 25 and 25 to 45 cm soil depth increased at the lower HOC by 23 and 67%, respectively (Table 7). Furthermore, rooting of PR at the 10 to 25 cm soil depth was superior to KB. The effect of year and year interaction with species were significant (Table 6). Year 2012 and 2013 exhibited superior rooting dry weight than 2011 except at the 0 to 10 cm soil depth (Table 7). Rooting declined significantly with each year for all species at 10 to 25 and 25 to 45 cm soil depths while at the 0 to 10 cm soil depth no difference in rooting between years was observed with KB (Table 7). Rooting of KB was superior to all other species at this soil depth (0 to 10 cm) regardless of the year.

The objective of this study was to develop reliable $K_c$ values using the FAO 56 Penman-Monteith equation. To that end, one of the assumptions of FAO 56 (Allen et al., 1998) is that the reference crop is not short of water and is grown under optimal soil water conditions. Following these standard conditions for the reference crop, our field plots were never exposed to soil water limiting conditions and therefore plants were not subjected to negative water imbalances such as wilt (and drought). Wilting in turf is associated with increases in stomatal resistance (Perdomo et al., 1996; Kopp and Jiang, 2013), which is a major resistance to turf $ET_T$ not fully accounted for by the bulk surface resistance ($r_s$) as described by Allen et al. (1998). Such reductions in stomatal conductance and plant growth (LAI) would lower $ET_T$ and require adjustments (reductions) in $K_c$ values. Kopec et al. (1988) and Carrow (1995) reported 20 and 30% reductions in $K_c$ values, respectively, between non-stressed and moderate water stressed conditions.

Managing turf to promote deeper rooting has been shown to increase drought resistance (Carrow, 1996; Bonos and Murphy, 1999; Fu et al., 2007). Deeper rooting delays wilting tendencies, postpones reductions in stomatal conductance, and lengthens the irrigation cycle in KB (Ebdon and Kopp, 2004) and PR (Lanier et al., 2012). The 45% and 67% greater rooting of tall grass KB and PR at the 0 to 25 cm and 25 to 45 cm soil depth (Table 7), respectively, offers tall grass KB and PR with significant advantages over green and fairway HOC in terms of greater acquisition to soil water, despite short grass CB 20% lower $ET_T$ rates (Table 2). Ebdon and Kopp (2004) showed that turf $ET_T$ measured under non-limiting soil water played a secondary role to deep rooting in drought resistance. Irrigating turf according to $ET_T$ replacement in order to apply the proper amount of water as irrigation is an important practice for conserving water. In addition, cultural practices that will reduce turf $ET_T$ and promote deep rooting will increase drought resistance by enhancing avoidance characteristics (Carrow, 1996). Low ET and deep rooting are two major plant characteristics that help to lengthen irrigation intervals. Applying water in deficit amounts that do not fully replace all soil water lost as turf $ET_T$ can allow for additional water savings but some reductions is plant growth and function are expected depending on the level of deficit irrigation replacement (Feldhake et al., 1984; DaCosta and Huang, 2006).

Nitrogen fertilization in summer using primarily SRN (82%) as in our study promoted only 5% higher $ET_T$ (Table 2) but reduced rooting depth by 20% (10 to 25 cm soil depth) to 33% (25 to 45 cm soil depth) (Table 7). Inhibition of rooting in the deepest portion of the soil profile has been shown to be affected more by the incremental increase in WSN than rooting in the upper portions of the soil profile (Ebdon et al., 2013). Deep rooting during periods of drought is most important in maintaining turf growth and function in the field (Carrow, 1996). Opportunities to keep N rates to their lowest possible level are especially important for optimum water acquisition (deeper rooting, Table 7) and to minimizes leaf growth rates (Table 2) and in turn, reduce turf $ET_T$ and associated $K_c$ values (Fig. 3).

Mowing HOC offers competing effects on $ET_T$ and rooting as it relates to drought resistance because shorter HOC reduces turf $ET_T$ (Madison and Hagan, 1962; Shearman and Beard, 1973; Biran et al., 1981; Feldhake et al., 1983; Fry and Butler, 1989; Brown and Kopec, 2000) while rooting decreases with lower HOC (Madison and Hagan, 1962; Salaiz et al., 1995; Yelverton, 1999; Huang and Fry, 1999; Liu and Huang, 2002). While we observed significantly less rooting with short grass CB (0.3125 and 0.9375 cm) compared to taller KB and PR (3.125 and 6.25 cm), no difference in rooting was observed between HOC within the species. Similarly, Madison and Hagan (1962) did not observe any effect on Merion KB rooting (soil water extraction) by lowering the HOC within the species adapted range from 5 and 2.5 cm; rooting was not reduced significantly until HOC was lowered to 1.25 cm.

## Conclusions

FAO 56 Penman-Monteith reference $ET_0$ was effective in predicting actual turf $ET_T$ during the summer (July and August) over a 3-year period (2011 to 2013). The general regression equation using all data (n=79) indicated that FAO 56 $ET_0$ accounted for 67% ($P \leq 0.001$) of the total variation in actual ET of the turf but in some years (2012) the $r^2$ was as high as 0.84 (n=30, $P \leq 0.001$). Solar radiation when compared to other meteorological data measured by a nearby weather station was most correlated with FAO 56 $ET_0$ ($r$=0.88, $P \leq 0.001$). No significant difference was observed between years in FAO 56 $ET_0$ (evaporative demand) but July reference $ET_0$ was higher than August in two of three years.

Daily turf $ET_T$ using weighing lysimeters (314 $cm^2$) was measured and compared with the reference standard equation, FAO 56 $ET_0$. The effect of three species (CB, KB, PR) were evaluated as a 3 by 2 factorial treatment design with two N rates (0 and 49 kg N $ha^{-1}$ applied in July) as main plots. Main plots were then split according to HOC as short grass CB (0.3125 and 0.9375 cm HOC) and tall grass KB and PR (3.125 and 6.25 cm HOC). Crop coefficients ($K_c$ values) were derived as daily $ET_T$-to-$ET_0$ ratio and using linear regression derived slope estimates. Both methods that were used to estimate $K_c$ were in agreement according to the effects of species, HOC, and N on $K_c$ values.

Short grass CB exhibited 20% lower turf $ET_T$ (and $K_c$) compared to taller grass KB and PR. Short grass CB exhibited ½ the leaf growth rates, 5-fold greater shoot density, and 67% less rooting at the 25 to 45 cm soil depth than tall grass KB and PR. Turf $ET_T$ and $K_c$ values were correlated with leaf growth rates (r=0.66, n=48, $P \leq 0.001$)

and shoot density (r=–0.67, n=48, $P \leq 0.001$). The potential for greater bulk surface resistance ($r_s$) and aerodynamic resistance ($r_a$) along with lower LAI of short grass CB can account for golf green and fairway HOC lower turf $ET_T$ and lower $K_c$ values that were less than 1.

Confidence intervals according to slope derived $K_c$ values ranged from 0.90 to 1.00 for short grass CB. Tall grass KB and PR $K_c$ values ranged from 1.15 to 1.25. Turf $ET_T$ and $K_c$ values increased by approximately 5% with N fertilization in summer and by 10% with the higher HOC. Cultural practices promoting greater LAI and that diminish resistance to $ET_T$ will need to use higher $K_c$ values. Crop coefficients reported here for tall grass species were higher than previous studies when grown under similar meteorological conditions because of the use of different reference $ET_0$ equations. For short grass CB, $K_c$ values observed in our study were identical to other studies that used FAO 56 Penman-Monteith reference $ET_0$ when grown under similar meteorological conditions.

This study provides turf practitioners with an estimate of FAO 56 Penman-Monteith $ET_0$ crop coefficients for various cool-season species used in golf, sports, and lawn turf when grown under non-stressed and similar meteorological conditions to this study. Meteorological scheduling of irrigation in summer using FAO 56 $ET_0$ will need to select crop coefficients dependent on practices such as HOC and N fertilization in addition to numerous other practices and conditions.

Table 1. Analysis of variance indicating significant sources of variation for the effects of three species (creeping bentgrass, CB; Kentucky bluegrass, KB; perennial ryegrass, PR), two nitrogen rates, and two heights of cut (HOC) on crop coefficients ($K_c$), turf ET ($ET_T$), and shoot growth measured over a three year period.

| Source of variation | df | $K_c$ | $ET_T$ | Leaf growth | Shoot density | Leaf width |
|---|---|---|---|---|---|---|
| | | $ET_T/ET_0$ | mm $d^{-1}$ | mm $d^{-1}$ | No. $dm^{-2}$ | mm |
| Block | 3 | *** | *** | NS | NS | NS |
| Species (S) | 2 | *** | *** | *** | *** | *** |
| CB vs. All | 1 | *** | *** | *** | *** | *** |
| KB vs. PR | 1 | NS | NS | * | NS | ** |
| N, low vs. high | 1 | * | * | ** | NS | NS |
| S × N | 2 | * | * | *** | NS | NS |
| CB vs. All × N | 1 | * | * | *** | NS | NS |
| KB vs. PR × N | 1 | NS | NS | NS | NS | NS |
| HOC, short vs. tall | 1 | ** | ** | NS | * | * |
| S × HOC | 2 | NS | NS | ** | NS | NS |
| CB vs. All × HOC | 1 | NS | NS | *** | NS | NS |
| KB vs. PR × HOC | 1 | NS | NS | NS | NS | NS |
| N × HOC | 1 | ** | ** | * | NS | NS |
| S × N × HOC | 2 | NS | NS | NS | NS | NS |
| CB vs. All × N × HOC | 1 | NS | NS | NS | NS | NS |
| KB vs. PR × N × HOC | 1 | NS | NS | NS | NS | NS |
| Year (Y) | 2 | * | * | *** | *** | NS |
| Y × S | 4 | *** | *** | *** | *** | NS |
| Y × N | 2 | NS | NS | NS | NS | NS |
| Y × HOC | 2 | ** | ** | *** | NS | NS |
| Y × S × N | 4 | NS | NS | ** | NS | NS |
| Y × S × HOC | 4 | NS | NS | *** | NS | NS |
| Y × N × HOC | 2 | NS | NS | * | NS | NS |
| Y × S × N × HOC | 4 | NS | NS | * | NS | NS |

*, **, *** Indicates significance at $P \leq 0.05$, 0.01, and 0.001, respectively.
NS Indicates not significant.

Table 2. Means for the effects of three species (creeping bentgrass, CB; Kentucky bluegrass, KB; perennial ryegrass, PR), two nitrogen rates, and two heights of cut (HOC) on crop coefficients ($K_c$), turf ET ($ET_T$), and shoot growth measured over a three year period.

| Source of variation | $K_c$ | $ET_T$ | Leaf growth | Shoot density | Leaf width |
|---|---|---|---|---|---|
| Species (S) | $ET_T/ET_0$ | mm $d^{-1}$ | mm $d^{-1}$ | No. $dm^{-2}$ | mm |
| CB | 0.97b† | 4.11b | 0.96c | 1239a | 1.04c |
| KB | 1.21a | 5.16a | 1.91b | 223b | 1.89a |
| PR | 1.17a | 4.99a | 2.11a | 256b | 1.79b |
| N, kg $ha^{-1}$‡ | | | | | |
| 0 | 1.09b | 4.64b | 1.49b | 564a | 1.58a |
| 49 | 1.14a | 4.86a | 1.83a | 582a | 1.58a |
| HOC§ | | | | | |
| Short | 1.06b | 4.52b | 1.63a | 621a | 1.57b |
| Tall | 1.17a | 4.98a | 1.68a | 525b | 1.59a |
| Year (Y) | | | | | |
| 2011 | 1.13a | 4.81a | 2.04a | 640a | 1.59a |
| 2012 | 1.13a | 4.82a | 1.66b | 632a | 1.59a |
| 2013 | 1.09b | 4.63b | 1.28c | 445b | 1.55a |
| S × N | | | | | |
| CB + 0 | 0.99cd | 4.22cd | 0.91e | 1219 | 1.04 |
| CB + 49 kg N $ha^{-1}$ | 0.94d | 4.01d | 1.00e | 1260 | 1.05 |
| KB + 0 | 1.19ab | 5.08ab | 1.68d | 202 | 1.91 |
| KB+ 49 kg N $ha^{-1}$ | 1.23a | 5.23a | 2.13b | 243 | 1.87 |
| PR + 0 | 1.09bc | 4.62bc | 1.86c | 270 | 1.77 |
| PR+ 49 kg N $ha^{-1}$ | 1.26a | 5.35a | 2.37a | 242 | 1.82 |
| S × Y | | | | | |
| CB 2011 | 0.98e | 4.17e | 1.30c | 1370a | 1.03 |
| CB 2012 | 0.96e | 4.07e | 0.87e | 1356a | 1.01 |
| CB 2013 | 0.96e | 4.10e | 0.71f | 992b | 1.09 |
| KB 2011 | 1.28a | 5.43a | 2.46a | 244c | 1.92 |
| KB 2012 | 1.28a | 5.46a | 2.13b | 248c | 1.93 |
| KB 2013 | 1.08d | 4.58d | 1.14d | 176cd | 1.83 |
| PR 2011 | 1.13cd | 4.82cd | 2.36a | 306c | 1.82 |
| PR 2012 | 1.16bc | 4.94bc | 1.98b | 293c | 1.82 |
| PR 2013 | 1.22ab | 5.20ab | 2.00b | 168d | 1.73 |

†Means followed by the same letter(s) within the same response variable and source of variation are not statistically different at $P \leq 0.05$. No mean separations are reported for non significant 2-factor interactions.

‡Fertilization with N during the experimental period was applied 16, 12, and 24 July in 2011, 2012, and 2013, respectively.

§HOC for short grass CB, KB, and PR was 0.3125, 3.125, and 3.125 cm, respectively, and 0.9375, 6.25, and 6.25 cm, respectively, for tall grass.

Table 3. General statistics by month and year for $ET_0$ and crop coefficients.

| Variable | Mean | Minimum | Maximum | 95% CI† | CV |
|---|---|---|---|---|---|
| FAO 56 $ET_0$ | ------------------------mm $d^{-1}$------------------------ | | | | % |
| $ET_0$ 2011, n=23 | 4.32 | 3.02 | 5.42 | 4.05 to 4.60 | 15.1 |
| $ET_0$ 2012, n=30 | 4.24 | 2.25 | 5.64 | 3.90 to 4.58 | 21.4 |
| $ET_0$ 2013, n=26 | 3.90 | 2.42 | 5.28 | 3.60 to 4.19 | 18.8 |
| | | | | | |
| $ET_0$ July, n=38 | 4.59 | 2.25 | 5.64 | 4.31 to 4.87 | 18.5 |
| $ET_0$ August, n=41 | 3.74 | 2.87 | 4.71 | 3.60 to 3.88 | 11.7 |
| | | | | | |
| $ET_0$ July, 2011, n=9 | 4.95 | 4.37 | 5.42 | 4.67 to 5.24 | 7.5 |
| $ET_0$ August, 2011, n=15 | 3.94 | 3.02 | 4.71 | 3.69 to 4.20 | 11.6 |
| $ET_0$ July, 2012, n=15 | 4.81 | 2.25 | 5.64 | 4.31 to 5.32 | 19.1 |
| $ET_0$ August, 2012, n=15 | 3.67 | 2.99 | 4.66 | 3.45 to 3.88 | 10.7 |
| $ET_0$ July, 2013, n=15 | 4.15 | 2.42 | 5.28 | 3.69 to 4.61 | 20.0 |
| $ET_0$ August, 2013, n=11 | 3.55 | 2.87 | 4.34 | 3.29 to 3.81 | 10.9 |
| | | | | | |
| Crop Coefficient ($K_c$) | --------------------$ET_T$-to-$ET_0$ ratio-------------------- | | | | |
| $K_c$ July | 1.10 | 0.57 | 1.79 | 1.07 to 1.14 | 18.3 |
| $K_c$ August | 1.14 | 0.63 | 1.85 | 1.10 to 1.17 | 17.5 |
| | | | | | |
| $K_c$ July, 2011 | 1.12 | 0.79 | 1.51 | 1.07 to 1.17 | 15.7 |
| $K_c$ August, 2011 | 1.15 | 0.81 | 1.62 | 1.09 to 1.21 | 17.4 |
| $K_c$ July, 2012 | 1.14 | 0.71 | 1.55 | 1.08 to 1.20 | 17.6 |
| $K_c$ August, 2012 | 1.13 | 0.68 | 1.57 | 1.07 to 1.19 | 17.5 |
| $K_c$ July, 2013 | 1.04 | 0.57 | 1.79 | 0.98 to 1.11 | 20.7 |
| $K_c$ August, 2013 | 1.13 | 0.63 | 1.85 | 1.08 to 1.19 | 17.9 |

†95% confidence interval.

Table 4. General statistics for July and August 2012 for meteorological data including 95% confidence intervals. Correlation coefficients (*r*-value) between meteorological data and FAO 56 reference $ET_0$ are reported.

| Variable | Mean max. air temp. | | Mean relative humidity | | Mean solar radiation, $R_n$ | | | |
|---|---|---|---|---|---|---|---|---|
| | °C† | *r* with $ET_0$ | %† | *r* with $ET_0$ | MJ $m^{-2}$ $d^{-1}$† | *r* with $ET_0$ | $R_n/R_{n\ max.}$ | CV, $R_n/R_{n\ max.}$ |
| 2012, n=30 | 30.7±1.0 | 0.53** | 69.8±2.4 | −0.73*** | 21.2±1.4 | 0.88*** | 0.75±0.05 | 18.1% |
| July, 2012, n=15 | 31.6±1.3 | 0.43 | 66.4±3.5 | −0.72** | 23.1±2.5 | 0.87*** | 0.82±0.09 | 19.3% |
| August, 2012, n=15 | 29.7±1.5 | 0.56* | 73.2±2.3 | −0.14 | 19.4±1.0 | 0.71** | 0.84±0.04 | 9.1% |

*, **, *** Statistically significant at the 0.05, 0.01, and 0.001 levels, respectively.

†95% confidence intervals reported.

Table 5. Crop coefficients ($K_c$ values) derived using slope estimates from regression analysis with turf $ET_T$ as dependent and FAO 56 $ET_0$ as independent variables reported for three growing season (2011, 2012, and 2013) during July and August. Regression slopes were derived with regression intercept set to zero to calculate $K_c$. Individual regression slopes are shown for Kentucky bluegrass (KB), perennial ryegrass (PR) and creeping bentgrass (CB) maintained at two heights of cut (HOC) and two N rates.

| | 2011 growing season | | | 2012 growing season | | | 2013 growing season | | | General regression | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Factor | Slope | $R^2$ (n=23) | Slope† (95% CI) | Slope | $R^2$ (n=30) | Slope† (95% CI) | Slope | $R^2$ (n=26) | Slope† (95% CI) | Slope | $R^2$ (n=79) | Slope† (95% CI) |
| Species | -------------------------------------------------------------------------------------------------$d\mathrm{ET}_T/d\mathrm{ET}_0$--------------------------------------------------------------------------------- | | | | | | | | | | | |
| CB | 0.99 | 0.591*** | 0.90 to 1.09 | 0.95 | 0.474*** | 0.87 to 1.03 | 0.94 | 0.596*** | 0.89 to 0.98 | 0.96 | 0.464*** | 0.92 to 1.00 |
| KB | 1.29 | 0.589*** | 1.22 to 1.37 | 1.29 | 0.911*** | 1.25 to 1.33 | 1.05 | 0.396*** | 0.99 to 1.12 | 1.23 | 0.621*** | 1.18 to 1.27 |
| PR | 1.14 | 0.584*** | 1.06 to 1.23 | 1.19 | 0.881*** | 1.14 to 1.24 | 1.21 | 0.817*** | 1.17 to 1.25 | 1.18 | 0.711*** | 1.15 to 1.22 |
| Kg N ha$^{-1}$‡ | | | | | | | | | | | | |
| 0 | 1.11 | 0.712*** | 1.04 to 1.19 | 1.13 | 0.834*** | 1.07 to 1.18 | 1.04 | 0.680*** | 1.00 to 1.09 | 1.10 | 0.708*** | 1.07 to 1.13 |
| 49 | 1.17 | 0.491*** | 1.08 to 1.27 | 1.16 | 0.823*** | 1.12 to 1.20 | 1.09 | 0.647*** | 1.04 to 1.14 | 1.15 | 0.605*** | 1.11 to 1.19 |
| HOC§ | | | | | | | | | | | | |
| Short | 1.12 | 0.634*** | 1.04 to 1.20 | 1.08 | 0.773*** | 1.03 to 1.13 | 0.98 | 0.607*** | 0.93 to 1.03 | 1.07 | 0.608*** | 1.03 to 1.10 |
| Tall | 1.16 | 0.561*** | 1.08 to 1.25 | 1.21 | 0.876*** | 1.16 to 1.25 | 1.15 | 0.762*** | 1.11 to 1.20 | 1.18 | 0.698*** | 1.15 to 1.22 |
| Yearly ave. | 1.13 | 0.610*** | 1.06 to 1.24 | 1.14 | 0.837*** | 1.10 to 1.19 | 1.07 | 0.675*** | 1.02 to 1.11 | 1.12 | 0.672*** | 1.09 to 1.16 |

*** Statistically significant at the 0.001 level.

†95% confidence intervals from regression.

‡Fertilization with N during the experimental period was applied 16, 12, and 24 July in 2011, 2012, and 2013, respectively.

§HOC for short grass CB, KB, and PR was 0.3125, 3.125, and 3.125 cm, respectively, and 0.9375, 6.25, and 6.25 cm, respectively, for tall grass.

Table 6. Analysis of variance indicating significant sources of variation for the effects of three species (creeping bentgrass, CB; Kentucky bluegrass, KB; perennial ryegrass, PR), two nitrogen rates, and two heights of cut (HOC) on rooting at four soil depths measured over a three year period.

| Source of variation | df | 0 to 10 cm | 10 to 25 cm | 25 to 45 cm | 45 to 65 cm |
|---|---|---|---|---|---|
| | | mg dry weight $cm^{-3}$ | | | |
| Block | 3 | NS | * | NS | NS |
| Species (S) | 2 | ** | * | * | NS |
| CB vs. All | 1 | ** | ** | ** | NS |
| KB vs. PR | 1 | * | NS | NS | NS |
| N, low vs. high | 1 | NS | * | ** | NS |
| S × N | 2 | NS | NS | NS | NS |
| CB vs. All × N | 1 | NS | NS | NS | NS |
| KB vs. PR × N | 1 | NS | NS | NS | NS |
| HOC, short vs. tall | 1 | NS | NS | NS | NS |
| S × HOC | 2 | NS | * | NS | NS |
| CB vs. All × HOC | 1 | NS | * | NS | NS |
| KB vs. PR × HOC | 1 | NS | * | * | NS |
| N × HOC | 1 | NS | NS | NS | NS |
| S × N × HOC | 2 | NS | NS | NS | NS |
| CB vs. All × N × HOC | 1 | NS | NS | NS | NS |
| KB vs. PR × N × HOC | 1 | NS | NS | NS | NS |
| Year (Y) | 2 | NS | *** | *** | NS |
| Y × S | 4 | * | * | *** | NS |
| Y × N | 2 | NS | NS | NS | NS |
| Y × HOC | 2 | NS | NS | NS | NS |
| Y × S × N | 4 | NS | NS | NS | NS |
| Y × S × HOC | 4 | NS | NS | NS | NS |
| Y × N × HOC | 2 | NS | NS | NS | NS |
| Y × S × N × HOC | 4 | NS | NS | NS | NS |

*, **, *** Indicates significance at $P \leq 0.05$, 0.01, and 0.001, respectively.

NS Indicates not significant.

Table 7. Means for the effects of three species (creeping bentgrass, CB; Kentucky bluegrass, KB; perennial ryegrass, PR), two nitrogen rates, and two heights of cut (HOC) on rooting at three soil depths measured over a three year period.

| Source of variation | 0 to 10 cm | 10 to 25 cm | 25 to 45 cm |
|---|---|---|---|
| | -----------mg dry weight $cm^{-3}$-------------- | | |
| Species (S) | | | |
| CB | 1.5b | 0.28b | 0.08b |
| KB | 3.2a | 0.48a | 0.20a |
| PR | 2.2b | 0.58a | 0.24a |
| N, kg $ha^{-1}$‡ | | | |
| 0 | 2.4a | 0.49a | 0.21a |
| 49 | 2.2a | 0.40b | 0.14b |
| HOC§ | | | |
| Short | 2.3a | 0.47a | 0.19a |
| Tall | 2.3a | 0.42a | 0.17a |
| Year (Y) | | | |
| 2011 | 2.2a | 0.28b | 0.06c |
| 2012 | 2.3a | 0.52a | 0.14b |
| 2013 | 2.5a | 0.53a | 0.32a |
| S × HOC | | | |
| CB short | 1.6 | 0.29d | 0.07c |
| CB tall | 1.5 | 0.28d | 0.09c |
| KB short | 3.3 | 0.53b | 0.25a |
| KB tall | 3.0 | 0.43c | 0.15b |
| PR short | 2.1 | 0.59a | 0.23a |
| PR tall | 2.3 | 0.57a | 0.25a |
| S × Y | | | |
| CB 2011 | 1.4e | 0.20e | 0.05c |
| CB 2012 | 1.5e | 0.32d | 0.07c |
| CB 2013 | 1.7de | 0.32d | 0.13b |
| KB 2011 | 3.5a | 0.31d | 0.06c |
| KB 2012 | 2.9abc | 0.53c | 0.15b |
| KB 2013 | 3.1ab | 0.60bc | 0.39a |
| PR 2011 | 1.6e | 0.34d | 0.08c |
| PR 2012 | 2.4cd | 0.72a | 0.20b |
| PR 2013 | 2.5bc | 0.66ab | 0.44a |

†Means followed by the same letter(s) within the same response variable and source of variation are not statistically different at $P \leq 0.05$. No mean separations are reported for non significant 2-factor interactions.

‡Fertilization with N during the experimental period was applied 16, 12, and 24 July in 2011, 2012, and 2013, respectively.

§HOC for short grass CB, KB, and PR was 0.3125, 3.125, and 3.125 cm, respectively, and 0.9375, 6.25, and 6.25 cm, respectively, for tall grass.

Figure 1. Linear relationship between the reference $ET_0$ calculated using the FAO 56 Penman-Monteith equation and measured $ET_T$ using mini-lysimeters reported for three years.

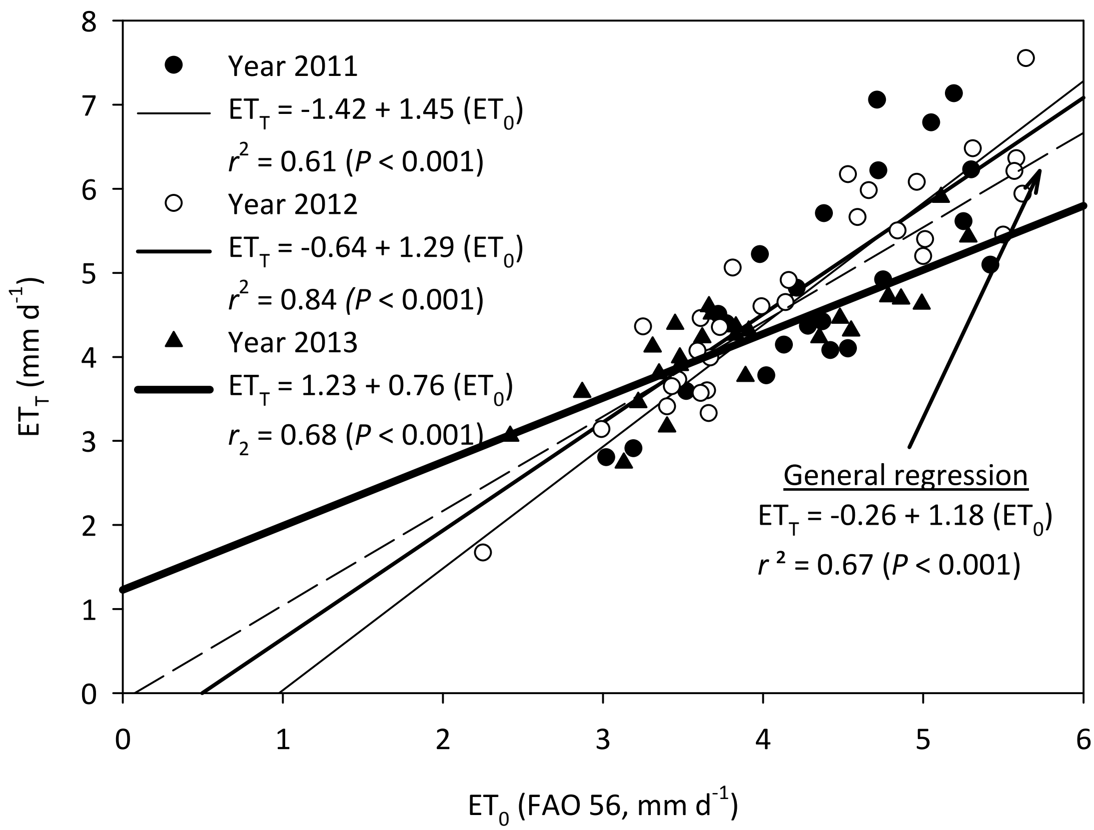


Figure 2. Linear relationship between FAO 56 reference $ET_0$ and measured $ET_T$ using min-lysimeters reported for three years with intercept forced through the origin.

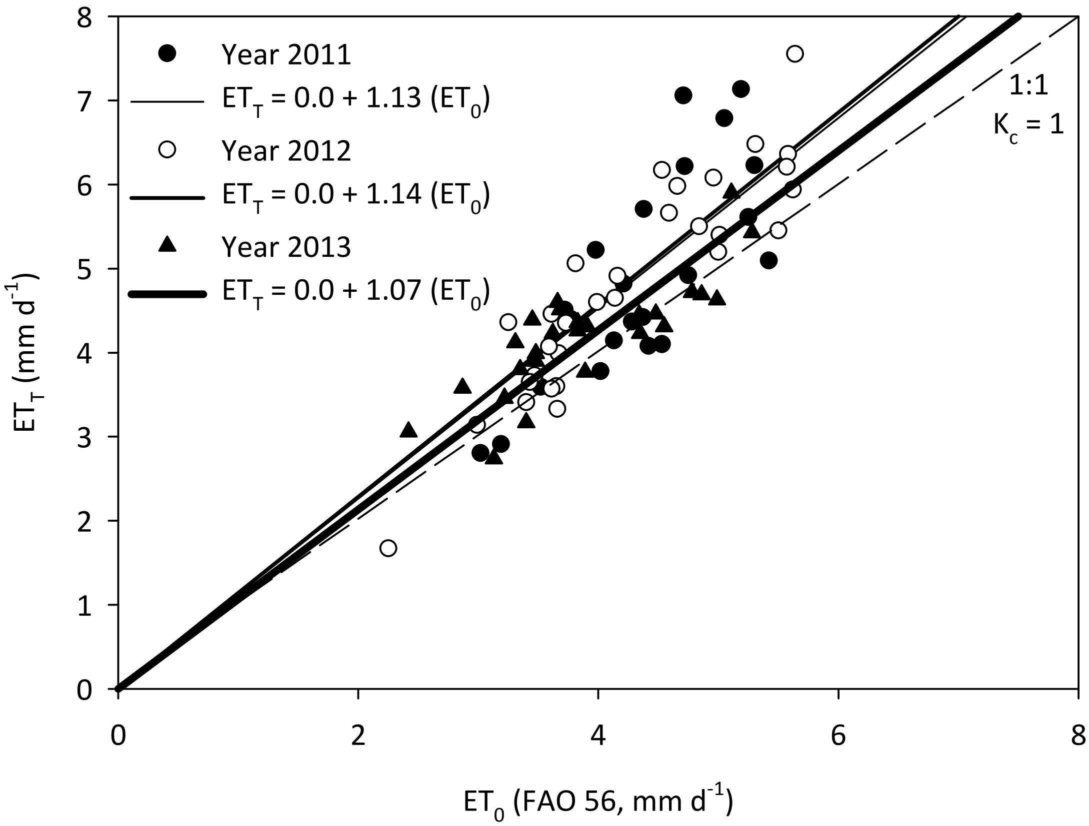


Figure 3. Relationship between 3-year averages of crop coefficients ($K_c$ values) and leaf growth rate averages reported for three species (CB, KB, and PR), two HOC and two N rates (n=48).

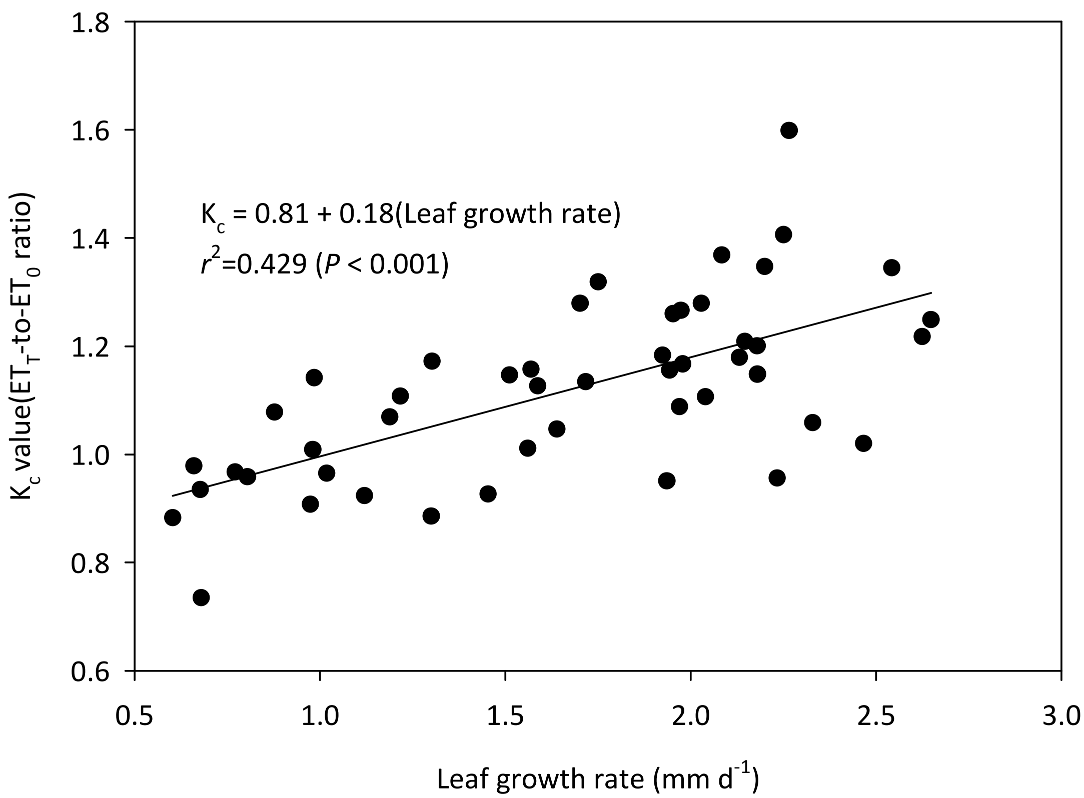
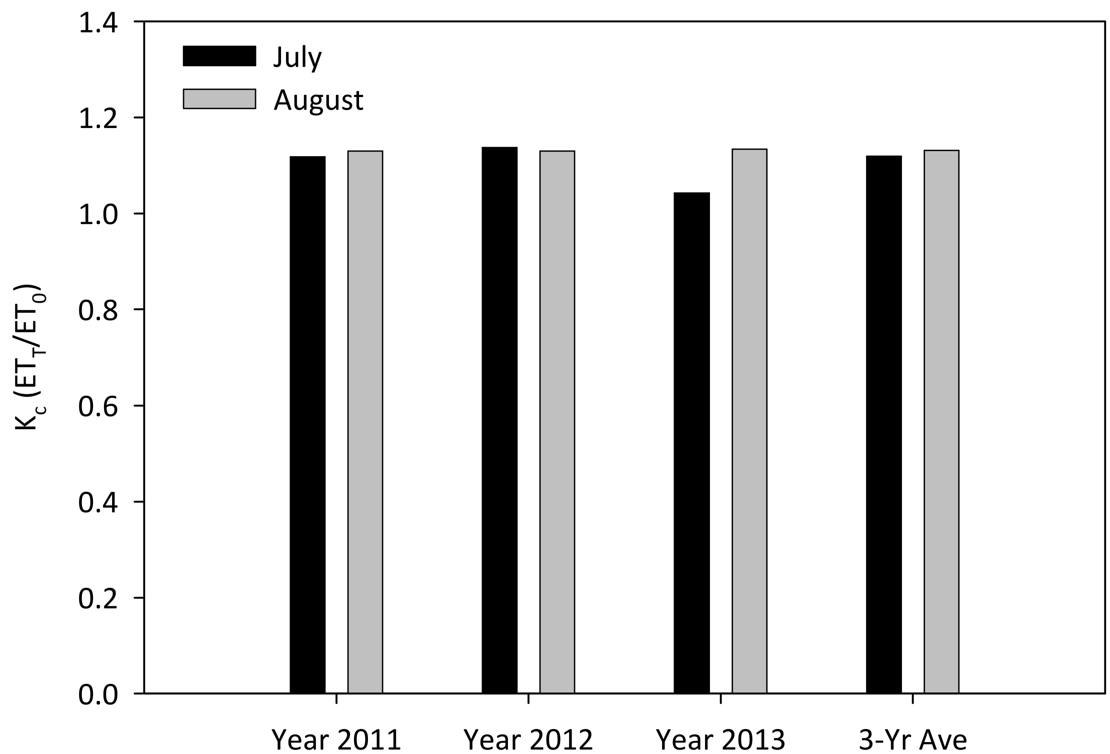


Figure 4. Year to year variation by month for crop coefficients ($K_c$) calculated over the experimental period.



## LITERATURE CITED


Aboukhaled, A., A. Alfaro, and M. Smith. 1982. Lysimeters. FAO Irrigation and drainage paper 39. Food and Agriculture Organization of United nations. Rome, Italy.

Allen, R.G. 1986. A Penman for all seasons. J. Irrig. Drain. Eng. 112:348-368.

Allen, R.G., M.E. Jensen, J.L. Wright, and R.D. Burman. 1989. Operational estimates of evapotranspiration. Agron. J. 81:650-662.

Allen, R.G., L.S. Pereira, D. Raes, and M. Smith. 1998. Crop evapotranspiration: Guidelines for computing water requirements. Irr. & Drain. Paper 56. FAO, Rome, Italy.

Allen, R.G., M. Smith, L.S. Pereira, and A. Perrier. 1994. An update for the calculation of reference evapotranspiration. ICID Bull: 43(2):35-92.

Aronson, L.J., A.J. Gold, R.J. Hull, and J.L Cisar. 1987. Evapotranspiration of cool-season turfgrasses in the humid northeast. Agron. J. 79:901-905.

Atkins, C.E., R.L. Green, S.I. Sifers, and J.B. Beard. 1991. Evapotranspiration rates and growth characteristics of ten St. Augustinegrass genotypes. HortScience. 26(1):1488-1491.

Barton, L., G.G.Y. Wan, R.P. Buck, and T.D. Colmer. 2009. Nitrogen increases evapotranspiration and growth of a warm-season turfgrass. Agron. J. 101:17-24.

Beard, J.B. 1973. Turfgrass: Science and Culture. Prentice-Hall, Englewood, N.J.

Biran I., B. Bravdo, I. Bushkin-Harav, and E. Rawitz. 1981. Water consumption and growth rate of 11 turfgrasses as affected by mowing height, irrigation frequency, and soil moisture. Agron. J. 73:85-90.

Bonos, S.A., and J.A. Murphy. 1999. Growth responses and performance of Kentucky bluegrass under summer stress. Crop Sci. 39:770–774.

Bowman, D.C., and L. Macualay. 1991. Comparative evapotranspiration rates of tall fescue cultivars. HortScience. 26(2):122-123.

Brede, A.D., and J.M. Duich. 1986. Plant interaction among *Poa annua*, *Poa pratensis*, and *Lolium perenne* turfgrasses. Agron. J. 78:179184.

Brown, P., and D. Kopec. 2000. Converting reference evapotranspiration into turf water use. The University of Arizona Cooperative Extension (AZ1195).

Brown, P. W., D. Kopec, and C.F. Mancino. 1988. Estimating turfgrass water use with AZMET.Turfgrass and Ornamentals Research Summary. Arizona Agric. Exp. Stn. P-75:23-33.

Brown, P. W., C.F. Mancino, M.H. Young, T.L. Thompson, P.J. Wierenga, and D.M. Kopec. 2001. Penman-Monteith crop coefficients for use with desert turf systems. Crop Sci. 41:1197-1206.

Brown, P.W., T. Thompson, D.M. Kopec, M.H. Young, P. Wierenga, and B. Whitlark. 1998. Turfgrass irrigation with municipal effluent: nitrogen fate, turf crop coefficients and water requirements. Final Proj. Rpt. U.S. Golf Assn., Far Hills, NJ.

Burman, R.D., P.R. Nixon, J.L. Wright, and W.O. Pruitt. 1980. Water requirements. Chap. 6. In M.E. Jensen (ed.) Design and operation of irrigation systems. ASAE Monograph 3. American Society of Agricultural Engineers, St. Joseph, MI.

Carrow, R. N. 1995. Drought resistance aspects of turfgrasses in the southeast: Evapotranspiration and crop coefficients. Crop Sci. 35:1685-1690.

Carrow, R.N. 1996. Drought avoidance characteristics of diverse tall fescue cultivars. Crop Sci. 36:371–377.

Carrow, R. N. 2005. Can we maintain turf to customers' satisfaction with less water? Agricultural Water Management. 80:117-131.

Crookston, M.A., and M. Hattendorf. 2010. Meeting irrigation demands in a water-challenged environment. *In* Gibbons and Andersen (ed.) SCADA and technology: tools to improve production. 28 Sept. to 1 Oct, 2010. Fort Collins CO.

DaCosta, M., and B. Huang. 2006. Minimum water requirements for creeping, colonial, and velvet bentgrasses under fairway conditions. Crop Sci. 46:81-89.

Dewitt, D.A., R.L. Morris, and D.C. Bowman. 1992. Evapotranspiration, crop coefficients, and leaching fractions of irrigated desert turfgrass systems. Agron. J. 84:717-723.

Ebdon, J.S., M. DaCosta, J. Spargo, and W. M. Dest. 2013. Long term effects of nitrogen and potassium fertilization on perennial ryegrass turf. Crop Sci. 53:1750-1761.

Ebdon, J. S., and K. L. Kopp. 2004. Relationship between WUE, 13C discrimination, and turf performance in genotypes of Kentucky bluegrass during drought. Crop Sci. 44:1754-1762

Ebdon, J.S., and A.M. Petrovic. 1998. Morphological and growth characteristics of low- and high-water use Kentucky bluegrass cultivars. Crop Sci.38:143-152.

Ebdon, J. S., A. M. Petrovic, and R. W. White. 1999. Interaction of nitrogen, phosphorus, and potassium on evapotranspiration rate and growth of Kentucky bluegrass. Crop Sci. 39:209-218.

Ebdon, J. S., A. M. Petrovic, and R. W. Zobel. 1998. Stability of evapotranspiration rate in cultivars of Kentucky bluegrass across low-and high-evaporative environments. Crop Sci. 38:135-142.

Environmental Institute for Golf: Golf course environmental profile volume II. 2009. GCSAA. http://www.eifg.org/programs/EIFG_GCEP_Vol_2.pdf.

Erickson, J.E., and K.E. Kenworthy. 2011. Nitrogen and light affect water use and water use efficiency of zoysiagrass genotypes differing in canopy structure. HortScience. 46(4):643-647.

Ervin, E. H., and A.J. Koski. 1998. Drought avoidance and crop coefficients of Kentucky bluegrass and tall fescue turfs in the semiarid west. Crop Sci. 38:788-795.

Feldhake, C.M., R.E. Danielson, and J.D. Butler. 1983. Turfgrass evapotranspiration. I. Factors influencing rate in urban environments. Agron. J. 75:824-830.

Feldhake, C.M., R.E. Danielson, and J.D. Butler. 1984. Turfgrass evapotranspiration. II. Response to deficit irrigation. Agron. J. 76:85-89.

Fernandez, G.C.J., and B. Love. 1993. Comparing turfgrass cumulative evapotranspiration curves. HortScience. 28(7) :732-734.

Fougerouze, J. 1966. Quelques problemes de bioclimatolgie en Guyanne Francaise. L'Agron. Tropicale 3:291-346.

Fry, J.D., and J.D. Butler. 1989. Annual bluegrass and creeping bentgrass evapotranspiration rates. HortScience. 24:269-271.

Fry, J., and B. Huang. Applied turfgrass science and physiology. 2004. John Wiley and Sons, Hoboken, N.J.

Fu, J., J. Fry, and B. Huang. 2007. Tall fescue rooting as affected by deficit irrigation. HortScience. 42:688-691.

Gauch, H.G., J.T.G. Hwang, and G.W. Fick. 2003. Model evaluation by comparison of model-based predictions and measured values. Agron. J. 95:1442-1446.

Green, R.L., J.B. Beard, and D.M. Casnoff. 1990. Leaf stomatal characterizations and evapotranspiration rates of 12 cool-season perennial grasses. HortScience. 25(7):760-761.

Green, R.L., S.I. Sifers, C.E. Atkins, and J.B. Beard. 1991. Evapotranspiration rates of eleven Zoysia genotypes. HortScience. 26(3):264-266.

Haydu, J. J., A.W. Hodges, and C.R. Hall. 2008. Estimating the economic impact of the U.S. golf course industry: Challenges and solutions. HortScience. 43 (3):759-763.

Hoffman, L., J. S. Ebdon, W. D. Dest and M. DaCosta. 2010. Effects of Nitrogen and Potassium on Wear Mechanism in Perennial Ryegrass: II. Anatomical, Morphological and Physiological Characteristics. Crop Sci. 50:367-379.

Huang, B., and J.D. Fry. 1999. Turfgrass evapotranspiration. In: M.B. Kirkham, editor, Water use in crop production. Food Products Press, New York. p.317-334.

Huang, B., and H. Gao. 1999. Physiological responses of diverse tall fescue cultivars to drought stress. HortScience. 34(5):897-901.

Jiang, H., J. Fry, and N. Tisserat. 1998. Assessing irrigation management for its effects on disease and weed levels in perennial ryegrass. Crop Sci. 38:440-445.

Johns, D., J.B. Beard., and C.H.M. van Bavel. 1981. Resistance to evapotranspiration from St. Augustinegrass turf canopy. Agron. J. 75:419-422.

Johns, D., J.B. Beard., and C.H.M. van Bavel. 1983. Resistance to evapotranspiration from St. Augustinegrass turf canopy. Agron. J. 75:419-422.

Jordan, J.E., R.H White, D.M. Vietor, T.C. Hale, J.C. Thomas, and M.C. Engelke. 2003. Effect of irrigation frequency on turf quality, shoot density, and root length density of five bentgrass cultivars. Crop Sci. 43:282-287.

Kim, K.S., and J.B. Beard. 1988. Comparative turfgrass evapotranspiration rates and associated plant morphological characteristics. Crop Sci. 28:328-331.

Kneebone, W.R., D.M. Kopec, and C.F. Mancino. 1992. Water requirement and irrigation. p. 441-472. *In* D. Waddington et al. (ed.) Turfgrass Agron. Monogr. 32. ASA, CSSA, SSSA. Madison WI.

Kopec, D.M., R.C. Shearman, and T.P. Riordan. 1988. Evapotranspiration of tall fescue turf. HortScience. 23(2):300-301.

Kopp, K.L., and Y. Jiang. 2013. Turfgrass water use and physiology. p. 319-345. *In* J.C. Stier et al. (ed.) Turfgrass: Biology, use and management. Monogr. 56. ASA, CSSA, SSSA. Madison WI.

Lanier, J.D., J.S. Ebdon, and M. DaCosta. 2012. Physiological changes associated with wilt-induced freezing tolerance among diverse turf performance perennial ryegrass cultivars. Crop Sci. 52:1393-1405.

Leinauer, B., and D.A. DeVitt. 2013. Irrigation science and technology. p. 1075-1131. *In* J.C. Stier et al. (ed.) Turfgrass: Biology, use and management. Monogr. 56. ASA, CSSA, SSSA. Madison WI.

Liu, X., and B. Huang. 2002. Mowing effects on root production, growth, and mortality of creeping bentgrass. Crop Sci. 42:1241-1250.

Madison, J.H., and R.H. Hagan. 1962. Extraction of soil moisture by ‘Merion’ bluegrass (*Poa pratensis* L. ‘Merion’) turf, as affected by irrigation frequency, mowing height, and other cultural operations. Agron. J. 54:157-160.

Martin, D.L., D.J. Wehner, and C.S. Throssell. 1994. Models for predicting the lower limit of the canopy-air temperature difference of two cool season grasses. Crop Sci. 34:192-198.

Massachusetts Water Resource Commission. 2012. Massachusetts water conservation standards. Executive Office of Energy and Environmental Affairs. Boston, MA . p 1-75.

Mather, J.R. 1959.Determination of evapotranspiration by empirical methods. Transaction of ASAE 2(1):35-43.

McGroary, P.C., J.L. Cisar, G.H. Snyder, J.E. Erickson, S.H. Daroub, and J.B. Sartain. 2011. Water use of St. Augstinegrass and bahiagrass under varying nitrogen rates. Agron. J. 103:100-106.

Meyer, J. L., V.A. Gibeault, and V.B. Youngner. 1985. Irrigation of turfgrass below replacement of evapotranspiration as a means of water conservation: Determining crop coefficient of turfgrasses. Proceedings of the Fifth International Turfgrass Research Conference. p. 357-364.

Monteith, J.L. 1965. Evaporation and environment. In G.E. Fogg (ed.) Symposium of the Society for Experimental Biology, The State and Movement of Water in Living Organisms. Academic Press. Vol. 19:205-234.

Murphy, J. A., and J. S. Ebdon. 2013. Study and Management of Turfgrass Traffic Stress. In J.C. Stier et al., editors. Agron. Monogr. 52, ASA-CSSA-SSSA, Madison, WI. p.1029-1074.

Penman, H.L. 1948. Natural evaporation from open water, bare soil and grass. Proceedings of the Royal Society. Proc. A. 193:120-146.

Perdomo, P., J.A. Murphy, and G.A. Berkowitz. 1996. Physiological changes associated with performance of Kentucky bluegrass cultivars during summer stress. HortScience 31(7):1182–1186.

Petrovic, A. M. 1990. The fate of nitrogenous fertilizers applied to turfgrass. J. Environ. Qual. 19(1):1-14.

Pinter, P.J., Jr., M.E. Stanghellini, R.J. Reginato, S.B. Idso, A.D. Jenkins, and R.D. Jackson. 1979. Remote detection of biological stresses in plants with infrared thermometry. Science. 205:585-587.

Qian, Y.L., J.D. Fry, S.C. Wiest, and W.S. Upham. 1996. Estimating turfgrass evapotranspiration using atmometers and the Penman-Monteith model. Crop Sci. 36:699-704.

Qian, Y.L., and J.D. Fry. 1996. Irrigation frequency affects zoysiagrass rooting and plant water status. HortScience. 31:234-237.

Qian, Y.L., and M.C. Engelke. 1999. Performance of five turfgrasses under linear gradient irrigation. HortScience. 34(5): 893-896.

Rosenburg, N.J., B.L. Blad, and S.B. Verma. 1983. Microclimate, the biological environment. New York: John Wiley and Sons.

Salaiz, T.A., G.L. Horst, and R.C. Shearman. 1995. Mowing height and vertical mowing frequency on putting green quality. Crop Sci. 35:1422-1425.

Salaiz, T.A., R.C. Shearman, T.P. Riordan, and E.J. Kinbacher. 1991. Creeping bentgrass cultivar water use and rooting response. Crop Sci. 31:1331-1334.

Sass, J. F., and B.P. Horgan. 2006. Irrigation scheduling on sand-based creeping bentgrass: Evaluating evapotranspiration estimation, capacitance sensors, and deficit irrigation in the Upper Midwest. [Online] Appl. Turfgrass Sci. p. [1-14].

Sharma, M.L. 1985. Estimating evapotranspiration. p. 213-282. In D. Hillel. (ed.). Advances in irrigation. Vol. 3. Academic press, New York.

Shearman, R.C. 1986. Kentucky bluegrass cultivar evapotranspiration rates. HortScience. 21(3):455-457.

Shearman, R.C. 1989. Perennial ryegrass cultivar evapotranspiration rates. HortScience. 24(5): 767-769.

Shearman, R.C., and J.B. Beard. 1973. Environmental preconditioning affects on water use rates of *Agrostis palustris* Huds., cultivar Penncross. Crop Sci:13:424-427.

Sheffer, K.M., T.L. Watschke, and J.M. Duich. 1978. Effect of mowing height on leaf angle, leaf number, and tiller density of 62 Kentucky bluegrasses. Agron. J. 70:686-688.

Steiner, J.L., T.A. Howeel., and A.D. Schneider. Lysimetric evaluation of daily potential evapotranspiration models for grain sorghum. 1991. Agron. J. 83:240-2247.

Synder, R., W.O. Pruit, D.W. Henderson, and A. Dong. (ed.). 1985. California Irrigation Management Information System Final Report. Univ. of California-Davis. Land, Air and Water Resource Paper # 10013.

Turgeon, A.J. 2002. Turfgrass management. Prentice Hall, Upper Saddle River, N.J.

Wright, J.L. 1982. New evapotranspiration crop coefficients. J. Irr. & Drain. Div., Am. Soc. of Civil. Eng. 108:57-74.

Yelverton, F. 1999. Season rooting and mowing height effects on Penncross bentgrass in the southern United States. Turfax7:4.

Youngner, V.B., A.W. Marsh, R.A. Strohman, V.A. Gibeault, and S. Spaulding. 1981. Water use and quality of warm-season and cool-season turfgrasses. p. 251-257. *In* R.W. Sheard (ed.). Proc. of the Fourth Intntl. Turfgrass Research Conf., Guelph, Ontario.