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

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

A Thesis Presented

By

JAMES W. PORO

Submitted to the Graduate School of the
University of Massachusetts in partial fulfillment
of the requirements for the degree of
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Plant and Soil Sciences

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ENGLAND: EVAPOTRANSPIRATION AND CROP COEFFICIENTS**

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JAMES W. PORO

Approved as to style and content by:

J. Scott Ebdon, Chair

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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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I would first like to acknowledge my advisor and committee chair, Dr. J. Scott Ebdon, for his continual support and guidance. He is always available for my questions and concerns, often surpassing the role as advisor and acting as mentor. Thank you for giving me the freedom to pursue other passions of turfgrass management alongside my research. I wouldn't be where I am today without your guidance.

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ABSTRACT

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

FEBRUARY 2015

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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 (*Lolium perenne* L.), 'Touchdown' Kentucky bluegrass (*Poa pratensis* L.), and 'Memorial' Creeping bentgrass (*Agrostis stolonifera* 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.

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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 perenne* 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:

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

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 C₃ turfgrass species managed under similar evaporative and cultural conditions typically exhibits a higher ET rate than C₄ turfgrass (Biran et al., 1981; Feldhake et al., 1983). This is due to differences between the C₃ and C₄ pathways with C₄ turfgrass exhibiting higher water use efficiency (g dry wt-to-g H₂O ratio) over C₃ 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 (Kopeck 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 m² plot area with a 0.0491 m² 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_{s0} 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_{s0} 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:

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

where I is irrigation, and P is precipitation, which are additions into the system (+ values), while ΔS is the change in 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 (ΔS) 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 C₄ and C₃ 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 ET₀ 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:

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{37}{T_{hr} + 273} u_2 (e^s(T_{hr}) - e_a)}{\Delta + \gamma (1 + 0.34u_2)} \quad \text{Equation 4}$$

where

ET₀ 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 [$^{\circ}\text{C}$],

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

λ psychrometric constant [$\text{kPa } ^{\circ}\text{C}^{-1}$],

$e^{\circ}(T_{hr})$ 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 perenne* 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.

ET₀) 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 ET₀ 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 perenne* 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 al., 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 K_c 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 ET₀ (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 ΔS is the change in 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 (ΔS) 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 2nd 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) ET₀

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 ET₀ 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 ET₀ value. Allen et al. (1998) describe the exact form of the FAO 56 Penman-Monteith equation for hourly time steps that was used:

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{37}{T_{hr} + 273} u_2 (e^s(T_{hr}) - e_a)}{\Delta + \gamma (1 + 0.34u_2)}$$

where

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

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

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

T_{hr} mean hourly air temperature [$^{\circ}\text{C}$],

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

λ psychrometric constant [$\text{kPa } ^{\circ}\text{C}^{-1}$],

$e^{\circ}(T_{\text{hr}})$ 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 cm²) than the Feldhake et al. (1983) study in Colorado (62,500 cm²). However, our smaller lysimeter area (81 cm²) compared to the Feldhake study (491 cm²) 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) \times 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 $\frac{1}{2}$ 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 $Y \times S$ 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 ($Y \times S$ and $Y \times HOC$) 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 ($1239 \text{ shoot dm}^{-2}$) compared to tall grass species (KB and PR), which averaged approximately $240 \text{ shoot dm}^{-2}$ (Table 2). No difference between tall grass species (KB and PR) was observed (Tables 1 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 ($r=-0.67$, $n=48$, $P\leq 0.001$). 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 $\frac{1}{2}$ 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 $\frac{1}{2}$ 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 $27.1 \text{ }^\circ\text{C}$, and average wind speed of 1.65 m s^{-1} during the measurement period. Canopy temperature average for short grass CB was $26.1 \text{ }^\circ\text{C}$, which was significantly higher ($P \leq 0.001$) than tall grass KB and PR, which averaged 24.3 and $24.2 \text{ }^\circ\text{C}$, respectively. Feldhake et al. (1983) also reported that short grass (2 cm HOC) exhibited higher leaf temperatures ($30 \text{ }^\circ\text{C}$) than 5 cm HOC turf ($29 \text{ }^\circ\text{C}$). 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 southwest for fairway HOC bermudagrass (*Cynodon dactylon* L. × *C. transvaalensis* 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 $S \times N$ 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 $S \times \text{HOC} \times N$ 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 $S \times HOC$ 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 in 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 minimize 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 $\frac{1}{2}$ 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/ET_0	ET_T $mm\ d^{-1}$	Leaf growth $mm\ d^{-1}$	Shoot density $No.\ dm^{-2}$	Leaf width 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 ET₀ 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			
	$^{\circ}C^{\dagger}$	r with ET_0	$\%^{\dagger}$	r with ET_0	$MJ\ m^{-2}\ d^{-1}\ ^{\dagger}$	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.

Factor	2011 growing season			2012 growing season			2013 growing season			General regression		
	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	----- dET_T/dET_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.

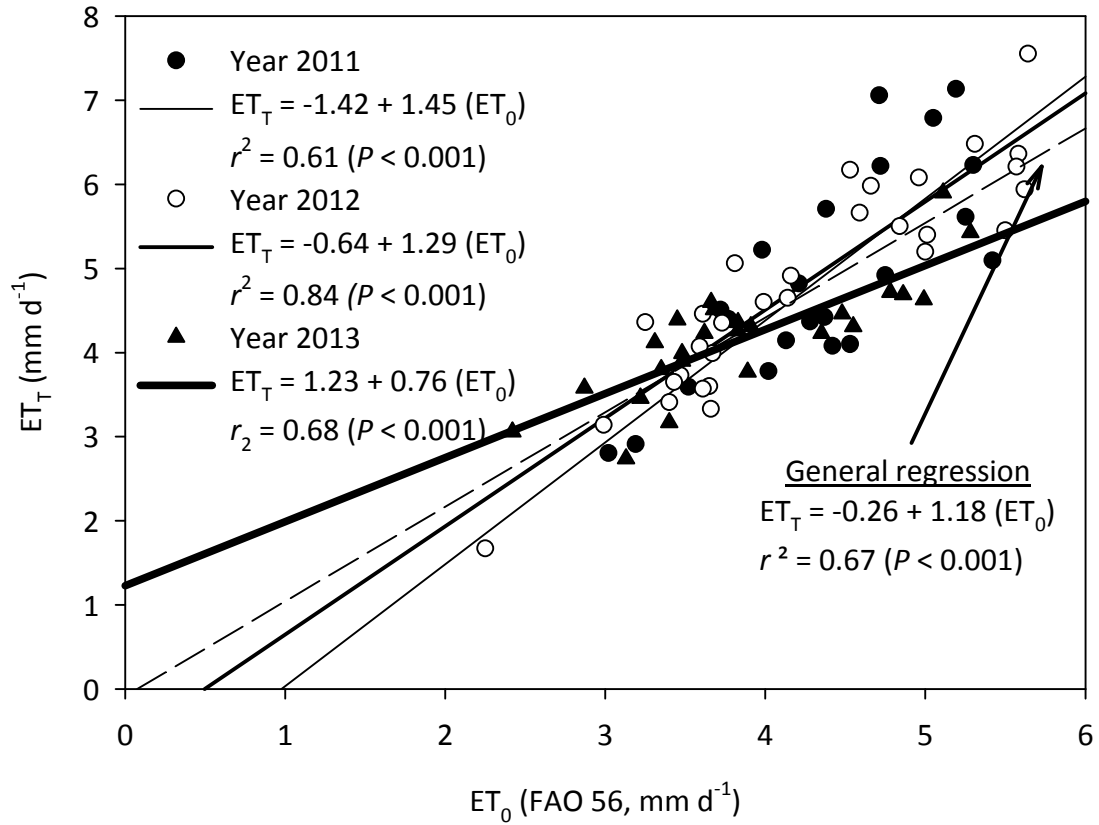


Figure 2. Linear relationship between FAO 56 reference ET_0 and measured ET_T using min-lysimeters reported for three years with intercept forced through the origin.

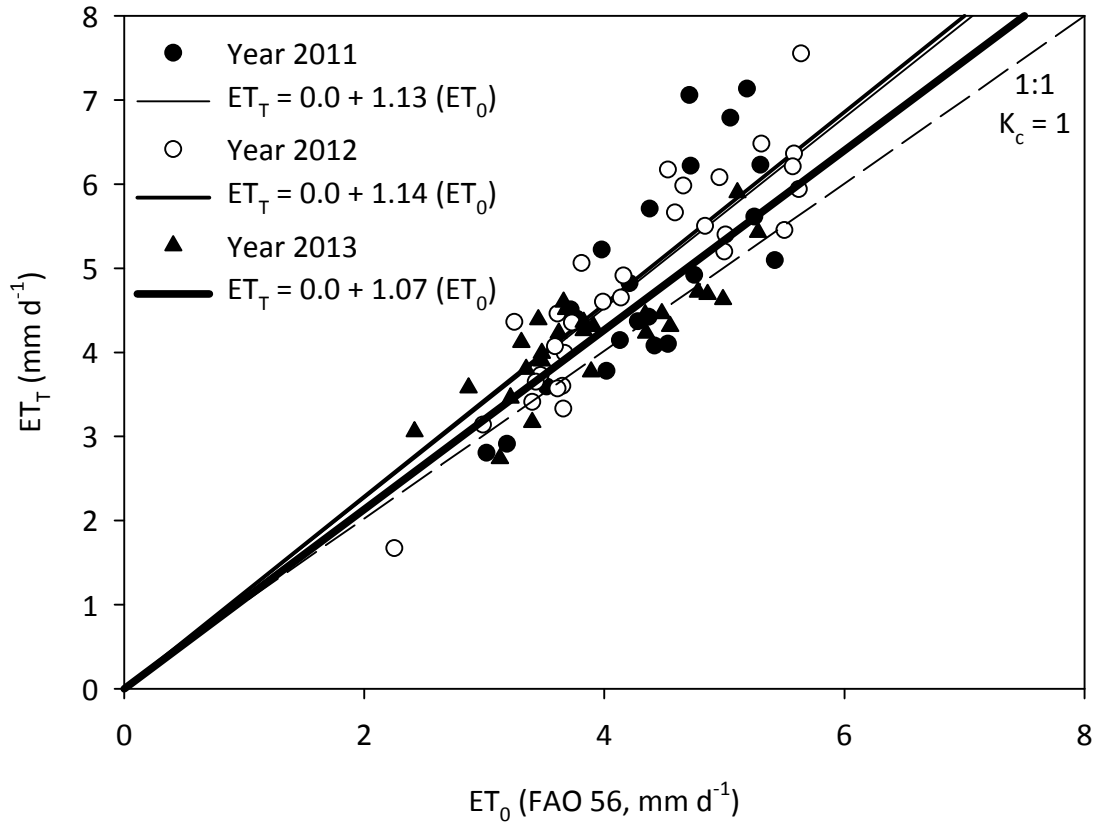


Figure 3. Relationship between 3-year averages of crop coefficients (K_c values) and leaf growth rate averages reported for three species (CB, KB, and PR), two HOC and two N rates (n=48).

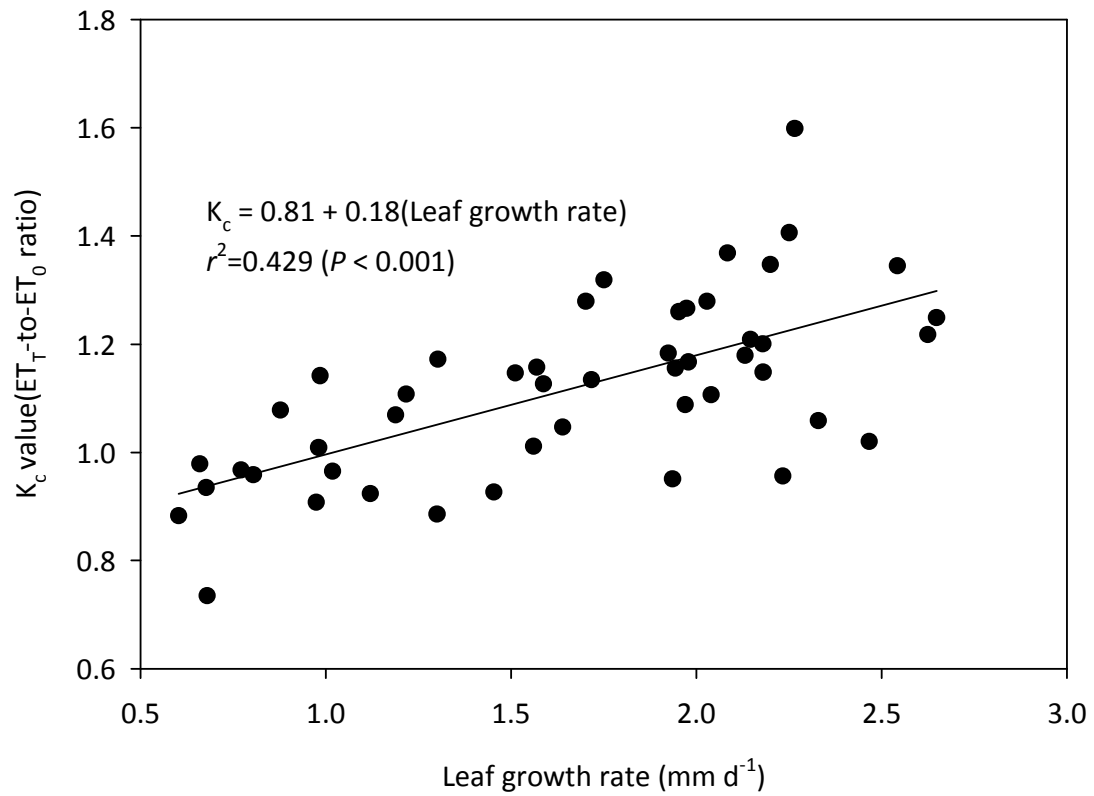
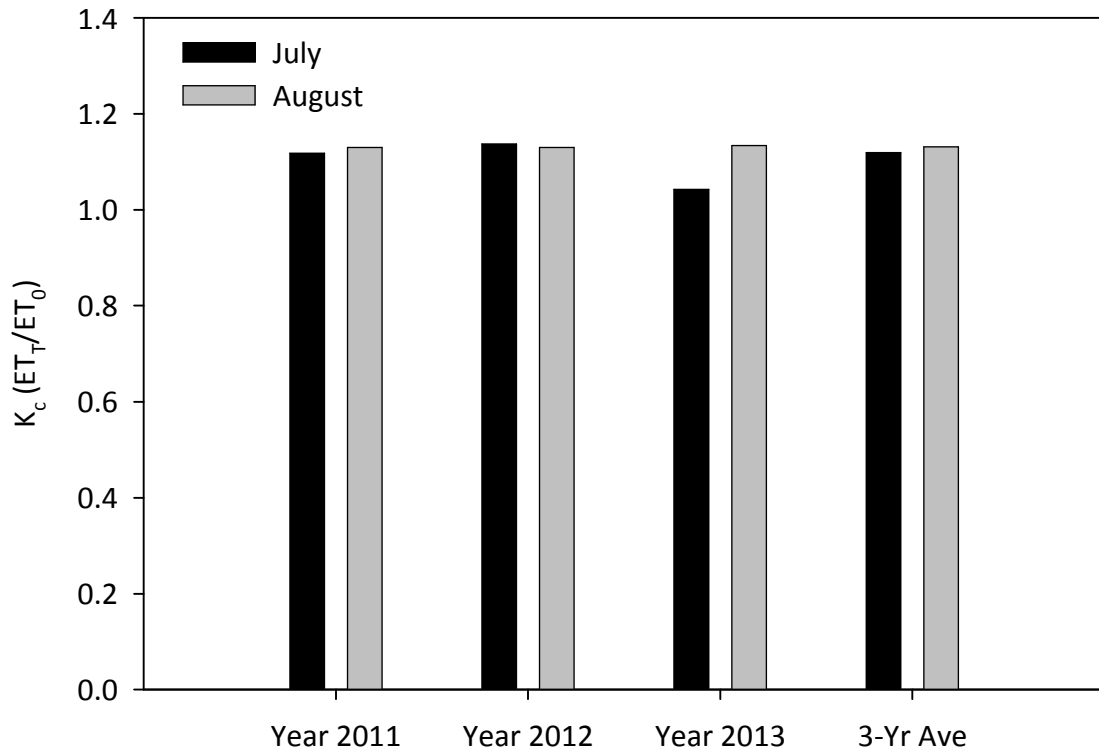


Figure 4. Year to year variation by month for crop coefficients (K_c) calculated over the experimental period.



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. Macaulay. 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.* 78:179-184.
- 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, $\delta^{13}C$ 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 bioclimatologie 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. Augustinegrass 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. Pruitt, 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. *Turfax*7:4.
- 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.*