AN ABSTRACT OF THE THESIS OF

Tod M. Blankenship for the degree of Master of Science in Horticulture presented on June 9, 2011.

Title: Water Use Characteristics of Ten Newly Established Cool-Season Turfgrass Species

Abstract approved:

_______________________________________________
Robert C. Golembiewski

Water use restrictions are continuing to have an impact on the way turf is managed today and will be managed in the future. The objective of this research was to evaluate the irrigation requirements of ten newly established cool-season turfgrass species maintained under two different mowing height and nitrogen fertility regimes. The site was treated with glyphosate to eliminate existing plant material, scalped to remove foliage, leveled, and graded to provide adequate surface drainage. All plots were seeded with a blend of three cultivars for all turfgrass species (Kentucky bluegrass, perennial ryegrass, velvet bentgrass, creeping bentgrass, colonial bentgrass, strong creeping red fescue, chewings fescue, slender creeping red fescue, tall fescue) except for annual bluegrass which was sodded. Plots were mowed at 1.6 and 5.1 cm three times and one time per week respectively. Nitrogen was applied at either 0.45 or 1.81 kg per 92.9 m² per year. Water moisture stress was assessed visually as well with a Time Domain Reflectometer (TDR) moisture probe at a 3.8 cm depth for the same 45-day period in 2009 and 2010. Irrigation was applied based on predetermined water replacement values through a hand-held hose with a flow and batch meter attachment. Significant irrigation input differences were observed between mowing height treatments but not among nitrogen fertility treatments. Tall fescue, perennial ryegrass, Kentucky bluegrass, creeping bentgrass and velvet bentgrass were all lower water users under both high and low heights of cut in this
trial. The higher water use species, annual bluegrass and red fescues, all required more water in the low mown plots than the high mown plots. A lower crop coefficient for irrigation could be utilized for most species in the Pacific Northwest. Stress detection glasses were able to detect water stress in all turfgrass species tested by a minimum of 1.2 days on average and a maximum of 2.4 days in advance of the unaided visual assessment. The glasses were evaluated across a broad range of species and were effective regardless of the different turf canopies and variation in color present in the different species. The early detection of stress would enable turf managers to schedule irrigation in advance while conserving water. For most species the TDR could reliably measure the percent Volumetric Water Content (VWC) at which irrigation was required to maintain a functional turf surface. At the typical recommended mowing height of most species, if maturity was achieved, this was at approximately 30% VWC. The TDR could be used to more accurately guide irrigation scheduling and reduce water use.
Master of Science thesis of Tod M. Blankenship presented on June 9, 2011.

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I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

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Tod M. Blankenship, Author
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CHAPTER 1

GENERAL INTRODUCTION

General Water Use Information

There are an estimated 50 million acres of maintained turfgrass in the United States on home lawns, golf courses, sports fields, parks, playgrounds, cemeteries, and highway right-of-ways with an annual economic value estimated to be $40 billion (Beard and Kenna, 2008). The demand for freshwater to meet agricultural, municipal, and industrial needs has increased more than 35-fold during the last three centuries and as demand for this finite supply of water continues to increase, the allocation of water for irrigation has decreased, especially for non-food commodities such as turfgrass (Githinji et al., 2009).

Turfgrass constitutes total ground cover, may be used daily, and is a perennial crop hence separating it from other “crops”. Because of these factors, irrigation methods commonly used for other crops, such as flood and furrows, are unsuitable (Bastug and Buyuktas, 2003). Increasing demand for scarce water resources, coupled with the highly visible practice of turfgrass and associated landscape irrigation, has fostered concerns regarding turfgrass water conservation (Ervin and Koski, 1998). Horgan and Sass (2006) point out that in addition to concerns over the scarcity of water supplies, the increasing monetary cost of water, electricity, and irrigation system components are factors for conserving water resources. Irrigation is necessary to produce aesthetic and functional turfgrass and maximized use of irrigation and rainwater is critical for proper turfgrass management, especially where water supplies or water quality may not be ideal for turfgrass (Young et al., 2000).

Turfgrass irrigation trends are influenced by concepts which stress water conservation and lower maintenance costs yet allow the turfgrass sites to achieve the particular goals of the site (Gibeault et al., 1989). Water requirements for functioning turfgrass vary not only among turfgrass species (Youngner et al., 1981; Aronson et al., 1987; Kim and Beard, 1988; Fry and Butler, 1989; Fu et al., 2004) but also within cultivars of the same species (Shearman, 1986; Kopec et al., 1988; Shearman, 1989; Salaiz et al., 1991; Ebdon and Petrovic, 1998). Knowledge of water use requirements of various turfgrass species is important for identifying...
turfgrasses that persist with reduced water inputs and also for developing efficient irrigation management practices (DaCosta and Huang, 2006b). In addition to differences among species; under restricted irrigation or limiting soil moisture conditions, turfgrasses may use significantly less water compared with well-irrigated plants (Kneebone and Pepper, 1984; Qian and Engelke, 1999). Conversely higher water use rate has also been associated with increases in soil water availability (Beard, 1973; Biran et al., 1981; Gibeault et al., 1985; Kneebone et al., 1992).

In addition to water-saving management practices, the identification of turfgrasses with low-water use and high-water use is crucial for turfgrass areas with limited rainfall or restricted irrigation (DaCosta and Huang, 2006b). For instance, the rainfall pattern in the Pacific Northwest consistently produces periods of summer drought even though annual precipitation exceeds annum ET rates (Brauen, 1989).

Irrigation Legislation

To reduce irrigation and meet established water use levels set forth by government agencies, flattening the peak demand is typically an objective and should focus on management practices such as irrigation scheduling or selecting drought-tolerant grasses (Beard and Kenna, 2008). A single-issue approach of not permitting irrigation on all or a portion of land area, such as grassed lawns, can lead to other potentially serious problems (Beard and Kenna, 2008; Steinke et al., 2009). Beard and Kenna (2008) state San Antonio, TX has decreased per-capita water use by more than 40% since the early 1980s and has avoided conflict over landscape watering.

The San Antonio Water System (SAWS) recognized the value of lawns to its citizens and worked with them to develop a comprehensive water conservation program that addressed infrastructure improvements, inefficient plumbing, industrial technology, and other water-saving opportunities, along with savings in landscape watering. The example provided by San Antonio shows water use can be decreased in a manner that takes advantage of turfgrass benefits and is consistent with local positive attitudes toward turfgrass use (Beard and Kenna, 2008). In addition, the SAWS has drafted a list of drought-tolerant turfgrass species and cultivars approved for planting but little additional data is available (Steinke et al., 2009).
**Site Requirements**

In addition, the question of how much water turfgrasses require depends on the quality of turfgrass desired (Kneebone and Pepper, 1982). When water resources become limited, the turfgrass manager is restricted in irrigating turfgrass and acceptable quality turf must be maintained with less water (Ebdon et al., 1999). The primary objective of turfgrass production is to achieve a functional stand that provides a uniform and resilient playing surface and/or a high quality stand from a visual perspective therefore turfgrass quality cannot be successfully measured by yield (Mantell and Stanhill, 1966; Christians et al., 1979; Ebdon et al., 1999). Gibeault et al. (1989) state irrigation inputs must be sufficient to maintain turfgrasses at a level capable of performing the required task, which could merely be turfgrass survival therefore irrigation inputs may minimally be applied at a rate adequate to simply keep the grass alive corresponding to a small percentage of the ET value.

The crop water requirements of turfgrass are defined in terms of meeting quality and performance standards for the specific site (Kneebone et al. 1992). Gibeault et al. (1989) categorizes turfgrass into four groups: aesthetic, land protection, fine turf, and high-traffic turf. Gibeault et al. (1989) states within each level of performance various expectations can exist and specialty or high-traffic turfgrasses require maximum management experience, knowledge, and optimum resources. Therefore it is misleading to criticize turfgrass as wasteful citing the maintenance of fine turf as the example (Gibeault et al., 1989). In addition, the general public often times views golf courses as excessively resource and chemical dependent turf areas (Koeritz and Stier, 2009).

Turfgrass scientists and managers are therefore faced with the task of developing strategies for maintaining turfgrass sites that retain a certain level of quality and utility while considerably reducing irrigation inputs (Ervin and Koski, 1998). Moreover Beard and Kenna (2008) note it is important to point out turfgrass plants do not conserve water; people do. Beard and Kenna (2008) go on to point out and advise turfgrasses belong to the grass family, which evolved over millions of years without pesticides and irrigation systems. In addition, Gibeault et al. (1989) agree all irrigation trends point to the need for better informed water managers.
Plant Characteristics

Water use rates vary with turfgrass species and cultivar and are affected by many external factors, especially environmental conditions (Beard and Kenna, 2008). Turfgrass growth characteristics that affect water use include differences in canopy configuration or leaf orientation, tiller or shoot density, growth habit, rooting depth, and root density (Beard and Kenna, 2008). In the turfgrass industry, the ability of a species or cultivar to use less water is an important consideration, especially where rainfall and irrigation water are insufficient. Identifying turfgrass species and cultivars that use little water and remain functional during drought is of primary importance to turfgrass managers (Fernandez and Love, 1993). In fact, turfgrasses can survive on much lower amounts of water than most people realize and several turfgrass species have good drought resistance (Beard and Kenna, 2008).

These materials can resist the stress of low water application through various mechanisms, including dormancy, deep roots, and low rates of water use (Gibeault et al. 1989). Therefore knowledge of turfgrass water use patterns is important for developing efficient water management practices and also for selection of drought resistant cultivars (Githinji, et al. 2009). Responses of turfgrass to drought can be viewed in a number of ways.

Drought stress affects visual quality, growth rate, ET rate, and recuperative ability following drought-induced dormancy (Beard, 1973; Aronson et al., 1987b). Turfgrass species and cultivars have been found to respond differently to drought stress through drought resistance (Levitt, 1980; Minner and Butler, 1985).

Major components of drought resistance are drought escape, drought avoidance, and drought tolerance (Githinji et al., 2009; Salaiz et al., 1991). Turfgrasses can tolerate drought by escape or by having hardiness to low tissue water deficits (Gibeault et al. 1989). Under water limiting conditions, plants may maintain survival or even growth by avoiding drought stress, tolerating cellular water deficit, or both (DaCosta and Huang, 2006).

The mechanisms for drought resistance involve physiological and structural adaptations, which allow plants to survive extended periods of limited water availability. By selecting turfgrass species and varieties having superior drought resistance adaptations, turfgrass managers can delay or postpone drought stress injury and the associated decline in turfgrass
quality and function during extended periods of little or no water availability (Githinji, et al., 2009).

Drought avoidance is short-term survival adaptations of a plant to avoid tissue damaging water deficits while growing in a drought environment favoring the development of water stress through development of a deep, viable root system, high root hair density, rolled leaf blades, thick cuticle or the ability to quickly form a thick cuticle following water stress initiation, reduced leaf area, slow leaf extension rates, and leaf orientation and density that give high canopy resistance, or inherently low ET (Gibeault et al., 1989, Carrow, 1996). Presumably, greater root density at deeper depths allows plants to extract soil water deeper in the profile (Fry and Huang, 2004). Drought avoidance also contributes to the maintenance of high tissue water potential (i.e. the maintenance of green, turgid tissue) during a period of high evaporative demand or a period of increasing soil water deficit (Jones et al., 1981). Drought avoidance adaptations are often more important to turfgrass managers because they ensure turfgrass survival (without dormancy) and enhance sustained growth and function.

Drought tolerance is another component to drought resistance. Drought tolerance is defined as the ability of a turfgrass to tolerate a drought period and endure low tissue water deficits caused by drought (Jones et al., 1981, Gibeault et al., 1989; Carrow, 1996). More specifically drought tolerance involves the maintenance of positive turgor pressure at low tissue water potential and includes osmotic adjustment and dehydration tolerance achieved through protoplasm resistance (Jones et al., 1981, Gibeault et al., 1989; Carrow, 1996). Carrow (1996) found greater drought tolerance was associated with low basal osmotic potential before stress, osmotic adjustment, maintenance of positive turgor pressure, and delayed leaf rolling during stress. In addition, Minner and Butler (1985) defined drought tolerance as the ability of a large number of turfgrass plants (at least 70 percent) to regrow within a specified time. Simply put drought tolerance is a nebulous term that usually refers to the ability of a plant to function under deficit plant and/or soil water conditions and may imply the ability to remain green and growing during periods of moisture stress or the ability to simply survive a drought period (Minner and Butler, 1985).

Water consumption is only one factor to be considered when evaluating the overall drought resistance ranking of a particular species and/or cultivar (DaCosta and Huang, 2006). Some turfgrasses, such as tall fescue, may have high water use rates and medium drought resistance
while some turfgrasses have high water use rates and fair or poor drought resistance such as the ryegrasses and bluegrasses (Gibeault et al., 1989).

Ambient Temperature

Throssell et al. (1987) found canopy-air temperature differential (AT) to be a good indicator of moisture stress for Kentucky bluegrass turf. The authors found well-watered bluegrass turf had lower values of AT than slightly stressed turf, which had lower values of AT than moderately stressed bluegrass turf. Therefore, Throssell et al. (1987) concluded plant canopy ambient air temperature differential to be a good indicator of the water status of a plant. Additionally, work performed by Madison (1960) suggests day temperatures were hot enough to explore the possibility that growth was depressed by heat, though this was offset in part by the cool night temperatures and daily growth of the turfgrass was directly proportional to the night temperatures. These plant responses result in a reduction of leaf area and water absorption capability which could contribute to a lower water use rate in shaded environments.

Stomatal Characteristics

Although stomata comprises only ~1% of the total leaf blade surface area, they serve as key sites for transpiration and thus Green et al. (1990) deemed them areas of interest in reducing water loss. Stomatal regulation can control up to 90% of the total water lost to the atmosphere by transpiration (Beard, 1973). Stomatal density can be affected by both environmental and cultural conditions during leaf development (Green et al., 1990). Numerous factors (e.g., humidity, CO2 concentration, incident light intensity, and leaf age) can affect stomatal opening (Carroll and Petrovic, 1991). Data by Green et al. (1990) indicated stomatal densities were greater on the adaxial than on the abaxial surface for most turfgrasses and significant differences in stomatal density were found among the 12 cool-season turfgrasses in their study yet no significant correlation was found between ET rate and either adaxial or abaxial stomatal density. Therefore Green et al. (1990) concluded, under non-limiting soil moisture conditions, stomatal density was not reliably associated with ET rate and breeding programs designed to develop water-conserving turfgrasses especially for irrigated conditions, should place priority on plant characteristics that increase canopy resistance and decreased leaf area, rather than attempting to manipulate leaf stomatal density.
Light Influence

Plants grown at low light intensities have reduced cuticle thickness, reduced epidermal cell wall thickness, and increased intercellular space compared to plants growing at higher light intensities (Shearman and Beard, 1973). Research by Butler and Minner (1985) indicated a positive linear relationship of ET to the amount of light received.

Primary Cultural Factors

Among the cultural factors that directly impact vertical elongation rate, leaf surface area, canopy resistance, rooting characteristics, and resultant water use are species and cultivars (Biran et al., 1981; Shearman, 1986; Aronson et al., 1987; Kopec and Shearman, 1987; Kim and Beard, 1988), mowing height (Madison, 1962; Shearman and Beard, 1973; Biran et al., 1981; Feldhake et al., 1983), mowing frequency, (Shearman and Beard, 1973), Nitrogen fertility (NF) (Mantell, 1966; Shearman and Beard, 1973; Feldhake et al., 1983) and irrigation inputs (Beard and Kenna, 2008). Murphy (2002) simply states, healthy turfgrass, encouraged by proper mowing, fertilizing, cultivation, and other management practices uses water more efficiently and is more drought resistant.

According to Barton et al. (2009) previous research has demonstrated converting from cool-season to warm-season turfgrasses can save from 15 to 48% water, decreasing NF rates can save up to 31% water, and lowering cutting heights of cool-season grasses can decrease ET by up to 27% depending on the species and the change in height. Admittedly cultural factors are more easily manipulated than environmental parameters yet one single factor in a maintenance program may not be significant. However, manipulation of a combination of cultural factors could significantly reduce water requirements of a turfgrass.

Manipulation of these parameters where irrigation is limited by the water supply, irrigation capacity, and facilities could be very important in maintaining turfgrass quality (Sherman and Beard, 1973). Fortunately, turfgrass managers have opportunities to alter many cultural practices to conserve water and can reduce irrigation requirements by managing turfgrass to maximize rooting potential (which increases the size of the plant-available soil moisture reserve), by reducing water lost through evapotranspiration, and by applying irrigation water more intelligently (Ebdon and Petrovic, 2000). Perhaps of most importance to note, cultural
practices that promote extensive root development are important for enhancing drought avoidance (White et al., 1993; Carrow, 1996; Qian et al., 1997, Jiang and Huang, 2001, Githinji et al; 2009).

Shearman and Beard (1973) investigated the relative importance of preconditioning (prior to drought stress exposure) environmental and cultural factors on physiological and anatomical characteristics of the plant that in turn influenced the water use rate of ‘Penncross’ creeping bentgrass (*Agrostis palustris*) and found preconditioning treatment effects of cutting height, light intensity, and NF level have the greatest influence on water use rate. Mowing frequency and irrigation inputs were intermediate in their effects, and ambient air temperature had the least effect on water use rate. Madison (1960) also indicates verdure on an individual plant basis showed plant size to be relatively less affected by fertilizer but appreciably increased by higher mowing and a longer interval between irrigations.

Madison (1960) goes on to infer irrigation practices can influence water-use rate, and frequent irrigations increase water use rate because of increased loss of water due to evapotranspiration.

*Mowing*

Increasing mowing height of a turfgrass stand may increase water use rate as a larger leaf area index leads to an increased amount of transpiring leaf area exposed to the atmosphere and the amount of water being lost (Ebdon, 1999). Research has also shown that although taller cut turfgrass may use more water than lower cut turfgrasses, it is more efficient, probably because of a better root system (Butler and Minner, 1985). Butler and Minner (1985) also agree turfgrasses mown higher perform better under stress conditions than lower cut turfgrass. Murphy (2002) indicates, drought induced dormancy of turfgrasses in New Jersey is rarely long enough to cause failure of higher cut turf, as long as it is healthy going into dormancy. Madison (1960) found roots per individual turfgrass plant were reduced by fertility and short, frequent mowing, as are roots in forage studies.

*Nitrogen Fertility (NF)*

As NF rates increase so does water use by turfgrass due to increased shoot growth thus responsible for increased ET from well irrigated turfgrass canopies (Shearman and Beard,
In fact, Mantell and Stanhill (1966) declare without any NF, an increase in irrigation frequency had no significant effect on plant density and was, in fact, deleterious in early work done by Madison (1960). Bastug and Buyuktas (2003) also studied the influence of irrigation practices on NF. However, traditional turfgrass fertility programs seldom apply N, P, and K individually (Ebdon, et al., 1999).

**Secondary Cultural Factors**

Secondary cultural practices, such as turfgrass cultivation, topdressing, wetting agents, plant growth regulators, and pest management, also influence turfgrass top and root growth and subsequently influence potential water conservation (Beard, and Kenna, 2008). Aeration increases water infiltration, root growth and depth and often increased turfgrass density and this can lead to increased water use due to an improved turfgrass stand (Carrow and Duncan 2003).

**Thatch**

Thatch serves as an important environmental buffer, intercepting and cycling NF and preventing a large portion of the N from reaching the soil (Miltner et al., 1996). Increased water use efficiency is evident when thatch is maintained at acceptable depths and not allowed to dry out (Gibeault et al., 1989). Moreover, a deep thatch layer, if hydrophobic, reduces or eliminates water infiltration into the turfgrass profile leading to inefficient water use (Gibeault et al., 1989). Compacted soil is another factor that contributes to thatch buildup (Murphy, 2002). Thatch development is also dependent upon growth habit of the turfgrass plant and is generally not a problem in tall fescue (*Festuca arundinacea*) and perennial ryegrass (*Lolium perenne*) turfs (Minner and Butler, 1985).

**PGRs/Hormones**

Murphy (2002) indicates abscisic acid (a plant hormone) can also lower water use. In addition Murphy (2002) also admits greenhouse research has shown that some growth regulators (i.e., melfluidide, ethephon, and trinexapac-ethyl) lower evapotranspiration, which potentially would extend the carrying capacity of the soil presuming adverse effects on root growth do not occur with use of a growth regulator.
Soil

Water infiltration rate, in most instances, should be used as the primary criterion for evaluating the soil physical conditions of turfgrass (Lodge and Baker, 1993). A reduction in soil bulk density of severely compacted soil will enhance water retention (storage) and encourage deeper rooting, thus increasing the carrying capacity of the soil (Murphy, 2002). Allowing an unhealthy turf to go dormant on poor quality soil will result in severe thinning (loss) of turfgrass (Murphy, 2002).

ET Specific/Water Use

Turfgrass water use is defined as the total amount of water required for growth plus the amount of water lost through evapotranspiration (ET) per unit time (Beard, 1973). ET is comprised of the sum of soil evaporation and plant transpiration (Beard, 1973). Typically 97-99 percent of the water absorbed by the turfgrass plant is lost to the atmosphere through transpiration and thus transpiration accounts for most of the water lost from a dense turfgrass canopy (Beard, 1973; Beard and Kim, 1989; Kome, 1993). Because the amount of water used for turfgrass growth is so small, water use is typically referred to as ET yet the ET of a turfgrass is not synonymous with its ability to resist drought (Gibeault et al., 1989). Water use or ET is given in units such as inches (in.) or millimeters (mm) per day, per week or per month (Gibeault et al., 1989). Pruitt (1964) notes the water use for any one day or small groups of days can be considerably higher or lower than the monthly mean.

Cool-season turfgrasses may consume 3-8 mm of water per day (Beard and Kenna, 2008). The amount of water required for maintaining healthy, functional turfgrass depends on turfgrass species, soil type and texture, soil moisture, cultural practices and climatic conditions such as rainfall intensity and frequency, temperature, solar radiation and duration, wind speed and relative humidity and all of these impact the vapor pressure deficit of the atmosphere which is the driving force for transpiration (Shearman and Beard, 1973; Beard, 1981; Feldhake et al., 1983; Butler and Minner, 1985; Gibeault et al., 1989; Kome, 1993; Huang and DaCosta, 2006; Beard and Kenna, 2008). Kim and Beard (1988) give classifications of ET rates as follows: low (<5.5 mm per day), medium low (5.5-6.0 mm per day), medium (6.0-7.0 mm per day), medium high (7.0-7.5 mm per day), and high (>7.5 mm per day).
DaCosta and Huang (2006) also explain water use efficiency is commonly calculated from gas-exchange measurements as the molar ratio of CO₂ assimilated during photosynthesis to the amount of water lost through transpiration. The key to developing water saving irrigation programs is to understand the water requirements of specific turfgrass species, identify turfgrasses with lower water requirements, and external factors affecting water use, and to design and utilize irrigation systems for maximum water use efficiency (Gibeault et al., 1989; Huang and DaCosta, 2006).

Aronson et al (1987a) indicated transpiration was governed mainly by meteorological factors when soil water is available, but declined linearly with soil water potential after a critical soil water level is reached. ET rates are not constant but vary with time under progressive water stress (Kneebone et al., 1984; Fernandez and Love, 1993) and various studies have indicated ET increases with water availability (Biran et al., 1981; Kneebone and Pepper, 1984). Yet as soil moisture approaches field capacity, the implied assumption has been ET approaches its full maximum potential for existing evaporative demand (Kneebone and Pepper, 1984). Some researchers have reported a higher water-use associated with higher water availability (Beard 1973; Biran et al. 1981; Kneebone and Pepper, 1984; Githinji, et al. 2009).

Plant Characteristics

The comparative water use rates of turfgrass species are distinctly different from the relative drought resistances, because each is a distinctly different physiological phenomenon. Kome (1993) believes efficient water use strategies may be divided into two main groups: (1) management or cultural factors and (2) plant factors. Cultural or environmental factors that cause a drastic change in leaf area or shoot density of a given species may result in a significant shift in its relative ranking compared to the other species (Beard and Kim, 1989).

Kim and Beard (1988) state ET rate differences among species/cultivars are associated, to varying degrees, with shoot density, number of leaves per unit area, leaf orientation, leaf width, and vertical leaf extension rate. The first three plant parameters contribute to a high canopy resistance to ET, while the latter two parameters affect the total leaf area and resultant amount of evaporative surface. The external canopy resistance to ET has been shown to be much greater than the internal plant resistance (Kim and Beard, 1988). Gibeault et al. (1989) found turfgrasses with a low leaf blade area, including narrow leaves with slow vertical
extension rates and turfgrasses that had a high shoot density with a high leaf number, were lower ET turfgrasses.

Data from Gibeault et al. (1989) indicated 36% less water was applied to warm-season species studied than cool-season species to achieve acceptable turfgrass quality. Gibeault et al. (1989) explained the difference in water use between warm-season and cool-season turfgrasses as being derived from changes in the photosynthetic process that occurred in grasses evolving under hot, dry conditions. These changes, which include modifications to biochemical reactions and internal leaf anatomy, greatly enhance the photosynthetic efficiency and therefore help to reduce water use. Increased photosynthetic efficiency indicates warm-season turfgrasses may maintain high levels of carbohydrate production and continue to grow even when stomata are partially closed and this partial closure of the stomata slows the plant’s resultant water use. While typically more efficient water users, Biran et al. (1981) found variation among the warm-season turfgrasses they studied and those plants with a sparse, vertical, growth habit had a higher growth rate and water consumption than the dense, low growing ones.

Beard (1981) states turfgrass characteristics and physiological hardiness associated with drought resistance can be much different than those plant characteristics that contribute to reduced water use rates and stresses. It should be recognized that a reduced water use rate will delay the onset of drought as will a turfgrass species whose root system extends through a greater portion of the soil profile. However, once the available soil moisture is exhausted the ability of perennial grasses to survive a subsequent drought is the ultimate concern and therefore turfgrasses with severe drought resistance may not necessarily be those possessing the lowest water use rates (Beard, 1981).

Dormant turfgrass plants have limited or no transpiration water loss, and thus low water usage. The leaves of dormant turfgrass turn brown in response to a water deficit, but the growing points in the stem are not dead. In general, turfgrasses, especially those with rhizomes (underground stems), can survive without water for several weeks or months with limited damage, depending on the air temperature. Allowing certain turfgrasses to go dormant in low-maintenance areas may result in significant water savings without loss of turfgrass.
Most turfgrasses utilized for sport and recreational activities will require irrigation to maintain adequate recuperative ability and turfgrasses selected should have a low water use rate if efficient water use is the objective. Thus the goal is to select turfgrasses that require the least possible supplemental irrigation (Beard, 1981; Beard and Kim, 1989).

Specific types of plant morphology affect the resistance to ET and the major factors are a low leaf area and a high canopy resistance (Beard and Kim, 1981). Selecting low-water-use and/or drought-resistant turfgrass species and cultivars are a primary means of decreasing water needs (Beard and Kenna, 2008). However, species that possess a high drought resistance potential might nevertheless have a high water consumption rate when water is available (Biran et al., 1981). Turfgrasses with low ET rates maintain favorable plant water potential by conserving water, while turfgrasses with deep, extensive root systems maintain favorable water potential by increasing the efficiency of water absorption (Salaiz et al., 1991).

Species Specific Comparisons

Water use rankings of cool-season turfgrasses under non-limiting soil moisture conditions have previously been reported as: tall fescue (Festuca arundinacea), Kentucky bluegrass (Poa pratensis), annual bluegrass (Poa annua var. reptans), and creeping bentgrass (Agrostis stolonifera) having the highest ET rates; rough bluegrass (Poa trivialis) and perennial ryegrass (Lolium perenne) ranked intermediate; and chewings (Festuca rubra subsp. trachyphylla), hard (Festuca brevipila), and red (Festuca rubra subsp. rubra) fescues had lowest ET rates (Miner, 1984; Aronson et al., 1987; Beard and Kim, 1989, Fernandez and Love, 1983). Beard and Kim (1989) have shown the fine leaved fescues rank medium in water use rate, while Kentucky bluegrass, annual bluegrass, and creeping bentgrass have exhibited very high water use rates when grown under non-limiting moisture conditions. Gibeault et al. (1989) point out turfgrasses, such as tall fescue, may have high water use rates and medium drought resistance while some turfgrasses have high water use rates and fair or poor drought resistance such as the ryegrasses and bluegrasses.

In addition, Green et al. (1990) found significant differences in ET rates among the 12 cool-season turfgrasses they studied. It should also be noted Aronson et al. (1987) state different species may transpire at different rates when water is not limited. Data from Fry and Butler (1989) indicates "potential ET" rates (i.e., ET when soil water is not limiting) of creeping
bentgrass (*Agrostis palustris*) and annual bluegrass (*Poa annua var. reptans*), when evaluated under putting green conditions, significant species differences were observed. However, the authors conclude the differences were small and irrigation requirements should not vary much between these species. DaCosta and Huang (2006) found velvet bentgrass (*Agrostis canina*) exhibited lower soil water depletion and higher water use efficiency compared with colonial bentgrass (*Agrostis capillaris*) and creeping bentgrass (*Agrostis palustris*) which exhibited intermediate water use characteristics among the three species.

Aronson et al. (1987b) found at moderate levels of humidity, perennial ryegrass exhibited greater ET rates than tall fescue and Kentucky bluegrass, while at higher humidity tall fescue used less water than either Kentucky bluegrass or perennial ryegrass. Aronson et al (1987a) also found leaf water potential of *P. pratensis* and *L. perenne* decreased by 50-75% when soil water potential declined to -80kPa, while that of *Festuca* species remained relatively constant to a soil water potential of -400kPa. Based on the parameters measured, *P. pratensis* and *L. perenne* exhibited a more rapid decline in ET rate, quality, and leaf growth under moisture stress than the two *Festuca* species, which demonstrated greater ability to thrive with limited soil moisture. Below -60 kPa, Chewings fescue generally sustained the highest crop coefficient and greatest ET of the four grasses, hard fescue was intermediate while the ET from Kentucky bluegrass and perennial ryegrass declined the most under drought-stressed conditions (Aronson et al., 1987a).

While comparing a turfgrass stand versus landscape perennial plantings consisting of native and drought-tolerant plants, Park and Cisar (2005) report ET from the turfgrass remained relatively consistent over the experimental period. Yet in comparison, water use increased approximately 30 percent from year one to year three in the perennial planting landscape, increasing approximately nine percent annually thereafter. The maturing landscape plants with an expanding canopy and increasing evaporative demand more than likely had a greater leaf surface area in contact with aerodynamic and thermodynamic factors that affect ET (Park and Cisar, 2005).

A study by Ervin and Koski (1998) included objectives to: (1) assess some of the physiological responses and morphological factors which contribute to the drought avoidance capabilities of Kentucky bluegrass and tall fescue turfs subjected to increasing levels of drought and (2) to develop water-conserving crop coefficients (Kc) to be used with Penman
equation estimates of alfalfa (*Medicago sativa*) reference evapotranspiration (ET) while maintaining these turfs at an acceptable level of quality.

**ET Comparisons by Region**

Selection of turfgrass species and cultivars that are adapted to local climatic conditions can result in significant water savings (Beard and Kenna, 2008). It is important to note comparative water use rankings of different species and cultivars may change across different environments, climatic conditions, and cultural regimes (Aronson et al., 1987; Butler and Minner, 1985; McCoy and McCoy, 2006). Therefore, it is important to use caution when extrapolating water-use results from different geographic zones (Ebdon and Petrovic, 2000). Most of the ET data reported by Beard (1985) were from the field using mini-lysimeters, from semi-arid or arid climates, and obtained under non-limiting soil moisture.

Data from Carrow (1995) suggests implications of ET results indicate (1) substantially lower ET under humid conditions and typical field conditions illustrate the need to obtain regional ET values if the data are to be used for water resource planning purposes, (2) these data provide a guideline for turfgrass water use only under similar climatic and soil conditions, and (3) ET data in a humid region is not a good means of ranking turfgrasses for water relationships in semi-arid and arid regions. For example, mean summer potential ET for Kentucky bluegrass in the arid West has been found to exceed potential ET in the humid Northeast by 30 to 65% (O’Neil et al., 1979; Feldhake et al., 1983; Aronson et al., 1987).

**ET Soil Moisture Considerations**

Non-limited soil moisture and a limited root system inherent in mini-lysimeters and most other controlled environments may result in ET data different from actual situations (Carrow, R. N. 1995). Turfgrass managers typically make irrigation decisions based on actual field water use, which normally includes a mild to moderate dry-down between irrigations therefore when studying drought avoidance mechanisms, plant factors influencing ET under well-watered conditions differ from those under limited soil moisture (Carrow et al., 1990).

Fernandez and Love (1993) agree water use measurements under non-limiting conditions are not good predictors of low water use patterns under restrictive water use, which may be appropriate to conserve water. Love (1993) measured the ET rates of 25 turf cultivars during
dry-down periods and found potential ET rates were not necessarily related to cumulative ET, which included periods when soil-water was limiting. Additionally, as soil moisture is depleted, there is a gradual reduction in water use even before turfgrass wilts (Fernandez and Love, 1993).

Soil

The standard definition of available water (AW) is the volume of water retained in the soil from field capacity to the permanent wilting point (McCoy and McCoy, 2006). Plants grow best when the soil is managed to hold 50 to 80% of the plant-available water for that soil (Murphy, 2002). An estimation of AW within the rooting depth is imperative to an efficient irrigation budget (McCoy and McCoy, 2006).

The term, carrying capacity of a soil, is used to describe the time required by turfgrass to deplete 50% of the plant-available soil water (Murphy, 2002). Soils with a longer carrying capacity provide greater flexibility in irrigation inputs, and more reliance can be placed on rainfall to extend the carrying capacity (Murphy, 2002). Irrigating more often than the carrying capacity of the soil may result in less efficient use of irrigation inputs due to greater water loss from evaporation, leaching, and runoff (Murphy, 2002). Murphy (2002) also notes turfgrass growing on loam soils can be irrigated less frequently with larger quantities of water while sandy soils hold less plant-available water and require more frequent irrigation with a smaller amount of water.

Drought stress often occurs in the soil surface although water reserve may be adequate deeper in the soil profile (Huang and Fu, 2001). Data from Kome (1993) indicates at the peak of a dry period, a complete reversal of soil moisture pattern by depth was observed: 15-25 cm > 10-15 cm > 5-10 cm > and 0-5 cm. Aronson et al. (1987a) note a soil water potential in the range of -50 to -80 kPa represents a threshold level of drought stress for cool-season grasses growing in southern New England.

Seasonal Influence

Even under drought conditions, irrigation frequency in the spring or fall is considerably less than irrigation in summertime because ET is rather low in the spring and fall (Murphy, 2002). Likewise Meyer et al. (1985) determined replacement of soil moisture can be scheduled daily
or two to three times per week depending on the time of year and soil moisture depletion during a given period.

*ET Measurement Methods*

Reference ET (ET) is calculated as: \( \text{ET}_{0} = E \text{pan} \times K \text{pan} \) (Meyer et al., 1985). Brown (1996) compared 5 methods of estimating ET and found them to differ by as much as 20%. The work performed by Brown (1996) determined turfgrass water use from daily changes in lysimeter weight and compared the changes to reference ET as computed by automated weather stations. This relationship between actual turfgrass water use and ET is known as the crop coefficient \((K_c)\) and is required to convert ET to turfgrass water use for irrigation purposes.

Early work by Pruitt (1964) discovered mean monthly ET for ryegrass was very close to the water loss from a USDA (BPI pan) which is a 6-foot diameter, 2-foot deep pan with the water surface maintained about 4 inches below the rim of the pan at about ground level. ET averaged about 0.7 to 0.8 as much as evaporation from the more exposed 4-foot diameter USWB pan which has its water surface about 14 inches above ground level. Although a water surface absorbs 90 - 95% of the incoming solar radiation (70 - 90% for crops); it normally has a smoother surface than crops; and can offer no control over water loss, as can plants yet a good relationship between evaporation from a water surface and ET for plants does exist (Pruitt, 1964).

Butler and Minner (1985) state weighing lysimeters permit a uniform and accurate study of environmental, cultural, and species influence on water use by weighing at sunrise and again at sunset. Salaiz et al. (1991) also acknowledge ET rates have been evaluated effectively using mini-lysimeters and also have been shown to differ between turfgrass species. Lysimeter evaluations, which typically measure PET, do not expose the turf to the moderate soil-drying cycles that normally occur between irrigations or precipitation events in the field (Keeley and Koski, 1997).

Keeley and Koski (1997) determined activity of deep roots lead to difficulties in obtaining accurate estimates of ET with both lysimetry and time domain reflectometry (TDR). In the work performed by Keeley and Koski (1997) water uptake by roots growing beyond the waveguide depth of 30 cm was unaccounted for in the ET measurement in initial trials.
therefore with the addition of waveguides installed per plot (52cm), the TDR system measured significant differences in ET and rates were low in comparison with those obtained from lysimeter studies (Feldhake et al. 1983; Schmidt and Everton 1985; Shearman 1986; Aronson et al. 1987; Green et al. 1990; Fernandez and Love 1993). A partial explanation offered by Keeley and Koski (1997) for the lower ET rates may be that soil-water became moderately limiting during the three- to four-day dry-down period. Even though visual stress symptoms were not readily apparent, Keeley and Koski (1997) infer turfgrass may exhibit decreased stomatal conductance in response to soil-drying even though the leaves remain fully turgid.

Dettman-Kruse et al. (2008) relied on hourly and daily ET estimates using a modified Penman equation (Campbell Scientific). Aronson et al. (1987b) found the Penman equation predicted ET more consistently, and may provide a reliable and useful tool for irrigation scheduling of turfgrass in southern New England. In a previous investigation comparing actual ET to PET, Qian et al. (1996) found that the Penman-Monteith model generally overestimated ET when evaporative conditions were low, and underestimated ET when water demand was high, such as under conditions of high air temperature, high solar radiation, and high wind.

\textit{ET Crop Coefficients}

Reference crop evapotranspiration (ET\textsubscript{o}) is the rate of evapotranspiration from an extensive surface of 8- to 15-cm tall, green grass cover of uniform height which is actively growing completely shading the ground and not short of water (Carrow, 1995). Crop coefficients (K\textsubscript{c}) will change during the season based on the plant cover, growth rate, root growth, and stage of plant development and turf management practices (Gibeault et al., 1989).

Carrow (1995) found actual ET of a particular turfgrass varied as much as 3.7-fold due to climatic conditions, soil moisture, and turfgrass growth. Therefore to effectively use weather-based irrigation scheduling, turfgrass managers must select crop coefficients based on the month and turfgrass species (Meyer et al., 1985; Carrow, 1995). Specifically, data from Ervin and Koski (1998) indicates water conservation can be encouraged while still maintaining acceptable turfgrass quality by irrigating every 3 days with the 1982 Kimberly-Penman equation estimates of ET that have been adjusted with K\textsubscript{c} in the range of 0.60 to 0.80 for Kentucky bluegrass and 0.50 to 0.80 for tall fescue. Ervin and Koski (1998) evaluated five irrigation levels at 65, 55, 50, 35, and 20% of ET\textsubscript{r} in 1993 and 75, 70, 60, 45, and 30% of ET\textsubscript{r}
in 1994. These estimates were summed every 3 d during the irrigation treatment cycle and multiplied by a cool-season turfgrass Kc of 0.80. The Kc of 0.80 for cool-season turfgrass is the most common average value recommended by the relevant research (Minner, 1984; Feldhake et al., 1985; Meyer et al., 1985; Meyer and Gibeault, 1987; Carrow, 1995). Likewise, Meyer et al. (1985) suggest the average crop coefficients of warm-season species to be 0.7.

Percentage ET

In many cases, there may actually be unnecessary over irrigation of turfgrass if irrigation regimes are based on replacing 100% ET (DaCosta and Huang, 2006b). DaCosta and Huang (2006b) irrigated their plots three times per week, generally between 0800 and 1100 h, at four levels of irrigation quantity based on different percentages of the maximum daily water loss through ETa as measured using mini lysimeters. Meyer et al. (1985) determined accurate monthly Kc for warm- and cool-season turfgrasses and stated water conservation effectively saves 20 to 40% of water needs when 60 to 80% of actual ET is applied.

Deficit Irrigation

A widely recognized irrigation scheduling protocol that employs rainfall and ET information with estimates of available water capacity within the root zone to schedule irrigation frequency and amount of irrigation is deficit irrigation. Deficit irrigation may be used with regional or site specific, monthly mean values of daily rainfall and ET and the procedure may be fine tuned to use actual daily rainfall and ET measurements (Biran et al., 1981; Feldhake et al., 1984; McCoy and McCoy, 2006; Githinji, 2009). With demand on urban water resources often exceeding available supplies, it has become important to understand and quantify the responses of turfgrass to deficit irrigation (Feldhake et al., 1984).

In addition to the benefit of decreased total water use (DaCosta and Huang, 2006b; Horgan and Sass, 2006), turfgrasses can tolerate certain levels of deficit irrigation with little or no loss in turf quality with the proper use of a deficit irrigation strategy, either through decreased irrigation quantity or irrigation frequency. Additionally, deficit irrigation has been found to promote plant tolerance to subsequent severe drought stress associated with increased root growth or enhanced osmotic adjustment (Beard, 1973; Qian, 1996; Jiang and Huang, 2001;
DaCosta and Huang, 2006b). Chalmers et al. (1981) reported that a slight plant water deficit could improve the distribution of carbohydrate to the reproductive structures and also control excessive vegetative growth.

Applying irrigation to 80% of field capacity reduced water use of Kentucky bluegrass by 20% and only reduced quality by 10% (Danielson et al., 1981). Huang and DaCosta (2006) found soil water content decreased when plots were irrigated at 60%-80% actual ET and soil water content did not reach detrimental levels that cause leaf wilting of bentgrass.

The data of Fry and Butler (1989) show that shallower and more frequent irrigations are needed for tall fescue when the irrigation level is at a considerable deficit (50% PET). Results from DaCosta and Huang (2006) suggest irrigating bentgrass species at 60 to 80% actual ET could be practiced to increase water use efficiency during summer and 40% actual ET during fall months under the conditions of their study.

Overall, studies on deficit irrigation of turfgrasses have shown that the extent of allowable deficit irrigation may vary between species and within cultivars of the same species, with warm-season grasses typically being better able to withstand greater levels of deficit irrigation compared with cool-season grasses (Meyer and Gibeault, 1986; Qian and Engelke, 1999).

**Irrigation Specifics**

The challenge with any turfgrass stand in many regions is annual precipitation is not sufficient or adequately spaced throughout the year to sustain turfgrass water needs; therefore, supplemental irrigation is needed (Gibeault, et al., 1989). Efficient irrigation, despite being one of the most important factors in maintaining healthy turfgrass is often an overlooked variable and to irrigate properly levels of consumptive water use and the factors which affect them must be known (Kneebone and Pepper, 1982).

Water moves into turfgrass roots from soil, from roots to leaves, and finally from leaves to atmosphere and viewed in this way the major factors affecting water use by a turfgrass stand is the soil moisture status, the plant, and the atmospheric evaporative demand (Kneebone and Pepper, 1982). Murphy (2002) believes turfgrass should be irrigated in a manner that applies enough water to moisten as much of the root zone as possible without loss to drainage or
runoff. Shearman and Beard (1973) noted frequent, light irrigations reduced drought tolerance and the extent of the root system.

A healthy, durable turfgrass stand that withstands minor drought is achieved by irrigating thoroughly but as infrequently as possible based on carrying capacity in essence allowing the soil to dry to 50% of its available water between irrigation events promotes deep rooting and helps plants to survive subsequent drought or heat stress (Murphy, 2002). The key to efficient irrigation is to apply only as much water as the turfgrass actually requires supplying enough water to last until the next irrigation cycle or precipitation event.

In general, the healthier the turfgrass when heat or drought stress begins, the longer it will stay green and the better it will withstand the stress. This strategy maximizes root growth in the soil and supports healthy, dense turfgrass that is better able to handle drought conditions. When developing an optimum turfgrass irrigation schedule, predominant turfgrass species, soil characteristics, nearby trees and shrubs that affect sun and shade, mowing height, potential for disease problems, and quantity of water your irrigation system can deliver must all be taken into account.

The recommendation for many years has been to irrigate just often enough to maintain acceptable visual turfgrass quality (Richie et al. 2002). Gibeault et al. (1989) agree water application must be sufficient to maintain the grasses at a level where they are capable of performing the required task, which can merely be grass survival and water can be applied at a rate adequate to simply keep turfgrass alive corresponding to a small percentage of the ET value. Murphy (2002) states healthy, high-quality turfgrass may need up to 45 ml of water per week to keep it vigorously growing under hot, dry, windy summer conditions. Githinji et al (2009) indicate early research suggested irrigation should be initiated when soil water potential is high enough so that the soil can supply water fast enough to meet the crop evapotranspiration, hence avoiding drought stress that would reduce yield or quality of the crop.

**Assessment Techniques**

Butler and Minner (1985) concluded there were various ways to determine soil moisture content and they vary in precision and actual usefulness as a tool for irrigating properly.
Among the methods used are those as simple as probing with a screwdriver or using gypsum or nylon moisture blocks to measure electrical flow, tensiometers to measure soil suction, soil samples can be taken and weighed, then dried and reweighed to determine water content, time domain reflectometry (TDR), and canopy temperature assessment.

The use of canopy temperature to detect water stress is based on the principle that water lost through the transpiration process cools the leaves below the temperature of the surrounding air under well-watered conditions and as soil water becomes limiting, transpiration is reduced and leaf temperature increases. Thus if transpiration is greatly reduced or ceases, leaf temperature will be greater than air temperature because of radiation absorbed by the leaf (Throssell et al., 1987).

Despite the introduction of various monitoring techniques, many turfgrass managers continue to rely on qualitative visual assessments of water stress in determining irrigation needs (Steinke et al., 2009). Murphy (2002) believes a sure sign turfgrass will benefit from irrigation is a wilted appearance. One initial symptom of wilting is “foot-printing,” where footprints on the turfgrass will not disappear within 30-60 minutes. This symptom is soon followed by actual wilt, where the leaves of the turfgrass plant lose an upright erect appearance and take on a grayish or purple-to-blue cast. Usually, only a few areas will appear wilted in the same general location and these areas typically serve as good indicator spots when assessing the need to water (Murphy, 2002).

Data from Shearman and Beard (1973) showed turfgrasses receiving irrigation only when wilt was visually evident (approximately every 4 days) were significantly lower water users than those irrigated three and seven times each week. In addition, Murphy (2002) also states wilt stress should be minimized for playing surfaces that are mowed at very low heights (i.e., putting greens) or receive high amounts of traffic from play or vehicles. Gibeault, et al. (1989) also admitted that watching for areas in a turfgrass site that show water stress first, and the regular use of soil probes and/or soil moisture measuring devices will help to perfect irrigation schedules and give the desired results with the most efficient use of water resources. Similarly, Biran et al. (1981) found delaying irrigation until the onset of temporary wilting caused a significant decrease in water consumption and growth (up to 35%) in most turfgrasses.
Irrigation Scheduling and Application

Many turfgrass managers currently schedule irrigations based on their experience and observations of the turfgrass site or irrigate on a set time interval. Optimizing irrigation scheduling is essential for environmentally responsible and efficient turfgrass management. Several irrigation scheduling methods have been suggested, and they can be categorized as soil, plant, and atmosphere based approaches (Githinji et al., 2009).

Variability of ET throughout many studies suggests that water savings can result if ET is monitored, and irrigation inputs adjusted accordingly (Fry and Butler, 1989). Horgan and Sass (2006) have found ET estimators are widely used to schedule turfgrass irrigation. In addition to the use of turfgrasses with inherently low ET rates as a drought avoidance component, Carrow (1995) indicated a second strategy for reducing turfgrass water use is the development of ET feedback systems to schedule irrigation such as the California CIMIS and Arizona AZ-MET systems. In fact, Arizona and California use ET estimation as the basis for establishing irrigation scheduling guidelines for all agricultural and horticultural crops, including turfgrass. In addition, Bastug and Buyuktas (2003) investigated the feasibility of basing irrigation on soil moisture rather than traditional time clock scheduling during periods of high and low rainfall. Where irrigation is automatically controlled, rates are typically selected to meet maximum evaporative demands, resulting in overwatering (Morton et al., 1988).

An ideal irrigation scheduling technique should use the plant as the indicator of water stress since the plant responds to both the aerial and soil environments. A highly water efficient irrigation scheduling program will limit losses to entrapment/evaporation at the soil surface as well as deep infiltration past the root zone (Horgan and Sass, 2006). Results from Horgan and Sass (2006) indicate both ET estimation and capacitance soil moisture sensors have the capability to serve as the foundation for turfgrass irrigation scheduling which should result in the conservation of water resources while maintaining turfgrass quality.

One critical element is to avoid applying the water too quickly and to apply the proper amount of water when the landscape needs the water to avoid potential losses as a result of; runoff from sloped sites, thatchy turfgrass, or turfgrass growing on highly compacted soils and deep percolation (apply the water as uniformly as possible) (Gibeault et al., 1989; Murphy, 2002;
Beard and Kenna, 2008). Nighttime is generally less windy, cooler and more humid, resulting in less evaporation and a more efficient application of water (Murphy, 2002). In addition, the newest sprinklers available combine lower precipitation rates to more nearly equal soil infiltration rates, thereby reducing or eliminating water runoff (Gibeault et al., 1985).

**Irrigation Frequency**

Turfgrass managers have taught and research has shown that light, frequent irrigation encourages shallow rooting and weed growth (Madison and Hagan, 1962; Shearman and Beard, 1973). In addition, excess watering will typically increase the amount of weeds that appear in a turfgrass stand and enhance the severity of certain turfgrass diseases (Murphy, 2002). Too frequent irrigation may result in roots significantly fewer and shallower (Madison and Hagan, 1962) and may subject plants to cycles of stress and recovery which frequently results in loss of plant quality (Kome, 1993). Conversely, research data from Butler and Minner (1985) revealed that with irrigation using equal amounts of water being applied at 2, 4, 7, and 14 day-intervals, quality declined from the 2-14 day interval.

In addition, DaCosta and Huang (2006b) noted minimum irrigation quantity was determined for three bentgrass species when irrigated three times weekly, and irrigation quantity is expected to change with changes in irrigation frequency. Shearman and Beard (1973) studied the effect of irrigation frequency on water use rate, stomatal density, and percent vegetative cover and their treatments consisted of (1) irrigation only when visual wilting occurred (an interval of approximately 4 days), (2) irrigation three times per week, and (3) irrigation seven times per week.

Morton et al. (1988) in their work chose to irrigate plots at two rates (1) a scheduled rate to avoid drought stress and to prevent percolation from the root zone, and (2) a rate to simulate over-watering which consisted of three applications per week of 1.25 cm per application (3.75 cm wk⁻¹), regardless of rainfall. Lodge and Baker (1993) decided upon irrigation treatments that represented replacement of 75%, 100% and 125% of ET losses in 1990 and 60%, 100% and 140% of ET losses in 1991 and 1992. Kneebone et al. (1984) chose rates of irrigation of 25, 50, and 80% of class A pan evaporation with respective ET values of 68, 109, and 119% of class A pan and three irrigation levels; 114, 243, and 364 mm per 7 days applied in increments of 57, 121.5, and 182 mm twice each week were used.
Huang and Fu (2001) subjected plots to three soil moisture treatments for 42 days: (1) well-watered control: the whole soil profile (40 cm) was well watered; (2) surface soil drying: the surface 20 cm of soil was allowed to dry down by withholding irrigation and the lower 20 cm was watered; (3) full drying: the whole soil profile (40 cm) was allowed to dry down. They found surface soil drying generally had no effects on turfgrass quality and leaf relative water content (RWC), except at 15 days for turf quality and 17 days for RWC.

Richie et al. (2002) noted visual turfgrass quality was significantly correlated with an increase in amount of water applied or soil water content. Data from Horgan and Sass (2006) validates the adage that watering daily with low irrigation volumes is less water efficient compared to deep and infrequent irrigation. They found under daily shallow irrigation, a large proportion of the irrigation volume applied remained in the upper 5 cm of soil and is subject to high rates of evaporation. Their data suggests the first 3 mm of irrigation applied daily was intercepted by the top 4 cm of soil. Because of this, a lower proportion of water delivered to the turf surface reaches the plant roots and is available for root uptake. Carrow (1996) delivered irrigation at 4.1 cm whenever TDR probes at 10 to 20 cm read 14.3% soil water content, this value represented approximately 56% plant available soil water depletion and soil water potential of -0.40 MPa. Biran et al. (1981) found that lowering irrigation frequency reduced water consumption of container-grown, warm- and cool-season turfgrasses.

The irrigation program for one study was chosen to evaluate turfgrass performance with decreased irrigation inputs, which may also suit velvet bentgrass since it requires less water to maintain quality turf than does creeping bentgrass (DaCosta and Huang, 2006b). Plots were irrigated three times per week, generally between 0800 and 1100 h, at four levels of irrigation quantity on the basis of different percentages of the maximum daily water loss through evapotranspiration (ETa) (DaCosta and Huang, 2006b).

Work performed by Park and Cisar (2005) found more irrigation was applied during the establishment year (year one) than the other three years combined and the turfgrass treatment received significantly more irrigation than the perennial planting landscape during the first two years of the experiment. Although not statistically significant in year three, but significantly different in year four, more irrigation was applied to the perennial planting landscape than the turfgrass landscape (Park and Cisar, 2005). Once the turfgrass landscape was established in year one, less irrigation was applied for the remainder of the experiment.
and while frequent irrigation was needed for the turfgrass, the amount applied was minimal (Park and Cisar, 2005). A higher irrigation requirement of the perennial planting landscape over time likely reflected maturing plant material with an expanding canopy (Park and Cisar, 2005).

**Water Use Reduction Research**

As the supply of available water for turfgrass irrigation becomes limited it is critical to identify water-efficient, drought tolerant turfgrasses, and direct turfgrass culture toward practices that lower water requirements as competition for water use increases (Aronson et al. 1987a).

The objective of a study by DaCosta and Huang (2006b) was to determine and compare minimum water requirements for maintaining acceptable quality fairways established to creeping, colonial, and velvet bentgrasses and results demonstrated irrigating at 100% actual ET was not necessary to maintain acceptable turfgrass quality and physiological processes and minimum water requirements depended on species and time of year. For example, colonial bentgrass required irrigating at 80 to 100% actual ET, while creeping and velvet bentgrasses required 60 to 80% actual ET to maintain acceptable turfgrass performance in the summer.

Similarly, Feldhake et al. (1983) determined that a 27% reduction in irrigation based on actual ET of Kentucky bluegrass would cause only a 10% reduction in turfgrass quality while tall fescue also showed a similar response to deficit irrigation. Biran et al (1981) determined regular irrigation applied at 20 to 50% of the available water was depleted was also acceptable.

Quackenbush and Phelan (1965) also reported turfgrass subjected to drought conditions for short periods could sustain a fairly good appearance by irrigating about half of its consumptive use whenever soil moisture level falls to near permanent wilting point (Bastug and Buyuktas, 2003).

**Mowing**

Mowing during the coolest part of the day (early morning) will minimize the added stress caused by mowing and should be stopped when the soil dries to the point that the turfgrass is
wilted because mowing wilted turf will cause damage to the lower leaf sheaths and crowns thus increasing the likelihood of turfgrass loss (Murphy, J. A. 2002).

**Physiological**

Biran et al. (1981) concluded the long-term result is higher water consumption for the quick growing turfgrasses. Recovery of quicker growing turfgrasses is faster than for the slow growing grasses probably as a result of a more rapid elongation of existing leaves, which is the first stage of grass growth following mowing (Madison, 1960).

Madison (1962) indicated that following mowing, two components dominate in growth: an extension of cut blades during the first four days, and then the growth of new blades from the base. Madison (1962) revealed mowing removes the most densely green area, exposing a previously shaded and younger area, which is less green and as the cut leaves elongate during the first four days, their color deepens under the stimulus of increased light. In addition, newer, immature leaves of pale color appear in the clippings on the fifth day thus "diluting" the color. Thus apical growth may also be slowed by reduced water intake following mowing, and this implies that mowing upsets the orderly processes of growth and production of photosynthate is reduced following mowing with the attendant loss of leaf surface (Madison, 1962). Additionally, taller cut grass should be expected to transpire more than short grass since, while no more solar radiation is intercepted per unit area, more advective energy can be intercepted (Feldhake et al., 1983).

**Mower Blade**

Under field and controlled environment conditions, Steinegger et al. (1983) found water use rates for turfgrasses to be reduced by repeated mowing with a dull blade. Water use rates under field conditions were 1.3 and 1.2 times greater, for turfgrasses mowed with a sharp versus dull mower blade. However, the reduced water use rate associated with dull mower treatments was positively correlated to reduced shoot density and verdure (Steinegger et al., 1983). Therefore total water use was reduced with dull mower blade treatments but this was offset by an unacceptable reduction in turfgrass quality. However, these results do refute the generally accepted premise that dull mower blade injury of turfgrass leaf tissue increases turfgrass water use (Steinegger et al., 1983). Steinegger et al. (1983) also found it required
22% less fuel to mow turfgrasses receiving a sharp mower blade treatment than those receiving dull mower blade treatments.

*Mowing Height and Frequency*

Gibeault et al. (1989) concluded in addition to irrigation practices, mowing affects turfgrass growth, including root system development, and water use. The authors explain higher cutting heights result in deeper root systems and higher water use rates. The higher water use rate with higher mowed turfgrass would be dependent upon the more open canopy, with reduced shoot density.

Conversely, close mowed turfgrass has higher shoot density, and a tight canopy. These are characteristics which have been shown to reduce ET, as previously mentioned. The frequency of mowing also affects ET. Infrequently mowed turfgrass with long leaves between mowings results in higher water use than more frequently mowed grass during the same time period. Infrequently mowed turfgrass is also aesthetically and functionally inferior to a turfgrass sward maintained consistently at an appropriate height. The desired balance is to use mowing practices that enhance root system depth and density yet efficiently use water resources (Gibeault et al., 1989).

Madison (1962c) noted frequent mowing resulted in a small reduction in root weight per unit of soil volume while previous work performed by Madison (1960) found the least variance resulted from height of cut. Madison and Hagen (1962) showed higher mowing heights result in deeper root systems which may improve drought tolerance, maximum surface cover, and lower evaporative water loss yet higher-cut turfgrass loses more water to transpiration and typically produces more thatch.

Biran et al. (1981) found that increased mowing height resulted in measurably higher ET. Yet the authors concluded mowing height has a limited effect on water use, when the turfgrass is maintained at an acceptable aesthetic and functional level. In their experiments, three factors were examined to determine the water consumption of various lawn grasses grown in containers under high temperature conditions. Observations were made on variables such as differences between species and cultivars, lowering irrigation frequency and changing shearing height.
The single most important factor was the photosynthetic pathway, with C-3 grasses having a 45% higher water consumption than C-4 grasses. Among the C-4 grasses the extremes differed by 19%. Lowering the irrigation frequency resulted in a decrease of water consumption from 6 to 18% and 24 to 34% for the C-4 and C-3 grasses, respectively. Raising the clipping height from 3 mm to 6 mm for a period of 6 weeks led to increased vigor in all grasses as evidenced by growth rate, chlorophyll content and water consumption (Biran et al., 1981). Increasing shearing height resulted in an increase of water consumption from 3 to 15% (for C-4 grasses) and 2 to 25% (for C-3 grasses) (Biran et al., 1981).

Fry and Butler (1989) determined that although turfgrass cut at 12 mm used more water than at 6 mm differences were small and irrigation requirements of putting greens should not differ greatly from those of the collars and aprons maintained at higher mowing heights. While Dernoden and Butler (1978) found with infrequent irrigation, tall turf maintained a better appearance than close mowed grass.

Specifically, studies by Feldhake (1979) and Madison and Hagan (1962) have shown water use by Kentucky bluegrass increases with increased mowing height. Biran et al. (1981) found a significant increase in water use by tall fescue and perennial ryegrass when mowing height increased from 3 to 6 cm but could show no significant increase for St. Augustinegrass. Feldhake et al. (1983) noted Kentucky bluegrass had vertical leaf blades and a canopy relatively open to convective air flow while Bermudagrass grew in a dense, closed mat with short horizontal leaf blades at the surface of the canopy and this could have reduced convective air flow through the canopy in turn reducing ET even though they were mowed at the same height.

Additionally, low mowing heights coupled with high temperatures can add stress by removing leaf matter used for photosynthesis, while respiration continues (Huang et al., 1998). Lower mowing tends to result in less growth but removes more new growth, producing a relatively larger sample (Madison, 1962).

Differences due to height of cut are greater at longer irrigation intervals, as frequent irrigation appears to limit expression of differences due to height of cut (Madison and Hagan, 1962). Shearman and Beard (1973) conclude water use rate increased with cutting height and mowing frequency; water use rate doubled between 0.7- and 12.5-cm cutting heights, and increased by
41% between the biweekly mowing frequency and mowing six times per week. This is associated with increased leaf area and extent of root growth at higher cutting heights, which enhances water adsorption and loss through transpiration.

Also noteworthy, Murphy (2002) suggests the lower mowing heights associated with putting greens, tees, and possibly fairways do not allow the plants to develop sufficient carbohydrate reserves necessary to survive drought-induced dormancy. The low mowing heights used for playing surfaces on the golf course require more frequent mowing than the higher cut roughs and utility areas (Murphy, 2002). Mowing rough and utility areas less than 5 cm decreases drought and heat resistance of the turfgrass and may increase the severity of insect and disease damage, and weed invasion (Murphy, 2002).

Roots

In addition to irrigation practices, mowing affects turfgrass growth, including root system development (Feldhake et al. 1984). Madison and Hagan (1962) noted a greater decrease in rooting with 1.25 cm and 2.5 cm mowing heights than with a 5 cm mowing height. Madison and Hagen (1962) also found both shorter mowing and more frequent irrigation resulted in more plants with disproportionately smaller root systems. They suggested this may reflect fewer roots per plant, but more plants. Beard and Kim (1981) denote turfgrasses with deep, extensive root systems, coupled with decreased water use, are more drought resistant and have greater water conservation potential.

Nitrogen

Increasing fertilizer costs (doubled since 2007), increasing environmental regulations, and a growing public desire for sustainable systems require investigations into using as little NF as possible to grow and maintain acceptable turfgrass stands (Koeritz and Stier, 2009). While most nutrients required for turfgrass growth are normally available in sufficient amounts in soil, air and water, some are needed in greater amounts than are naturally supplied. Nitrogen fertilization (NF) is the most important nutrient for promoting good turfgrass growth, cover, and color (Christians et al., 1979; Butler and Minner, 1985; Murphy, 2002) and considered the single most important nutrient affecting turfgrass growth and ET (Ebdon and Petrovic, 2000).
The greater the growth rate, the greater will be the water use rates so turfgrass fertilization practices, especially NF, directly influences water use. Turfgrass managers must monitor and adjust NF programs to produce the least amount of topgrowth and the greatest rooting possible within the use parameters of the turfgrass stand otherwise, rapid growing grasses will have an unnecessarily high water use rate (Gibeault et al., 1989).

In a study by Barton et al. (2006) increasing the irrigation from 70% to 140% replacement of pan evaporation did not improve growth or quality of turfgrass supplied with any of the NF types evaluated. While increasing irrigation inputs decreased root growth by 30% and decreased tissue N concentration in clippings.

Fertilization influences turfgrass growth (Ebdon et al., 1999). Manipulating the NF rate to match turfgrass requirements is one approach to minimizing turfgrass water use, but would only be a useful management strategy if the effect on turfgrass quality is understood (Christians et al., 1979).

Irrigation specific

Soil biological processes and root activity tend to be greater in the surface soil than in the subsurface soil. Hence, increasing the contact time and interaction between applied nutrients and the plant roots should increase nutrient assimilation by turfgrass. Contact with the surface soil will be increased if the dissolved nutrients move through micropores within aggregates rather than moving rapidly around aggregates, down cracks and channels. The paths by which dissolved nutrients move through a soil profile will vary according to soil structure and the rate at which the irrigation water is applied (Barton et al., 2006).

Mantell (1966) concluded that time and water could be saved by moderate applications of NF and only occasional irrigation as opposed to no N application and frequent irrigation. Optimizing NF rates may be a useful approach for decreasing turfgrass ET, if it can also be demonstrated that lowering NF applications does not compromise turfgrass quality (Barton et al., 2006). Ebdon et al. (1999) indicate that reducing NF would result in no substantial savings in water needed for irrigating turfgrass to replace that lost by ET and unless excessive NF levels are applied.
Ebdon and Petrovic (2000) indicated turfgrass grown under a deficient NF level did not exhibit a break in the response to decrease in ET; instead it was nearly linear over the entire ET range studied. The turfgrass with the lower NF level also had a lower maximum ET level when soil water was not limiting. This is likely due to the lighter color resulting in more reflected energy, and the slower growth rate resulting in shorter grass at the time of each mowing. With NF deficient soils, a moderate application of NF may improve the aesthetic appearance under dry conditions since the live biomass will be darker green (Ebdon and Petrovic, 2000).

Ebdon et al. (1999) noted a reduction in turfgrass ET loss with increasing applied K was highly dependent on N and P levels. Phosphorus and K applied alone had little influence on plant growth (and ET); however, their interactive influence with N cannot be evaluated in the context of this single nutrient study (Ebdon et al., 1999). While Ebdon and Petrovic (2000) conclude the effects of N, P, and K on water use (and shoot growth) is interactive and therefore mutually dependent on the rate of the other major nutrients yet such a large number of treatments make N-P-K interaction studies impractical.

Barton et al. (2006) conclude N uptake is mainly affected by fertilizer type and NF application rate. They found significant interactions between irrigation treatment and NF application rate, plus fertilizer type and NF application rate. For their high irrigation treatment, increasing the NF application increased the N uptake of inorganic fertilizers, but not necessarily for organic fertilizers. While for their low irrigation treatments, increasing NF application rates increased N uptake for all fertilizer types.

Ebdon and Petrovic (2000) stress it is apparent from their study that reducing nitrogen fertilization resulted in no substantial savings in water for irrigating turfgrass to replace that lost by ET. Unless high (excessive) NF was applied, water use and clipping production were unaffected.

Plant Age

Barton et al. (2009) conclude NF applications need to be optimized to maintain satisfactory turfgrass growth and quality, and rates may vary depending on turfgrass age. The authors conclude the greater leaf area associated with older turfgrass, in comparison with younger
turfgrass, promoted ET. In addition, in their study Barton et al. (2009) conclude not fertilizing older turfgrass in the initial year of the study would have decreased water consumption by 20% without compromising turfgrass quality and by contrast, not applying N fertilizer to the younger turfgrass would have also saved water, but at the cost of turfgrass quality.

Application Rates and Timing

Late season fertilization (September through early December) will prepare turfgrass for drought in the next growing season as it encourages a deep root system and minimizes surges in shoot growth in the spring that would more rapidly deplete soil water during green-up (Murphy, 2002). Additionally, under-fertilization results in weak turfgrass plants that cannot develop an adequate root system or compete with invasive weeds and reduces the drought resistance of turfgrass (Murphy, 2002). An adequate level of NF was provided by application of 4 kg N/1000 m2 each month (Feldhake et al. 1984).

Nitrogen Source

In the maintenance of established turfgrass, applying water-soluble fertilizers sparingly and frequently has provided consistent growth and color similar to that achieved by applying slow-release fertilizers less frequently, but at similar total N application rates (Barton et al., 2006). Overall, quick-release and slow-release inorganic fertilizers at 100 to 300 kg N ha/year have been shown to effectively maintain turfgrass growth and color (Barton et al., 2006). Ammonia released from urea at summer temperatures could, by its toxicity, cause injury that followed hot-weather urea applications (Madison, 1962c).

Nitrogen Losses

Nitrate leaching may present problems, however, in some segments of the turfgrass industry where NF rates have not been reduced to account for turfgrass age and clippings return (Beard and Kenna, 2008). Greater amounts of nitrate-N are leached from soluble-N sources than from slow-release sources and these studies indicate that N leaching was related to applied water (Augustin, B. J., and G. H. Snyder. 1984).

Overwatering significantly increased N losses from fertilized plots where low and high N overwatered treatments generated losses five and eleven fold greater than the overwatered
control plots, respectively (Morton et al. 1988). Applying NF when plant uptake is reduced could generate excess soluble N in the root zone and enhance the possibility for waterborne losses of N (Morton et al. 1988).

**Mowing Nitrogen Losses**

Miltner et al. (1996) found total N removed during mowing averaged 95 kg ha/yr over three years and was equivalent to 50% of the NF applied when clippings were returned while harvested N averaged 137 kg ha/yr (73% of applied NF).

**Rooting Effect**

Mantell (1966) found the effect of NF on rooting to be more pronounced than that of irrigation frequency. Similarly Madison (1962c) concluded root weight per plant was decreased by increasing nitrogen, whereas plant size was reduced most by frequent irrigation.

**Nitrogen (N) and Potassium (K) Interactions**

Carroll and Petrovic (1991) determined applying a commensurate amount of NF may reduce the tissue solute concentration by promoting excessive top growth and thereby offsetting the beneficial effects of K application. Enhanced leaf turgor maintenance may explain observations linking improved turfgrass growth and drought tolerance to high levels of K fertilization because plants able to maintain leaf turgor at lower stomatal closure permits C fixation to continue at greater soil moisture deficits.

Similarly, Christians et al. (1979) indicated an interaction between N and K in solution was observed in the quality response of creeping bentgrass explaining as the level of K was increased, less NF was required to attain maximum quality indicating it is possible that addition of higher levels of K can affect requirements for N.

**Remote Sensing Technology**

The majority of remote sensing literature has focused on detection of growth responses and plant stress in agricultural crop, turfgrass chlorophyll content, and turfgrass injury and quality. Results of these studies repeatedly indicate that remote sensing instruments can reliably detect plant stress by monitoring changes in reflectance in the vegetation (Dettman-Kruse et al.,
Reflectance measurements have been used to evaluate plant biomass, plant nitrogen content, and disease severity. The normalized difference vegetation index has been used to measure drought stress, turfgrass chlorophyll content, and turfgrass injury and quality (Bell et al., 2002). The need to better understand clear indicators of impending drought stress must be identified to minimize unnecessary application of irrigation water.

Turfgrass reflectance is influenced by water, fertility, mowing, disease, wear, traffic, cultivars, and species (Johnsen et al., 2009). As soil water decreases, plants exhibit a decrease in tissue water content, which in turn influences their reflectance properties (Dettman-Kruse et al., 2008). Assessing crop water stress in the field with remote sensing is based on two parameters: leaf temperatures measured with hand-held infrared thermometers, and the relationship between changes in reflectance patterns to crop variables that are responsive to the development of water stress (Hutto et al., 2006).

Effectively scheduling irrigation on a site-specific basis requires detecting those areas where the plants are beginning to experience drought stress, although they may lack visible symptoms. By identifying these areas before visible symptoms of drought stress develop, managers can schedule an irrigation event and minimize stress to the turfgrass plants (Dettman-Kruse et al., 2008). Many handheld and ground-based remote sensing systems include ambient light sensors, integrated light emitting diodes, or other auxiliary light sources to reduce or eliminate the effect of fluctuations in ambient radiation on the data collected by the instruments (Bell et al., 2000).

Due to the dense canopies formed by mature, healthy turfgrasses, the portion of spectral energy attributable to transmittance is negligible (Trenholm et al., 1999). Previous research has documented that as a plant becomes more drought-stressed, changes in the red, NIR, and SWIR reflectance are observed (Hutto et al., 2006). Stressed plants, in comparison to healthy plants, have increased red and variable infrared reflectance (Knipling, 1970). These data have the potential to be used as both research and management tools for a wide array of turfgrass operations and could be used to make irrigation system adjustments in design for more uniform application or scheduling for site-specific irrigation needs (Jiang and Carrow, 2007).

Trenholm et al. (1999) explain multispectral radiometry provides a method for assessing plant light reflectance at various wavelengths of light energy where the percentage of light not
reflected is either absorbed by the plant or transmitted downward to the soil surface. The authors explain environmental stresses can produce free radical molecules such as superoxide, hydrogen peroxide, hydroxyl radical, and singlet oxygen, which can damage lipids, proteins and nucleic acids in plant cells. In addition, plants exposed to high temperature stress may lose the ability to minimize damage from these free radical species due to a dysfunctional active oxygen scavenging system.

Physiological stresses lead to increased reflectance in the visible region (400 to 700 nm) (Carter, 1993). Radiation not reflected is either absorbed by the plant or transmitted to the soil. The amount of red (R) radiation (600–700 nm wavelengths) transmitted to the soil surface below a dense turfgrass canopy is small compared with that absorbed by the canopy (Knipling, 1970). Red reflectance from a turfgrass canopy is relatively low because of chlorophyll absorption, but near infrared (NIR) radiation (700–800 nm) is poorly absorbed by plants and more highly reflected (Daughtry et al., 1992). A portion of NIR radiation is reflected from green plant material and a portion is transmitted to the soil (Knipling, 1970; Bell et al., 2000a). Red reflectance increases and NIR reflectance decreases as greenness declines in a dying plant or leaf and this relationship between R and NIR reflectance and living and dead plant material provides a basis for plant health indicators (Knipling, 1970). Additionally, Trenholm et al. (1999) state in disease-free turfgrass, increased reflectance in the NIR range would be attributed to increased internal light scattering and reflective surfaces, possibly associated with leaf turgidity and cell growth.

Dettman-Kruse et al. (2008) explain leaf reflectance in the visible portion of the spectrum (400–700 nm) is relatively low due to increased absorption of energy by chlorophyll and is correlated with the concentration of leaf pigments. As plants become stressed, they exhibit decreased reflectance in the near-infrared (NIR) spectral region due to decreased cell layers and an increased reflectance in the red spectral region due to lower chlorophyll concentrations (Dettman-Kruse et al., 2008).

Bell et al. (2002) found optical sensors were not sensitive to solar radiation and therefore, cloud cover or time of day were not important yet the sensing unit was driven over the plots in the same order during each evaluation. However, Trenholm et al. (1999) was certain to take reflectance readings within a specified time period from 1100 to 1300h under conditions of minimal cloud cover. Objectives of research by Trenholm et al. (1999) were to determine if
data obtained by multispectral radiometry might accurately correlate with qualitative data (used as rapid estimates of color, density, and uniformity) typically used in turfgrass research.

Plant stress can be measured with the normalized difference vegetation index (NDVI), which is calculated by 

\[ \frac{\text{near infrared reflectance} - \text{red reflectance}}{\text{near infrared reflectance} + \text{red reflectance}} \]  

(Johnsen et al., 2009). DaCosta and Huang (2006) reported velvet bentgrass maintained higher NDVI values than creeping bentgrass and colonial bentgrass under the same management practices. In addition, results from (Trenholm et al., 2000; Bell et al., 2002; Hutto et al., 2006; Johnsen et al., 2009) indicate turfgrass species had significantly different reflectance measurements.

A reasonable goal for a remote sensing system is to use it for predicting the soil water status on a site-specific basis based on canopy reflectance before drought stress symptoms develop (Dettman-Kruse et al., 2008). If proven successful, this technology has the potential to increase the site-specific management practices used in turfgrass systems and reduce the risk of overwatering and drought stress (Dettman-Kruse et al., 2008).

**Species Specific**

Dettman-Kruse et al. (2008) observed a stronger predictive relationship for soil water content in creeping bentgrass 1 day before the onset of visual drought stress symptoms than what was observed in perennial ryegrass. The authors indicate this may be the result of variations in the spectral reflectance properties of creeping bentgrass and perennial ryegrass as they relate to genetic color and growth habit.

Data from Johnsen et al. (2009) revealed velvet bentgrass had the highest mean NDVI (0.76) and was statistically different from any other species in June 2006. In 2007, velvet bentgrass once again had a high mean NDVI (0.31 and 0.47, for June and August, respectively) however, at both rating periods it did not have the highest mean. In Jun 2007, tall fescue had the highest NDVI (0.53). In Aug 2007, hard fescue had the highest NDVI (0.39). On the opposite end of the spectrum, sheep fescue and chewings fescue had the lowest mean NDVIs in Jun 2006 (0.63). Creeping bentgrass had the lowest mean NDVI in 2007 (0.38 and 0.26, for Jun and Aug respectively).
Johnsen et al. (2009) data analysis also revealed some species were not significantly different. All fine fescues had low mean NIR/red ratios. In June 2007, tall fescue had the highest NIR/red ratio (3.33) and creeping bentgrass had the lowest NIR/red ratio (2.21). Creeping bentgrass was significantly different from colonial and velvet bentgrass, which had higher NIR/red ratios. In Aug 2007, there was many species with a high mean NIR/red ratio, however, creeping bentgrass once again had the lowest mean NIR/red ratio (1.70) (Johnsen et al., 2009). In addition, research by DaCosta and Huang (2006) found velvet bentgrass has significantly higher NDVI (0.90) than colonial (0.86) and creeping bentgrass (0.87) in the fall.

**Root Characteristics**

The word “rootzone” denotes the portion of soil in which roots may grow and turfgrasses are anchored (Wu, 1985). The soil profile of the rootzone may range from the soil surface to the depth of soil where the roots may reach (Wu, 1985). Butler and Minner (1985) state the key to using information on water availability, however determined, is dependent upon knowledge of the functional root depth of the turfgrass.

Butler and Minner (1985) indicate functional depth with the same root system is greater when plant water demands are low (spring and fall) than when they are high (summer). Huang and Liu (2003) found creeping bentgrass during midsummer had root mortality of 40 to 60% and root production was greatest during spring and fall periods, with little or no root growth occurring during the summer months, implying that about one-half of the roots produced prior to the summer died during the hot periods.

When considering turfgrass roots in the profile, it must be emphasized that turfgrass species naturally differ in their rooting ability. For example, Butler and Minner (1985) found when compared to Kentucky bluegrass, the rooting depth of creeping bentgrass and perennial ryegrass was shallower and tall fescue was deeper. Along with species variation, root depths are also influenced by seasonal fluctuations, management practices such as mowing and fertilization, and by on-site soil compaction (Butler and Minner, 1985; Wu, 1985; Hutto et al., 2002).

Yet overall root distribution is considered more important than total root production in selecting for drought avoidance (Salaiz et al., 1991). Sophisticated root evaluation techniques
like the minirhizotron imaging is capable of distinguishing newly produced roots, existing roots, and decaying or dead roots. This nondestructive technique involves tracking the fate of individual roots that have grown against clear plastic tubes with a miniature video camera. Because the same roots are repeatedly examined across time, the technique eliminates spatial variation being confounded with temporal variation and permits a high frequency of root examination (Huang and Liu, 2003).

Ultimately root growth inhibition and death reduce the supply of water, nutrients, and root-produced hormones such as cytokinins to the shoots, which is probably a major factor leading to decline in turfgrass quality (Carrow, 1996). In contrast, the formation and elongation of roots is controlled, in part, by carbohydrate relations and plant hormones that are governed by shoot growth (Huang, B., and X. Liu. 2003). Huang and Fu (2001) also suggest soil drying influences plant growth not only by water supply, but also possibly by non-hydraulic signals transmitted to leaves from roots. Abscisic acid (ABA) in roots has been found to be the chemical messenger that mediates plant responses to drought therefore water-stressed roots accumulate ABA and quickly transport it to leaves, which inhibits leaf growth (Huang and Fu, 2001).

Gibeault et al (1989) noted root depths and soil texture play an important role in both the amount of water to apply and the irrigation frequency. Work done by Mantell (1966) showed turfgrass irrigated at relatively infrequent intervals extracted proportionately more water from the deeper horizons than did those irrigated more frequently. Madison and Hagan (1962) noted a decrease in rooting occurred with frequent irrigation and noted roots in the top 10 cm increased but the increase was greatly offset by the great decrease at depths below 10 cm.

Additionally, soils can restrict root growth because of high soil strength, Al, Mn, and H toxicities, and/or Ca-Mg deficiencies and intraspecific tolerances to these edaphic stresses can markedly influence root growth and, thereby, drought resistance (Carrow, 1996). Sheffer et al. (1987) found small amounts of roots beyond 72 cm in a turfgrass stand growing in a silty clay loam soil. While Ervin (1995), working with a clay loam, measured root growth deeper than 60 cm. Butler and Minner (1985) noted under severe water stress, turfgrass grown on sand did not recover as well as that grown on good topsoil. Conversely, Madison and Hagan (1962) noted with infrequent irrigation, a decrease in rooting took place in the surface 20 cm, with increases in roots below 20 cm.
In addition to rooting (soil) depth, the quantity of water to apply is also a function of the soil’s texture, organic matter content, structure, and bulk density and in many cases, rooting is limited by poor soil conditions and subsequently such turfs require more frequent irrigation to produce healthy vigorous growth and an acceptable surface (Murphy, 2002).

Madison and Hagan (1962) state some turfgrasses have a largely perennial root system, which may take 2-4 years to reach a maximum development. Ervin and Koski (1998) sampled root dry weights following a 9-month well-watered establishment period for both cool and warm season turfgrasses, and found no significant differences between species for any of the three sample depths. Steinke et al. (2009) agree while turfgrass root systems in their study may not have been fully mature, a 10.5-month establishment period is sufficient to establish a healthy plant community across many turfgrass cultivars.

**Rootzone Temperature**

Madison and Hagan (1962) believe of all environmental factors; soil temperature correlates most significantly (inversely) with root growth. Beard and Daniel (1965, 1966) found root production occurred immediately following drops in soil temperature and suggested that lower soil temperatures encourage or are required for new root growth. While air temperature directly influences the ET rates of plants by affecting the water vapor pressure deficit, the temperature of the soil is known to influence water uptake by plants in terms of the capability of roots to absorb water and the resistance to water movement through the soil is temperature dependent (Kim and Beard, 1988).

Xu and Huang (2000) report high soil temperature is more detrimental than high air temperature to root growth and activity and lowering soil temperatures. Their study indicated turfgrass exposed to high air temperatures increased canopy net photosynthetic rate and carbohydrate content and reduced the carbon consumption to production ratio, which suggests that roots are more active in mediating carbohydrate responses than shoots when subjected to high temperatures.

Likewise lowering soil temperature improved creeping bentgrass quality and shoot and root growth that had been exposed to high air temperature (Hutto et al., 2006). Leaf injury under high soil temperatures has been associated with many factors that affect normal plant growth.
and development such as root growth inhibition, hormone synthesis and transport, water uptake, and nutrient uptake and high temperatures may also cause an imbalance between photosynthesis and respiration processes and carbohydrate depletion (Hutto et al., 2006).

Beard and Kim (1989) acknowledge extensive research has been done with the warm-season turfgrass species adapted to soil temperatures in the 25° to 35° C range yet among the cool-season species, which grow best at soil temperatures in the 10° to 18° C range, comparative information is more limited.

**Rootzone Water Use**

Surface soil is often dry; although water may be sufficient for plant uptake deeper in the soil profile in natural environments and drying of the upper portion of the soil profile has a profound impact on root functionality and growth in some plant species (Huang and Fu, 2001). Previous studies have reported greater root mass in the upper profile of a rootzone therefore resulting in a greater extraction of soil moisture near the surface (Madison and Hagan, 1962; Wu, 1985; Su et al., 2008). Interestingly, Carrow (1996) indicates high root length density in the surface 3 to 10 cm enhances wilt, perhaps by resulting in rapid depletion of the surface soil moisture.

Previous studies have also indicated that a larger percentage of water lost from the soil was taken up from the deeper layers once the shallower layers dried out (Carrow, 1995; Young et al., 1997; Young et al., 2000). Huang (1998) found that water absorbed by roots in deeper, moist soil could be transported to roots in the upper drying soil at night to maintain viable roots and nutrient uptake, suggesting growth can be maintained by efficient water use when water availability is limited in surface soil.

**Root Density, Length, and Production**

Quantity of turfgrass roots present at lower depths may be important for maintenance of verdure through periods of low rainfall (Sheffer et al., 1987; Salaiz et al., 1991). For example, tall fescue, though possessing a relatively high potential ET rate as measured in the field may avoid drought longer than Kentucky bluegrass by extracting water from a greater volume and depth of soil (Ervin and Koski, 1998). In addition, Su et al. (2008) determined under well-watered conditions, most roots were distributed in the shallowest soil layer (0–30 cm).
Creeping Bentgrass

Salaiz et al. (1991) note differences in ET rates and root distribution were observed among creeping bentgrass cultivars. Additionally, Huang and Liu (2003) found the majority of roots for creeping bentgrass were in the upper 10 cm of soil.

Tall Fescue

Su et al. (2008) found Tall Fescue had a more developed root system at deeper depths and its roots grew faster than the other turfgrasses their study. The researchers believe greater quantities of roots deep in the soil, however, may play an important role in a plant's ability to avoid drought stress even if deep roots are a small percentage of the total root mass.

Kentucky Bluegrass

Sheffer et al. (1987) found Kentucky bluegrass to have 75% of its root mass within 12 cm of the soil surface, while both perennial rye and tall fescue had only 50% of their roots at this depth. Although numerically small, these differences may be important for topgrowth during periods of low rainfall.

Soil Sensor Technology

It is increasingly important for turfgrass managers to carefully monitor the soil water status of the site and make adjustments in irrigation practices in response to water stress (Dettman-Kruse et al., 2008). Knowing how much water the turfgrass can receive from the soil will aid to develop an irrigation schedule to meet the turfgrass water needs (Githinji et al., 2009). One traditional measurement technique is gravimetric sampling (Gardner, 1986), in which a sample of soil is physically removed, weighed in the field, and then weighed again after oven drying indicating matric head (hm) values. Matric head is usually expressed in terms of the matric head value, and conventionally the matric head value of -33 kPa pressure is considered to represent field capacity (Githinji et al., 2009).

Although various irrigation scheduling and assessment techniques have proven to be effective compared to a set irrigation schedule or relying on the experience of a turfgrass manager there are limitations associated with each technique. For example, an evaporation pan measures evaporation at only one site and plant response is only indirectly considered through the use of
crop coefficients (Throssell et al., 1987). In addition, turfgrass managers have increased the use of available management tools through the use of on-site weather stations to schedule irrigation application and amount based on calculated ET (Dettman-Kruse et al., 2008).

An alternative approach for measuring turfgrass ET is to monitor changes in soil-water storage under the turfgrass for a specified period. There are two basic approaches to measuring soil moisture (Browne, 1985). One is on an energy basis, the other on a content basis. Tensiometers measure the energy or “tension” with which moisture is retained by soil particles. In other words, they measure the availability of soil moisture, or the work that plants must perform to extract moisture from a given soil. This energy increases as the soil dries, and the availability correspondingly decreases. A second approach is related to soil moisture content rather than tension, and moisture content is not necessarily a good indication of moisture availability. In contrast to tensiometers, their range of least sensitivity is that which is most critical to plant growth (Browne, 1985).

Over the last decade, a number of relatively accurate and precise devices to measure soil water content have been commercially developed. Although these devices have been used successfully in agricultural research and crop production systems, non-destructive soil water content meters have not been widely adopted in the turfgrass industry until very recently. These devices are portable and relatively inexpensive, and can provide a turfgrass manager the ability to rapidly assess soil water content.

Water is a good conductor of electricity and as soil dries, electrical resistance increases at a predictable rate and available moisture can be calculated (Gibeault et al., 1989). Routine measurement of soil water content is a good practice that can be used to develop an association between turfgrass performance and a certain range in soil water content. For example, measuring soil water content when turfgrass is wilting identifies the lower limit of water content for that soil/site (Murphy, 2002). Data from Hutto et al. (2006) demonstrated that as soil water content increased, reflectance decreased and suggested data collected in late spring/early summer may be the optimal time to detect areas of putting greens most susceptible to drought stress before unfavorable growth conditions occur.

Moisture sensors can be portable or stationary units that are wireless or connected by wire or telemetry to an irrigation controller and call for water when the turf needs it, not just by the
clock and calendar (Gibeault et al., 1989). Gibeault et al. (1989) point out the most critical factor in the use of soil moisture sensors is the location and depth of the instruments within the turfgrass site. They suggest for most turfgrass stands, putting the sensor in a dry spot at a depth of 10-15 cm is effective. In addition, Gibeault et al. (1989) state improper installation of moisture sensors is responsible for far more failures than the reliability of the equipment.

Hutto et al. (2006) indicate soil moisture is partitioned into free or gravitational water, capillary water and hygroscopic water based on the degree of tenacity of the water to the soil particles. Capillary water is available to plants while free water is also available but drains very rapidly. When all the free water has drained the soil is said to be at field capacity and the percent water at field capacity varies from soil to soil ranging from 3 percent in sandy soils to over 30 percent in heavy clay soils (Hutto et al., 2006).

Hutto et al. (2006) indicate soil moisture status is usually expressed on a percent basis by weight (gravimetric soil moisture content) or by volume (volumetric soil water content, VWC). VWC is defined as the volume of water within a given volume of soil and may also be expressed as the depth of water for a specific unit depth of soil (Hutto et al., 2006). For any given time period, Soil Moisture Content = Soil Moisture (at Start) + Precipitation - Evapotranspiration – Runoff (Kome, 1993).

Madison and Hagan (1962) determined percent soil moisture every second or third day for each 10 cm increment of depth up to 61 cm and at 76 and 91 cm. Over 95% of apparent water extraction by turfgrass cover occurred in the top 51 cm of soil (Madison and Hagan, 1962).

Su et al. (2008) measured VWC near the surface at 5 cm, which presumably was a region of denser root mass compared to deeper depths. VWC measurements near the soil surface were used to investigate possible differences in root activity (i.e., water absorption) among hybrid bluegrasses, Kentucky bluegrasses, and tall fescue during drought (Su et al., 2008). Kentucky bluegrass had more of its higher root mass within 12 cm of the soil surface compared to tall fescue or perennial ryegrass. Similar work performed by Sheffer et al. (1987) found Kentucky bluegrass had the highest VWC at 54 and 78 cm while tall fescue had the lowest VWC. Sheffer et al. (1987) found VWC was significantly different between species, depending on sampling depth.
Richie et al (2002) measured soil water content weekly at 30-, 61-, and 91-cm soil depths using neutron scattering. Richie et al. (2002) noted a consistent, although non-significant trend for higher soil water content as follows: two irrigation events per week > four irrigation events per week > three irrigation events per week.

*Weighing Lysimeters*

No less than 2 decades ago, Young et al. (1997) stated weighing lysimeters have become valuable tools for agronomic research, because they allow direct measurement of changes in mass that can be attributed directly to plant-root uptake or soil evaporation, or both and several weighing lysimeter systems are in use today for studying water use. ET rates measured by lysimetry may not accurately reflect normal field situations (Carrow, 1985) yet Beard (1985) promoted weighing lysimetry as a more likely method to give accurate estimates of *in-situ* turfgrass ET rates.

*Tensiometers*

Tensiometers are instruments that are used to measure the soil water tension, or the matric head (hm), which can be related to soil water content (Githinji et al., 2009). Tensiometers are only effective for measuring soil moisture over a limited range, the range most critical to plant growth (Browne, 1985). Bastug et al. (2003) reported that tensiometer readings of 10–30 cb, depending on soil texture, would indicate the field capacity of the soil. Meyer et al. (1985) utilized tensiometers placed at 76 and 150 mm depths in their cool season grasses and 200 and 300 mm in their warm season grasses. Tensiometer irrigation scheduling has been shown to reduce the amount of water applied when compared to set irrigation schedules or relying on the experience and judgment of a turfgrass manager (Throssell et al., 1987). Throssell et al. (1987) determined tensiometer scheduled irrigation was the most effective in terms of water applied and number of irrigation events. Minner and Butler (1985) determined soil moisture tension using gypsum blocks at the 10 cm depth. Percent soil moisture was converted to bars of tension using a calibration curve prepared for this soil (Minner and Butler, 1985).

*Time Domain Reflectometry (TDR)*

Water is a good conductor of electricity (Gibeault et al., 1989). The wetter the soil, the faster electricity will propagate through it (Kome, 1993). As soil dries, electrical resistance
increases at a predictable rate and available moisture can be calculated (Gibeault et al., 1989). Time domain reflectometry (TDR) has been used to monitor water content in many agricultural settings yet TDR is a relatively new method of measuring soil water content in turfgrass and has been developed for its ease in taking multiple water-content samples with no disturbance to the soil profile (Young et al., 1997; Young et al., 2000). Professional turfgrass managers might find these devices useful as TDR can provide quite accurate readings of the irrigation needs of turfgrass (Young et al., 2000). TDR measures the propagation velocity of a high-frequency voltage impulse sent down two or more parallel metal probes in the soil (Kome, 1993). TDR-measured diurnal changes in water content can be attributed mostly to plant-root uptake (Young et al., 2000). TDR measurements have been reported to give soil-water content estimates accurate to ±2% and have shown good correlation with gravimetric determinations (Keeley and Koski, 1997).

TDR units may be portable, hand-held units or buried in the rootzone. Buried moisture sensors can be connected by wire or telemetry to an irrigation controller and call for water when the turfgrass needs it (Gibeault et al., 1989). The most critical factor in the use of buried moisture sensors is the location and depth of the instruments within the turfgrass site (Gibeault et al., 1989). For most turfgrass stands, putting the sensor in a dry spot at a depth of 10-15 cm is effective (Gibeault et al., 1989). Improper installation of moisture sensors is responsible for far more failures than the reliability of the equipment (Gibeault et al., 1989). Combining ET information and moisture sensors provides the state of the art of science to maximize turfgrass irrigation efficiency (Gibeault et al., 1989).

Traditionally TDR results may have been confounded by the activity of roots growing beyond the waveguide depth. Keeley and Koski (1997) measured random root samples and detected no roots deeper than 45 cm; still, some of their ET rates measured seem abnormally low, hinting that all root activity may not have been accounted for, even with deeper waveguides. The researchers go on to admit it is possible some roots extended beyond 52 cm but escaped detection during root sampling.

Young et al. (1997) used weighing lysimeters to validate the use of vertically installed TDR probes for measuring ET of daily irrigated plants. When water accumulation at the bottom of the lysimeter was accounted for, comparisons between TDR and micrometeorological readings were within 8.5% and the TDR-measured water contents were statistically similar to
gravimetrically determined water contents. All TDR probes underestimated water added and lost compared with the lysimeter during daily irrigation, with shorter probes exhibiting larger differences than longer probes (Young et al., 1997).

Using vertical TDR probes of different lengths provides additional information about the depths of plant-root uptake and their changes with time (Young et al., 1997). Young et al. (2000) utilized TDR probes of four lengths: 20, 40, 60, and 80 cm; and they were installed vertically from the soil surface, spaced 30.5 cm apart. While horizontal TDR probes were 20 cm long and installed at 50 cm below the soil surface. Young et al. (2000) reported the 20 cm vertical probe reported less water content than the longer vertical probes and that the average water content reported for the profile increased when deeper soil is included. Young et al. (1997) showed longer TDR probes gave more accurate estimates of soil water storage than did the shorter probes, especially for a longer irrigation interval. Longer probes tended to smooth out the variability in near-surface water contents by averaging across thicker soil layers and this is fortunate given the rooting depth of turfgrasses, may range from just below the surface to 400 mm, requiring longer waveguides to better monitor total water use (Young et al., 2000).

Young et al. (1997) showed shorter TDR probes measured less water loss than the lysimeters, presumably because the available soil water was depleted in the shallow soils, requiring plant-root uptake from deeper soil. Young et al. (1997) conclude it is reasonable to assume that a portion of water from each irrigation event was absorbed in the biomass, which was recorded by the lysimeter, but which remained above the effective sphere of influence of the TDR probe. The depth of irrigation could be accurately measured with the TDR system if interception by the thatch layer can be accounted for (Young et al. 2000).

Young et al. (1997) also determined water loss recorded by longer probes, attributable only to ET, is independent of probe length because the roots are shorter than the waveguides. Young et al. (1997) conclude the averaged water content values of vertical TDR probes show significant variations because of the large variations near the surface and daily reductions in near-surface water content were caused mostly by ET and to a lesser extent by drainage. Using a combination of short and long probes improves the estimate of drainage (Young et al. 2000).
Turfgrass water use was measured accurately using the shortest probe (20 cm) (Young et al. 2000). The shortest probe (20 cm) measured the least water loss, and the longer probes tended to record the greatest water losses (Young et al., 2000). The tendency for shorter probes to underestimate water use is likely influenced by water stored in the thatch layer above the waveguides, which cannot be measured by the probe and this error will have a greater effect on the readings from the shorter probes than on readings from the longer probes (Young et al., 2000). TDR users can account for vegetative material by adding a percentage of the biomass layer’s thickness to the TDR measurement (Young et al., 2000). Water absorption in the biomass layer can equal about 50 percent of the thatch depth (by volume) and the amplitudes of the daily fluctuations in water content recorded with the longer probes are less than those recorded by the shorter probes, but are still significant, because of the large variations near the soil surface (Young et al., 2000).

Note that standard error in water content measurements from TDR is very low, in most cases, an order of magnitude less than the calibration error, yet still significant when considering the total possible error in water stored in a given depth of soil (Young et al., 1997). Possible sources of variability considered for TDR measurements include calibration error, measurement bias (systematic error), simple random error, and analytical error. Others have reported errors in TDR because of temperature changes (Young et al., 2000).

Data by Kome (1993) reported the maximum VWC was in the 0-5 cm layer except during the dry down periods. The top layer also showed the greatest variation in volumetric soil moisture during the course of their experiment. The dynamic nature of this layer can be attributed to the high density of functional roots absorbing the moisture in addition to the high organic matter content and its vulnerability to fluctuations in atmospheric conditions such as rainfall, wind speed, radiation, temperature and relative humidity (Kome, 1993).

High variability in VWC data is considered to result from a combination of factors including the small sampling volume of the waveguides, the spatial variability in soil water content, air-gap formation around the waveguides, and waveform attenuation caused by the clayey soil and the long waveguides (Keeley and Koski, 1997). Keeley and Koski (1997) acknowledge soils with a high percentage of clay present an added difficulty because they strongly attenuate the TDR signal.
TDR measurements in high clay-content soils show less precision than measurements in coarser-textured soils and in a critique of TDR, it was concluded that the technique was best suited for use in coarser-textured soils (Keeley and Koski, 1997). For studies in high clay-content soils, Keeley and Koski (1997) recommend a maximum waveguide length of 30 cm to alleviate this problem but they also note long waveguides also increase the possibility of air-gap formation around the waveguides during installation. Air gaps are another potential source of error in measurements of soil-water content (Keeley and Koski, 1997).

Keeley and Koski (1997) indicate up to 20 replicate samples were necessary to obtain an accurate estimate of VWC in a 305 m by 5 m plot containing a high clay-content soil. Keeley and Koski (1997) also reported incorporating many samples (i.e., waveguides) per experimental unit in turfgrass ET research could make experiments prohibitively costly and time consuming if more than a few cultivars are included.

Horgan and Sass (2006) also performed comparison of lysimeter and soil moisture sensor irrigation inputs and found over 70% of soil moisture fluctuation occurred in the top 4 cm of soil. Prior to the field experiments, soil specific sensor calibration was achieved by comparing triplicate measurements of known volumetric water content against the sensor output (Horgan and Sass, 2006).

Augustin and Snyder (1984) concluded the greatest benefit of the sensor system was achieved during periods of frequent but unpredictable rainfall by eliminating unnecessary irrigations. Irrigation by sensor systems reduced applied water up to 83% over prevailing irrigation practices of local turfgrass managers during periods of hot dry weather, effectively reducing or eliminating unnecessary irrigations. Augustin and Snyder (1984) reported the amount of irrigation permitted by a sensor controlled system was 47 to 95% less than that used by the Daily Irrigation and at the conclusion of their study Sensor treatments had received only 26% of the water applied by daily treatments.

During the rainy season the combination of irrigation and rainfall provided excessive amounts of water regardless of N source, thus, sensor irrigation provides turfgrass managers a method for reducing both irrigation and N costs (Augustin and Snyder, 1984). Similarly, Augustin and Snyder (1984) reported reduced irrigation by the sensor system also resulted in better turfgrass appearance.
Carrow (1995) installed TDR probes in the center of each plot to determine the average soil water content over the depths of 0 to 10 cm, 10 to 20 cm, and 20 to 60 cm (maximum rooting depth observed at the site and daily TDR readings were made during soil dry-down periods following irrigation or rainfall events to determine spatial water extraction and ET (sum of water extraction over all depths since drainage was zero). Dettman-Kruse et al. (2008) calculated volumetric water content for each plot as an average from 20 random locations within each plot through TDR. This was in conjunction with collection of the remotely sensed data using 5 cm long probes inserted vertically at a 90 degree angle to the soil surface. Volumetric water content was measured with a three-rod probe of 5-cm length automated with TDR (TDR-100, Campbell Scientific) (Dettman-Kruse et al., 2008).

Research of TDR has shown that VWC can be assessed with reasonable accuracy for a wide variety of soils (Seyfried and Murdock, 2004). Although the use in high clay content soils often leads to an underestimation of VWC, TDR is generally regarded as the best available electronic technique for the measurement of VWC (Seyfried and Murdock, 2004). Additionally, those responsible for hand watering and syringing should be thoroughly trained regarding the most effective and efficient techniques for applying water during the day (Murphy, 2002).

**Species Specifics**

Concern for water conservation by the turfgrass industry establishes the need for drought-resistant species and cultivars (Salaiz et al., 1991). Data from Feldhake et al. (1983) indicated warm-season grasses used about 20% less water than the cool-season grasses under identical management and microenvironment conditions. Water-use varies among turfgrass species and also among cultivars of the same species (Githinji et al., 2009). Koeritz and Stier (2009) found responses tended to be cultivar specific rather than species specific. In addition, water use was not significantly different by species (Kome, 1993).

Beard and Kenna (2008) agree for grassed landscapes, the first step toward water conservation is selecting the correct turfgrass for the climate in which it will be grown. It is desirable to have a cultivar that minimizes water-use even when the water supply exceeds water requirements. Hence, the amount of water not used by the plant can be saved in the soil root zone for subsequent use during dry periods (Githinji et al., 2009). It should also be noted
savings in water use are more likely to come from irrigation control than from changes in cultivars used (Kneebone and Pepper, 1982).

Kim and Beard (1988) proposed that inter- and intraspecific differences in water consumption could be related to morphological characteristics such as shoot density, leaf orientation, leaf width, and vertical leaf extension rate, which may affect canopy resistance to ET and leaf area. They found turfgrasses with a low leaf blade area, including narrow leaves with slow vertical extension rate and grasses that had a high shoot density with a high leaf number, were lower ET grasses.

Difference in water-use among the three bentgrass species under well-watered conditions was not dramatic, but water-use rate generally ranked as colonial bentgrass > creeping bentgrass > velvet bentgrass from July through September (Huang and Fu, 2006). Generally, colonial bentgrass exhibited the highest water use rates and velvet bentgrass the lowest, and water-use rates for creeping bentgrass were intermediate among the three species (Huang and Fu, 2006).

To maintain minimum acceptable turfgrass quality; irrigation water to replace 80% ET water loss was required for colonial bentgrass, but 60%-80% actual ET irrigation was adequate for creeping and velvet bentgrass. Although 40% actual ET irrigation was inadequate to meet water demand and maintain physiological activities for bentgrasses in summer in both years, it was sufficient to maintain minimum acceptable turf quality for all three species in the fall as water-use rate for all three species decreased from July to October (Huang and Fu, 2006). Huang and Fu (2006) note species differences in water use were more pronounced when temperatures were highest. The optimum ambient growth temperature range for cool-season grasses are 15 to 24 C for shoots and 10 to 18 C for roots (Beard, 1973).

Under well irrigated conditions, the average daily actual ET rate in July 2003 was 6.8 mm for colonial bentgrass, 6.3 mm for creeping bentgrass, and 6.0 mm for velvet bentgrass. Velvet bentgrass also exhibited higher water use efficiency (measured as the amount of carbon fixation per unit of water loss through transpiration) and lower soil moisture depletion compared to colonial bentgrass (Huang and Fu, 2006).

Minner and Butler (1985) observed as drought conditions developed in their study the fine fescues displayed a brown patchy appearance rather than a uniform dormancy as noted for the
perennial ryegrasses and the Kentucky bluegrasses. Eventually tops of grass plants in the brown areas died and withered away while tops of plants in the clumped areas remained as a dormant mulch. Mulch, provided by dead leaves of dormant turfgrass, reduces water loss by evaporation and protects dormant plant tissues (Minner and Butler, 1985).

This may explain the observation that during the irrigated and fertilized recovery periods of their study the dead and dormant areas of fine fescue turfgrass never filled in with new growth. This resulted in a very rough turf that was difficult to mow. Thus, while some fine fescue plants survived, the overall appearance of the turfgrass was very undesirable (Minner and Butler, 1985). Murphy (2002) states fine fescues are less tolerant of traffic under drought stress than Kentucky bluegrass, tall fescue, and perennial ryegrass. Murphy (2002) noted recovery from drought damage and dormancy varies with species. For example, Kentucky bluegrass resumes growth faster than tall fescue after re-watering.

Cool Season

Water use rates are not necessarily correlated with increased drought tolerance, such that species with low consumptive water use are not necessarily more drought tolerant than a species with higher consumptive water use. For example, Fernandez and Love (1993) evaluated 25 commercially available cool-season turfgrass cultivars and found some tall fescue cultivars had higher water use, but still ranked higher in quality under progressive water stress compared with some perennial ryegrass cultivars with lower water use rates.

Ervin and Koski (1998) conclude acceptable season long tall fescue quality could be maintained by irrigating every 3 days at 50% of actual ET, while Kentucky bluegrass would need higher irrigation of 65% of actual ET every 3 days to maintain an acceptable level of quality. Kentucky bluegrass at all three irrigation levels declined in quality sooner and to a greater extent than tall fescue (Ervin and Koski, 1998).

Ervin and Koski (1998) speculate tall fescue, in order to remain greener longer than Kentucky bluegrass, was gaining access to more water on the average over the course of the season. Additionally, it appears Kentucky bluegrass, even though its leaves became fired faster than tall fescue, was still utilizing deep soil moisture. Sheffer et al. (1987) confirmed during periods of moderate drought stress, irrigation is needed to sustain growth of perennial ryegrass
and Kentucky bluegrass however; tall fescue often retains color and continues growth without irrigation during summers with minimal rainfall.

Minner and Butler (1985) evaluated the five best cultivars within a species and found as drought conditions developed perennial ryegrass remained green and viable longer than Kentucky bluegrass or fine fescue and when water became available in late summer, perennial ryegrass recovered faster than Kentucky bluegrass or fine fescue.

In general all grasses in this study decreased in turf quality as the non-irrigated stress period progressed from June through August. Although quality decreased perennial ryegrass maintained an acceptable level of quality (~7) until July 19, 1982, while Kentucky bluegrass and fine fescue began to show signs of drought stress and dormancy with quality values of six and five, respectively. The fact that perennial ryegrass produced better quality turf longer into the stress period may be related to Sheffer’s (1979) observation that perennial ryegrass had a greater portion of its roots below 12 cm than did Kentucky bluegrass (Minner and Butler, 1985). Minner and Butler (1985) determined tall fescue may extract 5 cm of available soil water with a 30 cm root system, whereas Kentucky bluegrass grown under similar conditions would extract a smaller amount of water (perhaps 2.5 cm in a 15 cm root system). Work performed by Minner and Butler (1985) determined fine fescues as a group did not perform as well as the Kentucky bluegrasses or perennial ryegrasses.

While there have been investigations conducted on deficit irrigation for other turfgrass species, information is generally lacking on the effects of deficit irrigation and general irrigation requirements of different bentgrasses under fairway conditions (DaCosta and Huang, 2006b). Minimum water requirements for bentgrass species were evaluated, particularly in regards to variability in requirements among different bentgrass species used for high maintenance, close-cut turf (DaCosta and Huang, 2006b).

DaCosta and Huang (2006b) found on the basis of visual observations, colonial bentgrass exhibited less shoot density, greater vertical leaf extension, and greater vertical leaf orientation, whereas velvet bentgrass exhibited very high shoot density, fine leaf texture, and slow leaf extension rates. The authors suggest differences in morphological characteristics may contribute to some of the variability in canopy resistance to ET, and thus differences in water use between the bentgrass species (DaCosta, M., and B. Huang, 2006). Data from Fry
and Butler (1989) indicate annual bluegrass used less water than creeping bentgrass 5 out of 7 weeks of their study.

**Tall Fescue**

Tall fescue is one of the more drought resistant cool-season turfgrasses, but it possesses a very high water use rate. Compared with other cool-season turfgrass species, tall fescue is reported to have very good high temperature tolerance and drought resistance yet Kopec et al. (1988) reported that tall fescue cultivars with decreased water use wilted sooner than those with higher water use rates. Richie et al. (2002) noted visual turfgrass quality was <6.0 between 14 June and 1 November, indicating that 85% ET was insufficient to maintain quality tall fescue that is subjected to the conditions of 1995 in Riverside, CA.

Results from Carrow (1996) showed tall fescue ET rates obtained under mild soil moisture stress conditions and in a humid climate can be 33 to 73% less than reported for non-limited soil moisture situations in an arid to semi-arid environment. Results from Huang and Fu (2001) suggest when water was sufficient for plant uptake in the deeper soil profile, tall fescue could adapt to surface soil drying gradually by developing deeper roots and lowering canopy and root respiration. This suggests frequent wetting of surface soil may not be necessary for tall fescue as along as water is available deeper in the soil profile. In summary, the results from Huang and Fu (2001) demonstrated tall fescue was able to adjust root to shoot relations, root distribution patterns, and carbon expenditure to maintain favorable water status, photosynthesis, and acceptable turf quality in soils with heterogeneous moisture. In addition, leaf growth and shoot dry matter production decreased with surface drying, which actually could be desirable in terms of reducing mowing. However, drying of the entire soil profile should be prevented to maintain vigorous tall fescue turf.

Kim and Beard (1988) explain the medium ET rate of 6.1 mm for tall fescue was associated with its fairly erect leaf orientation and low shoot density, which contributed to a low canopy resistance, plus an intermediate vertical leaf extension rate and a medium wide leaf as well as its C-3 photosynthetic pathway. Carrow (1996) showed reduced wilt and leaf firing of tall fescue cultivars was correlated with higher root length density in the deeper root zone (20- to 60-cm depth). In addition, Carrow (1996) showed that high root length density in the surface
3 to 10 cm of soil actually enhanced wilt, possibly due to rapid depletion of the surface soil water.

Well-established tall fescue visual quality was better when irrigated twice per week compared with three and four events per week (Richie et al., 2002). In the water-deficit treatment, the visual quality of tall fescue was consistently higher than other turfgrasses during both years while in well-watered conditions, visual quality in tall fescue was generally highest among the four turfgrasses during both years of the study (Su et al., 2008).

**Perennial Ryegrass**

Perennial ryegrass seed is inexpensive and widely available, germinates and establishes very quickly and whether established from seed or sod can produce a high quality turfgrass stand very quickly (Rinehart et al., 2005). Results from Minner and Butler (1985) indicate most of the perennial ryegrass cultivars in their study had the ability to avoid and/or tolerate summer drought conditions. Perennial ryegrass generally does not produce much thatch, so roots stay relatively deep in the soil and it can be easily mowed with a rotary mower.

Data from Dettman-Kruse et al. (2008) showed no correlation between visual drought stress ratings and the associated soil water content for samples collected 1 day before the onset of visible drought stress on the perennial ryegrass fairways.

**Fine Fescues**

Minner and Butler (1985) found none of the fine fescues tested produced suitable turfgrass stands under the severe drought conditions that existed. Common to both years was the inability of fine fescue to recover to a quality level greater than five. Fine fescues perform best in the shade but are adapted to sunny locations if well irrigated and are an excellent choice for turf areas receiving limited traffic and little to no irrigation (Murphy, 2002). Specifically, Murphy (2002) states Chewings fescue quickly turns brown under drought conditions and produces excessive thatch, which requires increased irrigation to avoid drought stress.
Kentucky Bluegrass

A weakness of Kentucky bluegrass is its tendency to produce excess thatch, which results in reduced rooting in the soil. Superior performance of drought stress-tolerant Kentucky bluegrass cultivars was associated with higher water use compared with less tolerant cultivars that adapted to drought by decreasing water use (DaCosta and Huang, 2006).

Minner and Butler (1985) noted no significant differences among Kentucky bluegrass cultivars studied and all displayed an acceptable quality value of seven or greater and at the end of stress and recovery periods. While turfgrass quality during stress and following a recovery period was cultivar dependent.

Richie et al. (2002) found frequent irrigation resulted in sparser and shallower rooting in Kentucky bluegrass. Richie et al. (2002) observed Kentucky bluegrass maintained at a higher mowing height had a deeper root system and this may improve drought tolerance.

Creeping Bentgrass

Madison (1960) showed growth of creeping bentgrass was significantly affected by height of cut, interval between cuts, season of the year, and their interactions.

Shearman and Beard (1973) found that container-grown bentgrass water use declined when irrigated less frequently. Reduction in water use, however, was strongly correlated with a decline in vegetative cover.

Salaiz et al. (1991) observed an ET difference among cultivars ranging from 39-84%. Similarly, DaCosta and Huang (2006) found variation in bentgrass water use characteristics depended on species, irrigation treatment, and time of the year or climatic conditions. Data from Huang and Fu (2006) demonstrated bentgrasses could be effectively managed for water conservation under fairway conditions by practicing deficit irrigation to certain levels, as long as no detrimental effects on turfgrass growth occur and soil water is occasionally replenished.

Velvet Bentgrass

Huang and Fu (2006) showed lower water use in velvet bentgrass was associated with higher water-use efficiency and slower water uptake. Excessive thatch production makes velvet
bentgrass difficult to maintain under home lawn conditions (Rinehart et al. 2005). While Koeritz and Stier (2009) conclude the light-green color of velvet bentgrass may lead turfgrass managers to over fertilize it, causing excessive thatch development, disease outbreaks, and annual bluegrass encroachment.

**Annual Bluegrass**

Murphy (2002) notes annual bluegrass is very susceptible to diseases and heat stress. Murphy (2002) states annual bluegrass has a very limited capacity to survive drought through dormancy. In fact, if allowed to wilt and turn brown, most annual bluegrass plants will not survive when rain or irrigation returns (Murphy, 2002). Fry and Butler (1989) stated annual bluegrass usually does not suffer from heat stress during Colorado summers due to nighttime coolness. Fry and Butler (1989) noted few seedheads were observed throughout their study indicating the plants were not undergoing natural senescence.

**Turfgrass Quality**

Kneebone and Pepper (1982) reported lower management levels resulted in a relatively low quality turfgrass similar to that of many campus, park, and home lawns. While turfgrass under higher management was better than that of many home lawns, but still not as lush as many commercial lawns. In addition, excellent-quality turfgrass may not always be as important as reducing inputs and maintaining acceptable and playable turf (Koeritz and Stier, 2009).

**Turfgrass Quality Assessment Technique Evaluation**

Turfgrass quality may be described by both visual and functional characteristics (Turgeon, 1991). Visual quality is often defined as an integrated value of shoot density, color, uniformity, and growth habit (Beard, 1973). Functional quality encompasses factors such as resiliency, rigidity, elasticity, regrowth capacity, verdure, and clipping yield while additional ratings are often ascribed for the singular characteristic of turfgrass density, determined visually by the number of shoots per unit area (Trenholm et al., 1999).

Visual evaluation of turfgrass quality is a subjective process that requires experienced personnel and this subjective approach has been accepted and used for many years to investigate the visual effects of fertilizer and pesticide applications or genetic variation among
cultivars but the data can be quite variable and difficult to reproduce (Trenholm et al., 1999; Richardson et al., 2001; Bell et al., 2002; Karcher and Richardson, 2005). Historically, turfgrass color, texture, and percent live cover (PLC) has been determined visually and therefore subjectively (Bell et al., 2002; Karcher and Richardson, 2005). Bell et al. (2002) state visual evaluation may require several weeks of experience before ratings are acceptable and many months before the evaluator becomes proficient yet was considered an accurate measure of turfgrass status for their study.

Although relevant information may result from such evaluations, final inferences may be questionable because of the subjective nature in which the data were collected as differences in quality scores may combine true quantitative differences in treatments as well as qualitative differences in interpretation by evaluators (Trenholm et al., 1999; Karcher and Richardson, 2005).

Bell et al. (2002) conclude on the basis of historic scientific acceptance of visual evaluation for turfgrass rating purposes, experimental unit means averaged over three human evaluators were deemed accurate measures of turfgrass color, texture, and percent live color (PLC) for their study. Richardson et al. (2001) note more variation is often found to be associated with the individual evaluator rather than the cultivars evaluated. Richardson et al. (2001) note as an alternative the line-intersect method has been effectively used in many forms of ecological research, but the time and labor required for data collection can limit the scope of a study as quantitative data are generally more precise than subjective data, the time and costs associated with collection of quantitative information often limits its use.

Richardson et al. (2001) also agree turfgrass establishment studies are often challenging under field conditions because of the time and labor involved in measuring and quantifying development and establishment parameters. Richardson et al. (2001) state the variances in these subjective ratings are generally so high that separation of performance is only possible between the very high performers and the very low performers, while many of the entries are not significantly different from each other. For example, quality had a more significant and closely associated response than density indicating the broader overall interpretation of turfgrass quality (i.e., density, color, and uniformity) provided a better fit than the narrower connotation of turfgrass density (Trenholm et al., 1999).
Leaf Firing

Leaf firing is often considered an aspect of drought tolerance. Leaf firing refers to leaf chlorosis starting at leaf tips and margins. Initial injury is a yellowing but often progresses into a tan or brown color with death of the tan or brown areas. Under field conditions leaf firing can become an overall measure of drought resistance since all climatic-soil-plant factors influencing drought stress are active (Carrow, 1996; Carrow and Duncan, 2003). Ervin et al. (1998) visually rated leaf firing at the same time as quality on a scale of one to nine, where nine indicated no fired leaves and one indicated that all leaves appear to be fired.

Carrow (1996) goes on to discuss wilt as a symptom of drought stress that includes a blue-green color and leaf rolling or folding that appears before leaf firing is observed. In his study, the percentage of leaves exhibiting wilt symptoms was determined while rating data reflect the percent of plot area covered with live turfgrass. Huang and DaCosta (2006) found VWC below 18% in sandy loam soils causes leaf wilting of bentgrass.

Turfgrass Quality Assessment Scale Based

Regarding turfgrass quality, Richardson et al. (2001) indicate the accurate measurement of green turfgrass in a plot area has potential in any research study where the amount of green tissue is an indication of health or growth, including turfgrass cover rates of seeded and sprigged grasses, injury ratings of various grasses, and disease or insect injury. In fact, numerous turfgrass water use studies use weekly or monthly visual turf quality assessments, utilizing a 1 to 9 visual rating scale based on turf quality, turfgrass density, and uniformity; where 1 equals dead turf; 9 equals ideal turf; and 5 to 6.5 equals minimally acceptable quality (Christians et al., 1979; Steinegger et al., 1983; Augustin and Snyder, 1984; Throssel et al., 1987; Carrow, 1996; Ervin et al., 1998; Trenholm et al., 1999; Huang and Fu, 2001; Rinehart et al., 2005; Horgan and Sass, 2006; Huang and Fu, 2006; Jiang and Carrow, 2007; Dettman-Kruse et al., 2008).

Minner and Butler (1985) used quality ratings dependent on turfgrass density and amount of green living plants; for example, a quality rating of 5 was given if 50 percent or the plants were green and actively growing. Feldhake et al. (1984) utilized a scale of 0 to 10 where 0 represented tan, dead leaves and 10 was the value for 100% lush, green growth. In addition,
twenty-one days after water stress began in a study by Fernandez and Love (1993), turfgrass cultivars were scored visually for green retention on a 0-10 scale, where 9 = 90% of the leaf tissue green and 1 = 90% of the leaf tissue scorched.

Augustin and Snyder (1984) also rated plots for moisture stress on a percent wilted area basis. Dettman-Kruse et al. (2008) evaluated plots for development of visible drought stress symptoms on a scale of 1 to 5, where 1 equaled no signs of drought stress, 3 equaled visible symptoms of wilt on at least 50% of the plot area, and 5 equaled permanent wilt. All visual data were collected immediately before collection of soil water readings and canopy reflectance data from each plot (Dettman-Kruse et al., 2008). DaCosta and Huang (2002) also evaluated turfgrass performance by measuring visual turfgrass quality, canopy spectral parameters, canopy photosynthetic rates, and soil moisture status.

In addition, visual rating is easier to perform during cloudy conditions and more difficult during early morning and late afternoon when the angle of direct solar radiation is approaching horizontal hence visual evaluators are expected to keep natural light at their backs without allowing a shadow to be cast on the turf under consideration (Bell et al., 2002).

**DIA Evaluation of Turfgrass Color and Quality**

Richardson et al. (2001) agree through the use of Digital Image Analysis (DIA), individual raters can independently evaluate studies without introducing bias or evaluator variability in the results. Digital image analysis (DIA) allows the investigator to collect more extensive, quantitative data in many types of studies including water use studies. Another advantage of DIA is that the development and condition of the particular turfgrass in the research plots can be fixed in time by taking a digital image and analyzing it at a later time if necessary (Richardson et al., 2001). In addition, Richardson et al. (2001) agree regional or national trial data can be more effectively conducted since the data collected from various sites can be compared in a valid statistical manner.

**Turfgrass Quality Rating Reflecting Water or Fertility**

Koeritz and Stier (2009) found cultivar, NF rate, and mowing height all affected turfgrass quality in both years of their study. In addition, Mantell (1966) found the highest visual
rating, most intense color, and greatest plant density were achieved by the most frequent irrigation schedule coupled with the high NF level.

Data from Richie et al. (2002) indicated visual turfgrass quality was primarily significantly affected by cultivar and mowing height in the first year of their study (1994) while in comparison with 1994, data from 1995 showed that visual turfgrass quality was significantly affected less by cultivar and mowing height, and more by irrigation frequency. Richie et al. (2002) noted the visual turfgrass quality of plots irrigated twice per week remained greater than 5.0 (minimally acceptable) for the duration of the 1995 study, with the exception of 6 September 1995, when quality dropped to 4.9. They also found plots irrigated with two irrigation events per week visually rated significantly higher than plots irrigated with three events per week on all rating dates when the irrigation treatment effect was significant.

**Future Research**

As indicated above there has indeed been a substantial amount of research performed regarding turfgrass and water use. However, much of the research performed has been on older varieties of turfgrass species. Therefore, there has been limited work evaluating newer, improved varieties of all of the most commonly used cool-season turfgrasses. There is also a substantial need to, if nothing else, confirm research findings of previous experiments regardless of the age of the species. In addition, the need for comparative turfgrass water use rates for juvenile stands is indeed imperative. There have been many, often times unsubstantiated, claims regarding water use rates of certain species with the age of the turfgrass stand never reported.

The ability to diagnose turfgrass water needs as well as rates is important for successful and sustainable turfgrass management. In recent years research methodology has become far more sophisticated with the advancements in technology. With respect to this, turfgrass professionals must also be able to confidently infer the findings of this research to real-life applications. The technology can only be useful if the end-user has confidence in the data.

It should be easy to see the need for the following research and the impact the data and results will have on the overall success of sustainable turfgrass management as we move forward as a collective profession.
CHAPTER 2

WATER USE OF TEN NEWLY ESTABLISHED COOL-SEASON TURFGRASS SPECIES AS INFLUENCED BY MOWING HEIGHT AND NITROGEN FERTILITY

Abstract

Comparison of water requirements to maintain acceptable turf quality of ten newly established cool season turfgrass species showed major differences between species in this trial that was conducted under water limited conditions with only enough water supplied to achieve a functional turf stand. Under these conditions, with the cultivars supplied, the turf required significantly less water than has often been reported in the literature. The higher water use species, annual bluegrass and red fescues, all required more water in the low mown plots than the high mown plots. A lower crop coefficient for irrigation could be utilized for most species in the Pacific Northwest. Most species could maintain adequate turf quality if subjected to the water restrictions many communities initially impose under drought conditions. Tall fescue, perennial ryegrass, Kentucky bluegrass, creeping bentgrass and velvet bentgrass were all lower water users under both high and low heights of cut in this trial.

Introduction

Turfgrasses require water and nutrients for growth and survival. Without adequate water and nutrition, turfgrass will be forced into dormancy, becoming brown, and ultimately desiccated, and in severe instances may even die (Murphy, 2002). A loss of ground cover by turfgrasses can have significant negative impacts on the functionality of the plant stand as well as the environment. In fact, previous research has routinely found that bare soils, stones, and other hard surfaces are heat sinks that can result in a buildup of maximum daytime temperatures ranging to more than 21°C higher than a transpiring turfgrass sward (Beard, 1973). Irrigation inputs are at times desirable to maintain the benefits of a healthy, actively growing turfgrass stand in areas where rainfall cannot meet the water demand of plants. Turfgrass water use rates have typically been determined using evapotranspiration (ET) rates of turfgrasses under well-watered conditions (Minner, 1985; Aronson et al., 1987; Beard and Kim, 1989; Fernandez and Love, 1993) and on mature stands of grass. There is limited research indicating the impact of
nitrogen fertility, mowing height and frequency on water use of a newly established turfgrass stand for the major cool-season turfgrass species.

Among the primary cultural factors that directly impact vertical elongation rate, leaf surface area, canopy resistance, rooting characteristics, and resultant water use are species and cultivars (Biran et al., 1981; Shearman, 1986; Aronson et al., 1987; Kim and Beard, 1988), mowing height (Madison, 1962; Shearman and Beard, 1973; Biran et al., 1981; Feldhake et al., 1983), mowing frequency, (Shearman and Beard, 1973), nitrogen fertility (NF) (Mantell, 1966; Shearman and Beard, 1973; Feldhake et al., 1983) and irrigation inputs (Beard and Kenna, 2008). These characteristics are of primary interest for turfgrass systems designed to conserve water. Mowing height and frequency, and NF directly affect water use by altering leaf area and canopy resistance. Leaf area decreases with decreasing mowing height, and therefore lowering ET. It is understood that decreasing mowing height stimulates lateral shoot development (tillering and shoot density) and promotes a more decumbent leaf orientation that increases canopy resistance, also theoretically lowering ET. Excessively close mowing can deplete carbohydrate reserves and reduces both rooting depth and drought resistance (Murphy, 2002). Conversely, mowing excessively high maximizes leaf area and increases water usage (Feldhake, 1983). In addition, mowing on an infrequent basis allows excess leaf area to accumulate between mowing events, which maximizes leaf area and ET (Madison, 1962). Hence, regular or frequent mowing is important in maintaining a dense turfgrass stand and in minimizing leaf area and water use.

Nitrogen is considered the single most important nutrient affecting turfgrass growth and ET (Christians et al., 1979; Butler and Minner, 1985; Murphy, 2002). Moderate levels of nitrogen that meet but do not exceed the nutritional requirement of the turfgrass are preferred. Excessive nitrogen will in the end increase ET and reduce rooting potential. Water use declines as turfgrass canopy resistance increases and leaf elongation rate and leaf area decreases (Barton et al., 2009). It has also been documented that increasing irrigation inputs to turfgrass without increasing NF rates typically has no beneficial effect on quality (Mantell, 1966). Matching irrigation inputs to turfgrass requirements has been shown to improve nitrogen uptake, growth, and color when maintained with water soluble fertilizer (Barton et al., 2006).

Traditional irrigation scheduling methods have evolved over the years for turfgrass stands and many of these methods are still in use today. These methods have ranged from measuring open-
evaporative pan water loss and then applying a known volume to return the amount of water lost from the stand or probing soil and physically testing the texture and moisture content and thus returning a known volume to satisfactorily wet or rewet the root zone (Githinji et al., 2009). Canopy temperature and light sensing technology have also been studied and used to predict required irrigation inputs (Throssell et al., 1987). While these methods are effective and at times still commonly practiced, most recently predictive methods have been based off of ET rates retrieved from on-site weather stations which more accurately represent the larger turfgrass stand (DaCosta and Huang, 2006). The ET number derived from a weather station utilizes a crop coefficient and typically results in a 1:1 ratio (Horgan and Sass, 2006). This ET number is derived from variables collected and stored in a data logger typically located within the weather station in use. These variables include wind speed, relative humidity, net solar radiation, and precipitation. More recently technologies have been made available and affordable for turfgrass managers such as portable and wireless soil moisture content meters (Horgan and Sass, 2006). While all of the above are practical methods the potential problem however, lies in the inability of turfgrass managers to effectively apply these technologies due to limited training and exposure.

The goal of this research was to evaluate and document water usage of ten major cool-season turfgrass species in a side by side field comparison as influenced by mowing height and nitrogen fertility. Previous studies have found that mowing height and frequency along with nitrogen fertility can impact water use, however, there has never been any documented research evaluating all ten cool season turfgrasses in a side by side comparison. In addition, there has been no previous work indicating water use requirements shortly after establishment.

**Materials and Methods**

The research plot area (11 m x 37 m) is located on the 2.83 hectare turfgrass research parcel at the OSU Lewis-Brown Horticulture Farm (44° 33’ 4” latitude and 123° 12’ 51” longitude) in Corvallis, OR. The native soil plot consists of a Chehalis and Malabon silty clay loam with a pH of 6.3. Preliminary soil test results indicate no fertility gradient and adequate potassium and phosphorous levels.

Prior to year one initiation the perennial ryegrass (*Lolium perenne*) area was treated twice with glyphosate (N-phosphonomethyl-glycine) herbicide at a 2% solution two weeks apart to kill
existing plant vegetation. When the existing vegetation was fully necrotic the area was incrementally mown down to a height of 1.6 cm and all foliage and debris was removed. Specialized equipment was then used to remove the remaining organic matter and the site was lightly graded to a (~1-2%) slope and leveled with minimal disruption to provide adequate surface drainage throughout the plot area and preserve soil structure. Second year establishment required no grading, otherwise establishment methods were identical to year one. The plots were reestablished over the previous plots so the species sprayed out varied in the second year.

Nine of the experimental units were established from seed while one was established from sod as a result of no proven commercially available seed. Three replications of each species plot (3.66 m x 3.66 m) were seeded on 23 April 2009 and 17 April 2010. Three top performing cultivars, each one from a different seed company, were blended prior to seeding to provide a better representation of each species (Table 2.1). Each cultivar was chosen by breeders from the respective seed companies for its ability to adequately perform under low-water and limited nitrogen inputs with respect to its individual genus. Due to lack of available seed, annual bluegrass (Poa annua var. reptans) plots were sodded on 7 May 2009 and 11 May 2010 using a greens source composite from western Canada.

Upon completion of seeding, the plots were covered with a single-layer woven polyethylene seeding blanket to aid in maintaining temperatures conducive to germination. In addition, the seeding blanket reduced seed movement and contamination from one plot to the next as a result of potential heavy rainfall events. The seeding blanket was removed on 11 May 2009 and 13 May 2010. For both years two separate 41.65 kg N/ha (urea) applications were made to the seedbed prior to seeding. Upon germination 9.8 kg N/ha (urea) was applied on 7-10 day intervals until 2 weeks prior to the initiation of the study thus equating to 132.3 kg N/ha. Following seeding plots were irrigated 3-5 times daily for 3 minutes using an in-ground irrigation system until all plots had adequately germinated. At that time, all plots received 100% ET replacement until the trial start date of 15 July.

The experiment is characterized by ten species as horizontal treatments and two mowing heights (16 mm and 51 mm) as vertical treatments and a subplot treatment of two nitrogen fertility levels (0 kg/ha and 49 kg/ha). This strip-split-plot design was selected to allow for
Table 2.1  List of turfgrass species and cultivars used for establishment.

<table>
<thead>
<tr>
<th>Species</th>
<th>Seeding Rate (kg/ha)</th>
<th>Cultivars</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kentucky bluegrass <em>Poa pratensis</em> L.</td>
<td>146.4</td>
<td>Prosperity, Langara, Touche</td>
</tr>
<tr>
<td>Creeping Bentgrass <em>Agrostis stolonifera</em> L.</td>
<td>73.2</td>
<td>Crystal Blue Links, 007, MacKenzie</td>
</tr>
<tr>
<td>Colonial Bentgrass <em>Agrostis capillaris</em> L.</td>
<td>73.2</td>
<td>Alistair, SR 7150, SR 7100</td>
</tr>
<tr>
<td>Velvet Bentgrass <em>Agrostis canina</em> L.</td>
<td>73.2</td>
<td>Greenwich, SR 7200, Vesper</td>
</tr>
<tr>
<td>Perennial Ryegrass <em>Lolium perenne</em> L.</td>
<td>292.8</td>
<td>Silverdollar, Express II, Zoom</td>
</tr>
<tr>
<td>Tall Fescue <em>Festuca arundinacea</em> Schreb.</td>
<td>292.8</td>
<td>Coronado TDR, SR 8650, Mustang 4</td>
</tr>
<tr>
<td>Slender Creeping Red Fescue <em>Festuca rubra</em> L. spp. <em>littoralis</em></td>
<td>195.1</td>
<td>Seabreeze GT, Shoreline</td>
</tr>
<tr>
<td>Chewings Fescue <em>Festuca rubra</em> L. spp. <em>commutata</em></td>
<td>195.1</td>
<td>Treasure II, SR 5130, Windward</td>
</tr>
<tr>
<td>Strong Creeping Red Fescue <em>Festuca rubra</em> L. spp. <em>rubra</em></td>
<td>195.1</td>
<td>Shademaster III, Garnet</td>
</tr>
<tr>
<td>Annual Bluegrass <em>Poa annua</em> var. <em>reptans</em></td>
<td>Sod</td>
<td>Northwest Greens Type</td>
</tr>
</tbody>
</table>

ease of mowing operations and to accommodate all of the treatments and factors in a predetermined area of the research parcel. Each replication contained a total of 40 experimental units (sub-sub plots) measuring 0.91 m by 0.91 m.

Upon adequate germination all plots were mowed at 16 mm to encourage lateral growth and encourage stand density for approximately 75 days. Clippings were routinely removed during all mowing operations to discourage stand contamination. Once established (approximately 75 days) each block was randomly split into two different mowing heights (16 mm and 51 mm). These mowing heights are representative of a golf course fairway (16 mm) and a home lawn (51 mm). The plots maintained at 16 mm were mowed three times per week (M, W, and F) while plots maintained at 51 mm were mowed once per week (Tue). All plots were mowed in the morning with the same, striping, rear-roller drive rotary mower (Hayter 56 model,
Seago International). This mower was used for its rear-drive roller to evenly distribute the weight of the unit and the associated rapid height of cut adjustment.

In addition, the main plots were randomly split into two separate nitrogen fertility levels stripped across the mowing height treatments. The low nitrogen plots received 0 kg/ha additional nitrogen during the course the study and the high nitrogen plots received an initial application one week prior to treatment initiation consisting of 49 kg N/ha with a granular Andersons 30-0-0 Contec DG SGN 150 (2.31% Ammoniacal N, 3.52% Urea N, 16.76% WIN, and 7.43% WSN).

Irrigation was applied to keep a functioning turfgrass stand with recuperative potential without allowing the entire subplot to enter dormancy or turn brown. As indicated above, all plots were initially irrigated uniformly replacing 100% of ET with an automated irrigation system utilizing Rainbird 5000 series rotor heads until one week prior to the trial start date of 15 July 2009 and 15 July 2010. Twenty-four hours prior to the initiation of the trial all plots were irrigated with 2.54 cm to bring them all to field capacity and allowed to drain. Once the trial was initiated 15 July 2009 and 2010, the automated irrigation system was turned off.

Plots were evaluated daily during the hottest part of the day between 1200h and 1400h and assessed on overall functionality (playability) and rated on a numerical scale (0-2; 0 = no water stress, 1 = some water stress, 2 = water stressed with a need to irrigate). The rating scale took into consideration; % cover (density), % dormant turfgrass, % stressed (fired) turfgrass, and overall stand need for irrigation inputs. Immediately following visual inspections, evaluations were then made using Stress Detection Glasses. The Stress Detection Glasses utilize technology developed by NASA that filters overpowering light in the center of the visual spectrum so the fringe spectra becomes more apparent indicating early plant stress. Weekly digital images were also taken and evaluated using SigmaScan Pro™ software in an attempt to legitimize visual assessments over the concern of the subjectivity of the ratings. At this time all plots (images) were also visually rated utilizing a 1 to 9 visual rating scale based on turf quality, turfgrass density, and uniformity; where 1 equals dead turf; 9 equals ideal turf; and 5 equals minimally acceptable quality. Results of the various assessment methods to determine stress will be reported separately.
Once an individual subplot was rated a 2, irrigation was applied by hand at a rate of 7.62 mm through a Precision™ Rainbow low flow nozzle equipped to deliver 37-53 LPM attached to a flow and batch meter. This amount of water was used because the intent was to deliver enough water to allow for adequate recharging of the various root-zones without running off of the plots. The amount applied each time was the same but the amount of root-zone replacement varied from 41% replacement of a reference ET to 89% of a reference ET. Water use was correlated with the rating scale and based on volumetric water content (VWC) readings taken daily at 3.8 cm with the TDR soil moisture probe (data not shown). Each time irrigation inputs were applied to a respective subplot, data was recorded. Environmental conditions such as high and low daily temperatures, reference ET rates, and precipitation due to rainfall were monitored and recorded using a Campbell-Scientific on-site weather station located within 50 meters of the research site. In conjunction with this, general soil temperature data at the surface, 5 cm, 10 cm, and 15 cm depths was routinely monitored and recorded throughout the study using an adjacent onsite data logger located within 15 meters of the trial site. The trial ran for the same 45 day period in 2009 and 2010 in an attempt to gather as much data as possible during an expected and naturally cyclic period of no precipitation.

Results and Discussion

Kenna (2006) has presented a mean rate of turfgrass ET rates table, based on multiple studies over many years, and related rankings among cool-season turfgrasses (Table 2.2). The table has been modified to only display the particular species utilized in our particular study. This table and others like it are very useful, and these are the numbers typically widely cited as the requirements for turfgrass maintenance, yet these numbers are indicative of results obtained from various studies under differing management levels. In addition, many of these trials were performed with older cultivars and under non-limited water conditions.

The most significant difference in water use in this study occurred between species and mowing heights (Table 2.2 and 2.3). Due possibly to the short length of the study and the initial nitrogen fertility used for establishment no significant nitrogen effect was seen. This study evaluated the ten most commonly used cool-season turfgrass species under the same field conditions in a side by side setting. It is understood within these respective turfgrasses there are varying growth habits and characteristics potentially explaining discrepancies in water use patterns previously reported from region to region.
Table 2.2  ET rates of cool season species based on multiple research trials (Kenna, 2006).

<table>
<thead>
<tr>
<th>Turfgrass Species</th>
<th>Mean Summer ET Rate (mm/day)</th>
<th>Relative Ranking</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hard Fescue</td>
<td>7 - 8.5</td>
<td>Medium</td>
</tr>
<tr>
<td>Chewings Fescue</td>
<td>7 - 8.5</td>
<td></td>
</tr>
<tr>
<td>Red Fescue</td>
<td>7 - 8.5</td>
<td></td>
</tr>
<tr>
<td>Perennial Ryegrass</td>
<td>6.6 - 11.2</td>
<td>High</td>
</tr>
<tr>
<td>Tall Fescue</td>
<td>3.6 - 12.6</td>
<td></td>
</tr>
<tr>
<td>Creeping Bentgrass</td>
<td>5 - 10</td>
<td></td>
</tr>
<tr>
<td>Annual Bluegrass</td>
<td>&gt;10</td>
<td></td>
</tr>
<tr>
<td>Kentucky Bluegrass</td>
<td>4 - &gt;10</td>
<td></td>
</tr>
<tr>
<td>Colonial Bentgrass</td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>Velvet Bentgrass</td>
<td>*</td>
<td></td>
</tr>
</tbody>
</table>

*Not reported.

Table 2.3  ANOVA of total water use for turfgrass plots.

<table>
<thead>
<tr>
<th>Effect</th>
<th>Water Use Pr &gt; F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Year</td>
<td>0.2376</td>
</tr>
<tr>
<td>Species</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Year*Species</td>
<td>0.0183</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>0.1927</td>
</tr>
<tr>
<td>Year*Nitrogen</td>
<td>0.2206</td>
</tr>
<tr>
<td>Species*Nitrogen</td>
<td>0.4790</td>
</tr>
<tr>
<td>Year<em>Species</em>Nitrogen</td>
<td>0.0446</td>
</tr>
<tr>
<td>Mowing</td>
<td>0.0028</td>
</tr>
<tr>
<td>Year*Mowing</td>
<td>0.3780</td>
</tr>
<tr>
<td>Mowing*Species</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Year<em>Mowing</em>Species</td>
<td>0.7364</td>
</tr>
<tr>
<td>Mowing*Nitrogen</td>
<td>0.4042</td>
</tr>
<tr>
<td>Year<em>Mowing</em>Nitrogen</td>
<td>0.5495</td>
</tr>
<tr>
<td>Mowing<em>Species</em>Nitrogen</td>
<td>0.3846</td>
</tr>
<tr>
<td>Year<em>Mow</em>Species*Nitrogen</td>
<td>0.0208</td>
</tr>
</tbody>
</table>
Results from 2009 and 2010 indicate there was no significance in the nitrogen treatments. This is likely due to the pre-plant available nitrogen. It is suspected if the current trial stand is continued to be maintained as a perennial stand nitrogen treatments will eventually become significant. Mantell (1966) observed it was originally thought water conservation could be achieved by substituting part of the irrigation regime with nitrogen and still maintain desired lawn quality yet there still is a general reluctance to apply nitrogen to turfgrass at regular and relatively frequent intervals for fear of stimulating unnecessary growth. In addition it was noted that turfgrass receiving a nitrogen application of 49 kg N/ha/month, and irrigated every 25 days did not produce a much greater yield than did non-fertilized turfgrass irrigated every 7 days. Therefore regular use of nitrogen fertility will not encourage excessive growth provided water is not applied at too frequent intervals (Mantell 1966). Whether it can be deemed sustainable or not, it was also reported by Mantell that the highest visual rating, most intense color, and greatest plant density were achieved by the most frequent irrigation schedule coupled with the high nitrogen level. More recently Barton et al. (2009) revealed increasing nitrogen rates increased ET rates for a juvenile as well as a mature stand of turfgrass. However, this research was also performed on warm-season turfgrass and therefore difficult to extrapolate upon. Barton et al. (2009) also confirmed the findings of Mantell by suggesting that while manipulating nitrogen rates to conserve water may be an option; turfgrass managers must understand the effect on overall turfgrass quality.

As indicated above, all treatments were irrigated with the same volume of irrigation once irrigation was deemed necessary in that plot. Total volumes of irrigation inputs for the treatment periods are available and can be found in Figures 2.1 and 2.2. To relate to these volumes more readily, data has been associated with a value of the reference ET obtained from the onsite weather station (RainBird Golf, Cambell Scientific, Logan, UT) (Figures 2.3 and 2.4). Data analysis indicates mowing height and species were significant and therefore has been separated for all graphical displays, with a significant year by species interaction as well as mowing by species interaction. Establishment problems occurred in some species, primarily the fine fescues, the second year of uncertain origin which may have contributed to some differences in the two years and higher water use rates in these species the second year.

The species could be subdivided into a higher water use and lower water use category for each cutting height. The higher water use species, annual bluegrass and red fescues, all used
### Figure 2.1 Total irrigation inputs for 2009 trial period.

<table>
<thead>
<tr>
<th>Grass Type</th>
<th>Low Mow</th>
<th>High Mow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual Bluegrass</td>
<td>203.2</td>
<td>189.23</td>
</tr>
<tr>
<td>Strong CRF</td>
<td>196.85</td>
<td>144.78</td>
</tr>
<tr>
<td>Slender CRF</td>
<td>184.15</td>
<td>128.27</td>
</tr>
<tr>
<td>Chewings Fescue</td>
<td>144.78</td>
<td>120.65</td>
</tr>
<tr>
<td>Colonial Bentgrass</td>
<td>138.43</td>
<td>105.41</td>
</tr>
<tr>
<td>Velvet Bentgrass</td>
<td>106.68</td>
<td>105.41</td>
</tr>
<tr>
<td>Kentucky Bluegrass</td>
<td>105.41</td>
<td>105.41</td>
</tr>
<tr>
<td>Creeping Bentgrass</td>
<td>96.52</td>
<td>96.52</td>
</tr>
<tr>
<td>Perennial Ryegrass</td>
<td>93.98</td>
<td>81.28</td>
</tr>
<tr>
<td>Tall Fescue</td>
<td>81.28</td>
<td>69.85</td>
</tr>
</tbody>
</table>

### Figure 2.2 Total irrigation inputs for 2010 trial period.

<table>
<thead>
<tr>
<th>Grass Type</th>
<th>Low Mow</th>
<th>High Mow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual Bluegrass</td>
<td>214.63</td>
<td>193.04</td>
</tr>
<tr>
<td>Strong CRF</td>
<td>219.71</td>
<td>157.48</td>
</tr>
<tr>
<td>Slender CRF</td>
<td>212.09</td>
<td>153.67</td>
</tr>
<tr>
<td>Chewings Fescue</td>
<td>213.36</td>
<td>166.37</td>
</tr>
<tr>
<td>Colonial Bentgrass</td>
<td>152.4</td>
<td>114.3</td>
</tr>
<tr>
<td>Velvet Bentgrass</td>
<td>95.25</td>
<td>97.79</td>
</tr>
<tr>
<td>Kentucky Bluegrass</td>
<td>111.76</td>
<td>109.12</td>
</tr>
<tr>
<td>Creeping Bentgrass</td>
<td>139.7</td>
<td>87.63</td>
</tr>
<tr>
<td>Perennial Ryegrass</td>
<td>81.28</td>
<td>72.39</td>
</tr>
<tr>
<td>Tall Fescue</td>
<td>69.85</td>
<td>58.42</td>
</tr>
</tbody>
</table>
Figure 2.3 Percentage of reference ET applied for 2009.

Figure 2.4 Percentage of reference ET applied for 2010.
significantly more water in the lower mown plots to maintain adequate turf cover than in the higher mown plots. During 2009 and 2010, weather conditions varied dramatically from day to day. 2009 trial weather was extremely hot at times while 2010 was closer to daily averages. However, the 45 day trial average ETs were similar for both years. As indicated above mowing height had a significant effect on the results. Overall, the fine fescue species, including slender creeping red fescue, strong creeping red fescue and Chewings fescue, required higher amounts of irrigation inputs to maintain active growth and stand uniformity.

It is worth noting these species once mature may require fewer inputs, yet during establishment years inputs should be expected to be higher than many other species. Additionally, fine fescue species are often left to go dormant during times of drought, yet the intent of this study was to maintain an actively growing stand with the ability to recuperate. Annual bluegrass is a weedy species that invades and takes over many turf sites but is often managed as a turf surface. It was the highest water user of any species.

The reference ET for year 1 (2009) was 5.10 mm/day and 4.97 mm/day for year 2 (2010). Many irrigation systems are set to utilize this number with a crop coefficient to calculate water requirements of turf areas. The crop coefficients utilized for cool season grasses are often 0.72 for low maintenance grass to 0.90 for high maintenance grass. The percentage of the reference ET utilized (Figures 2.3 and 2.4) is similar to the crop coefficient and suggests that these values could be significantly reduced for even high maintenance turf in the Pacific Northwest.

Tall fescue required the fewest irrigation inputs to maintain an adequate stand while perennial ryegrass also required very little irrigation inputs. While it was expected the tall fescue would perform well, the perennial ryegrass performance was surprising. One explanation for this may be the rapid establishment of the perennial ryegrass plots compared to the other species evaluated. Given the perennial ryegrass was at full cover shortly after seeding, it is suspected it had increased time to develop a more substantial root system and carbohydrate reserves. Turfgrass breeders have made extensive progress in breeding perennial ryegrass for greater stress tolerance, which may be reflected in this lower water requirement. It is also possible if the study were continued as a perennial stand the perennial ryegrass plots may exhibit less of an efficient means of water use.
An additional factor often utilized to reduce turfgrass water use is restrictions on the number of days turfgrass can be irrigated each week. When water restrictions are implemented this can vary from an every other day irrigation to twice a week irrigation. Other areas limit the total water applied for turfgrass irrigation. These restrictions are often put in place within 60 days after turfgrass installation. The days between watering for high quality turfgrass ranged from only 2 days for annual bluegrass up to 6 days for the tall fescue at the higher mowing height (Figures 2.5 and 2.6). At the higher mowing height most species could tolerate a twice a week watering schedule and maintain adequate turf quality. The lower mowing height demonstrates that even golf course fairway irrigations can be spaced out more.

Beard (1973) demonstrated with creeping bentgrass (*Agrostis stolonifera* L.) that the preconditioning treatment effects of cutting height, light intensity, and nitrogen had the greatest impact on creeping bentgrass water use rates. These factors are a result of their influence on the total plant surface area exposed to desiccating positions (Beard 1973).
It was hypothesized the bunch type fine fescue varieties (*Festuca tryachyphylla*, and *Festuca rubra*) because they have smaller, finer leaf blades in turn effectively reducing the total amount of stomata therefore likely reduce overall ET. It is also understood that the finer leaf blade and bunch type growth habit turfgrasses such as the fine fescues or velvet bentgrass (*Agrostis canina*) are seemingly less often affected by the addition of nitrogen in comparison with the more aggressive laterally growing turfgrasses such as Kentucky bluegrass (*Poa pratensis*) or creeping bentgrass (*Agrostis stolonifera*) indicating potentially less of an increase in water use with the addition of nitrogen. It was also thought the denser, compact growing turfgrasses will likely use less water versus the more upright growing turfgrasses. For example velvet bentgrass (*Agrostis canina*) would likely require less water when compared to tall fescue (*Festuca arundinacea*). It was thought the plots maintained at 51 mm versus the 16 mm mowing height will also likely require greater irrigation inputs due to the maximized leaf area and larger capacity for physiological activity such as photosynthesis and transpiration. Some of these effects may come into play later but rapidity of stand maturity seemed an underlying factor in the current study.
In Table 2.4 most species utilized less water than the level reported by Kenna (2006). Previous studies had emphasized well watered conditions while this study emphasized minimal water to maintain high quality turf. In comparison Lewis (2010) found Kentucky bluegrasses irrigated under a similar regime used between 23.4 to 40.0 cm over a 4 month period in Kansas which is 1.95 to 3.33 mm/day. This also supports a lower water use under reduced irrigation regimes. DaCosta and Huang (2006) reported velvet and creeping bentgrass could be maintained at 60 to 80% reference ET, while colonial bentgrass required 80% for adequate turf quality.

### Table 2.4 Average daily water requirements of cool season turfgrass species under two mowing heights.

<table>
<thead>
<tr>
<th>Turfgrass Species</th>
<th>Low Mow (mm/day)</th>
<th>High Mow (mm/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2009</td>
<td>2010</td>
</tr>
<tr>
<td>Tall Fescue</td>
<td>2.09</td>
<td>1.55</td>
</tr>
<tr>
<td>Perennial Ryegrass</td>
<td>2.14</td>
<td>1.81</td>
</tr>
<tr>
<td>Creeping Bentgrass</td>
<td>2.34</td>
<td>3.10</td>
</tr>
<tr>
<td>Kentucky Bluegrass</td>
<td>2.34</td>
<td>2.48</td>
</tr>
<tr>
<td>Velvet Bentgrass</td>
<td>2.37</td>
<td>2.12</td>
</tr>
<tr>
<td>Colonial Bentgrass</td>
<td>3.08</td>
<td>3.39</td>
</tr>
<tr>
<td>Chewings Fescue</td>
<td>3.22</td>
<td>4.74</td>
</tr>
<tr>
<td>Slender Creeping Red Fescue</td>
<td>4.09</td>
<td>4.71</td>
</tr>
<tr>
<td>Strong Creeping Red Fescue</td>
<td>4.37</td>
<td>4.88</td>
</tr>
<tr>
<td>Annual Bluegrass</td>
<td>4.52</td>
<td>4.77</td>
</tr>
</tbody>
</table>

### Conclusion

With increased regulatory and environmental pressures mounting throughout the country regarding the utilization of non-saline or freshwater in conjunction with nitrogen, these findings will enable legislators and turfgrass managers alike to make more informed decisions. Without data for newly developed varieties of the commonly used cool-season turfgrasses it becomes increasingly more difficult for individuals to make informed decisions regarding functionality. With many unsubstantiated claims regarding water use of various turfgrasses,
this data will help to substantiate what quantity of water inputs is actually necessary to keep these specific species alive and functioning indefinitely.

In addition, the findings from this data allows for informed decisions regarding necessary inputs and resources required to achieve a functioning and acceptable stand of turfgrass. Ultimately this research should allow end users to use as a measuring point from which they can base their decision making process regarding the most critical cultural inputs, water, nitrogen, and mowing.

References Cited


CHAPTER 3

EVALUATION OF THE EFFECTIVENESS OF STRESS DETECTION GLASSES TO DETECT DROUGHT STRESS

Abstract

Stress detection glasses were able to detect water stress in all turfgrass species tested by a minimum of 1.2 days on average and a maximum of 2.4 days. The purple lenses work by blocking out the green spectrum reflected from chlorophyll found in normal healthy vegetation, causing it to look black or gray. The early detection of stress would enable turf managers to schedule irrigation in advance while conserving water. The glasses were tested across a broad range of species and were effective with the different turf canopies and variation in color present in the different species.

Introduction

Turfgrasses, like all other agronomic, horticultural, and landscape vegetation, require water and nutrients for growth and survival. Without adequate water and nutrition, turfgrass will likely be forced into dormancy becoming brown, and ultimately desiccated, and in severe instances may even die (Murphy, 2002). A loss of ground cover by turfgrasses can have significant negative impacts on the aesthetics and functionality of the plant stand as well as the environment. In fact, previous research has routinely found that bare soils, stones, and other hard surfaces are heat sinks that can result in a buildup of maximum daytime temperatures ranging to more than 21°C higher than a transpiring turfgrass sward (Beard, 1973). In addition, temperatures in urban areas can average 3.2°C higher than nearby rural environments as a direct result of the transpiration of water from turfgrass leaves (Beard and Kenna, 2008). Therefore, irrigation inputs are at times desirable to maintain the functional benefits of a healthy, actively growing turfgrass stand in areas where rainfall cannot meet the water demand of plants. Moreover, as freshwater availability throughout the world is becoming increasingly limited and more costly, freshwater conservation in turfgrass culture has become extremely important to a viable future (Githinji et al., 2009).

Indeed irrigation may be required to maintain a functional turfgrass stand, yet determining when to irrigate can be very difficult. For example the use of on-site weather stations and soil
moisture sensors has become common practice among many turfgrass professionals. Yet these monitoring techniques are unable to display a real time synopsis of plant health. Therefore despite the introduction of various monitoring techniques, many turfgrass managers continue to rely on qualitative visual assessments of water stress in determining irrigation needs (Steinke et al., 2009).

Effectively scheduling irrigation on a site-specific basis requires detecting those areas where the plants are beginning to experience drought stress, although they may lack visible symptoms. By identifying these areas before visible symptoms of drought stress develop, managers can schedule an irrigation event and minimize stress to the turfgrass plants (Dettman-Kruse et al., 2008).

Stress Detection Glasses is a new technology developed by NASA and the USDA to allow an individual to detect potential plant problems long before they would be visible to the unaided eye. The glasses were designed so plant stress is evident as brilliant colors in the midst of a gray/black background. The purple lenses work by blocking out the green spectrum reflected from chlorophyll found in normal healthy vegetation, causing it to look black or gray. The human eye is very sensitive to light in this color range, so any off-green colors caused by disease, poor nutrition, or insects will stand out versus this black background as glowing red, coral, pink or other hues (Brock, 2005). For example, turfgrass shows signs of distress (disease or drought) by the way it absorbs and reflects sunlight. These early signals of stress are unseen by the unaided eye unless viewed through advanced technology.

Initially Dr. Len Haslim (NASA Ames Research Center Senior Scientist) was interested in being able to identify camouflaged objects in forests, grass or jungle environments using optical filters rather than infrared photography (Brock, 2005). Interestingly enough, while trying to make the green vegetation change color and leave the camouflaged object clearly visible, Dr. Haslim noticed in reality the filter/lens made the healthy vegetation change color (to gray or black), while the unhealthy parts of the vegetation became quite visible. This was due to a number of factors, mainly special filters and because the human eye is hyper-sensitive to greens (Brock, 2005).
Although the human retina is sensitive to colors ranging from ultra violet (about 400 nm) to near infrared (about 700 nm), human retinas are predominantly sensitive to the middle wavelengths, i.e., blues and greens (Brock, 2005). This center loading sensitivity to the middle wavelengths is so great the peripheral colors are overpowered (Brock, 2005).

Indeed, human color sensitivity follows the properties of a normal distribution curve between the shorter and longer wavelengths (Brock, 2005). There is also shift in color sensitivity of the human eye in low light environments. For example, this is evident in a darkened movie theater where the colors are more vivid because the eye sees more vivid colors. The curve which peaks between 500-600 nm represents color sensitivity in normal light, while the curve peaking at about 500 nm is the dark adapted (low light) sensitivity (Brock, 2005). Humans have evolved having great sensitivity to greens and much lower sensitivity at either end of the visual spectrum. By using a filter with a transmission curve opposite of human sensitivity, i.e., low transmission between 440-600 nm and high transmission in shortwave blue colors and especially the long wavelengths beginning with a sharp rise at 600nm (stress detection lens), the light perceived by the retina and brain using the filter allows the viewer to "see" what they normally may not (Brock, 2005). The purple lenses block about 95% of the visible light and shift colors to the edge of the visual spectrum.

Turfgrass functionality depends on plants converting sunlight into carbohydrates. At the center of this photosynthesis are two long chained carbon based molecules, Chlorophyll \(a\) (C\(_{55}\)H\(_{72}\)Mg N\(_4\)O\(_5\)) and Chlorophyll \(b\) (C\(_{55}\)H\(_{70}\)Mg N\(_4\)O\(_6\)) (Bell et al., 2002). Chlorophyll content and its function is a direct measure of plant health (Brock, 2005). Healthy chlorophyll-bearing vegetation absorbs and reflects sunlight differently than stressed or diseased vegetation (Brock, 2005). Dying plants signal their distress with changes in their reflective spectra primarily in the upper and lower ranges of the visual spectrum, i.e., 400-480 nm and 600-700 nm (Brock, 2005). For the observer attempting to identify early turfgrass disease and stress, this physiological fact means the slight shifts in greens to the reds, browns and yellows which often indicate disease and stress are difficult or impossible to see with the naked eye. Forests, fields, crops, farms, wetlands, yards and gardens around the world are negatively impacted because the human eye cannot detect an unhealthy plant's early warning signs.
The Stress Detection Glasses were reported to work with the human eye to identify plant stress and are: 1) inexpensive, 2) require no lab time or processing, 3) operate in real time, 4) work on everything seen, and 5) are easy to use. Additionally, the glasses protect the wearer from harmful ultraviolet radiation; function as safety glasses thereby protecting the eyes from objects.

The goal of this research was to evaluate the potential of the Stress Detection Glasses to identify drought stress earlier than the unaided human eye in ten different cool season turfgrass species maintained under different mowing and fertility regimes.

**Materials and Methods**

The research plot area (11 m x 37 m) is located on the 2.83 hectare turfgrass research parcel at the OSU Lewis-Brown Horticulture Farm (44° 33’ 4” latitude and 123° 12’ 51” longitude) in Corvallis, OR. The native soil plot consists of a Chehalis and Malabon silty clay loam with a pH of 6.3. Preliminary soil test results indicate no fertility gradient and adequate potassium and phosphorous levels.

Prior to year one initiation the perennial ryegrass (*Lolium perenne*) area was treated twice with glyphosate (N-phosphonomethyl-glycine) herbicide at a 2% solution two weeks apart to kill existing plant vegetation. When the existing vegetation was fully necrotic the area was incrementally mown down to a height of 1.6 cm and all foliage and debris was removed. Specialized equipment was then used to remove the remaining organic matter and the site was lightly graded to a (~1-2%) slope and leveled with minimal disruption to provide adequate surface drainage throughout the plot area and preserve soil structure. Second year establishment required no grading, otherwise establishment methods were identical to year one. The plots were reestablished over the previous plots so the species sprayed out varied in the second year.

Nine of the experimental units were established from seed while one was established from sod as a result of no proven commercially available seed. Three replications of each species plot (3.66 m x 3.66 m) were seeded on 23 April 2009 and 17 April 2010. Three top performing cultivars, each one from a different seed company, were blended prior to seeding to provide a better representation of each species (Table 3.1). Each cultivar was chosen by breeders from the respective seed companies for its ability to adequately perform under low-water and
limited nitrogen inputs with respect to its individual genus. Due to lack of available seed, annual bluegrass (*Poa annua var. reptans*) plots were sodded on 7 May 2009 and 11 May 2010 using a greens source composite from western Canada.

**Table 3.1** List of turfgrass species and cultivars used for establishment.

<table>
<thead>
<tr>
<th>Species</th>
<th>Seeding Rate (kg/ha)</th>
<th>Cultivars</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kentucky bluegrass <em>Poa pratensis</em> L.</td>
<td>146.4</td>
<td>Prosperity, Langara, Touche</td>
</tr>
<tr>
<td>Creeping Bentgrass <em>Agrostis stolonifera</em> L.</td>
<td>73.2</td>
<td>Crystal Blue Links, 007, MacKenzie</td>
</tr>
<tr>
<td>Colonial Bentgrass <em>Agrostis capillaris</em> L.</td>
<td>73.2</td>
<td>Alistair, SR 7150, SR 7100</td>
</tr>
<tr>
<td>Velvet Bentgrass <em>Agrostis canina</em> L.</td>
<td>73.2</td>
<td>Greenwich, SR 7200, Vesper</td>
</tr>
<tr>
<td>Perennial Ryegrass <em>Lolium perenne</em> L.</td>
<td>292.8</td>
<td>Silverdollar, Express II, Zoom</td>
</tr>
<tr>
<td>Tall Fescue <em>Festuca arundinacea</em> Schreb.</td>
<td>292.8</td>
<td>Coronado TDR, SR 8650, Mustang 4</td>
</tr>
<tr>
<td>Slender Creeping Red Fescue <em>Festuca rubra</em> L. spp. <em>littoralis</em></td>
<td>195.1</td>
<td>Seabreeze GT, Shoreline</td>
</tr>
<tr>
<td>Chewings Fescue <em>Festuca rubra</em> L. spp. <em>commutata</em></td>
<td>195.1</td>
<td>Treazure II, SR 5130, Windward</td>
</tr>
<tr>
<td>Strong Creeping Red Fescue <em>Festuca rubra</em> L. spp. <em>rubra</em></td>
<td>195.1</td>
<td>Shademaster III, Garnet</td>
</tr>
<tr>
<td>Annual Bluegrass <em>Poa annua var. reptans</em> Sod</td>
<td>132.3</td>
<td>Northwest Greens Type</td>
</tr>
</tbody>
</table>

Upon completion of seeding, the plots were covered with a single-layer woven polyethylene seeding blanket to aid in maintaining temperatures conducive to germination. In addition, the seeding blanket reduced seed movement and contamination from one plot to the next as a result of potential heavy rainfall events. The seeding blanket was removed on 11 May 2009 and 13 May 2010. For both years two separate 41.65 kg N/ha (urea) applications were made to the seedbed prior to seeding. Upon germination 9.8 kg N/ha (urea) was applied on 7-10 day intervals until 2 weeks prior to the initiation of the study thus equating to 132.3 kg N/ha. Following seeding plots were irrigated 3-5 times daily for 3 minutes using an in-ground
irrigation system until all plots had adequately germinated. At that time, all plots received 100% ET replacement until the trial start date of 15 July.

The experiment is characterized by ten species as horizontal treatments and two mowing heights (16 mm and 51 mm) as vertical treatments and a subplot treatment of two nitrogen fertility levels (0 kg/ha and 49 kg/ha). This strip-split-plot design was selected to allow for ease of mowing operations and to accommodate all of the treatments and factors in a predetermined area of the research parcel. Each replication contained a total of 40 experimental units (sub-sub plots) measuring 0.91 m by 0.91 m.

Upon adequate germination all plots were mowed at 16 mm to encourage lateral growth and encourage stand density for approximately 75 days. Clippings were routinely removed during all mowing operations to discourage stand contamination. Once established (approximately 75 days) each block was randomly split into two different mowing heights (16 mm and 51 mm). These mowing heights are representative of a golf course fairway (16 mm) and a home lawn (51 mm). The plots maintained at 16 mm were mowed three times per week (M, W, and F) while plots maintained at 51 mm were mowed once per week (Tue). All plots were mowed in the morning with the same, striping, rear-roller drive rotary mower (Hayter 56 model, Seago International). This mower was used for its rear-drive roller to evenly distribute the weight of the unit and the associated rapid height of cut adjustment.

In addition, the main plots were randomly split into two separate nitrogen fertility levels stripped across the mowing height treatments. The low nitrogen plots received 0 kg/ha additional nitrogen during the course the study and the high nitrogen plots received an initial application one week prior to treatment initiation consisting of 49 kg N/ha with a granular Andersons 30-0-0 Contec DG SGN 150 (2.31% Ammoniacal N, 3.52% Urea N, 16.76% WIN, and 7.43% WSN).

Irrigation was applied to keep a functioning turfgrass stand with recuperative potential without allowing the entire subplot to enter dormancy or turn brown. As indicated above, all plots were initially irrigated uniformly replacing 100% of ET with an automated irrigation system utilizing Rainbird 5000 series rotor heads until one week prior to the trial start date of 15 July 2009 and 15 July 2010. Twenty-four hours prior to the initiation of the trial all plots were
irrigated with 2.54 cm to bring them all to field capacity and allowed to drain. Once the trial was initiated 15 July 2009 and 2010, the automated irrigation system was turned off.

Plots were evaluated daily during the hottest part of the day between 1200h and 1400h and assessed on overall functionality (playability) and rated on a numerical scale (0-2; 0 = no water stress, 1 = some water stress, 2 = water stressed with a need to irrigate). The rating scale took into consideration; % cover (density), % dormant turfgrass, % stressed (fired) turfgrass, and overall stand need for irrigation inputs.

Immediately following visual inspections, evaluations were then made using Underhill TurfSpy™ Early Stress Detection Glasses. The intent of using the glasses was to see if it was possible to detect physiological water stress prior to observing without the glasses. When stress was detected with the glasses a “1” (1 = some water stress) was used to denote this using the 0-2 scale outlined above. Data was collected and analyzed to determine how far in advance water stress could be detected prior to detection with the unaided human eye for each treatment.

**Results and Discussion**

To be effective for the turf manager the Stress detection glasses should detect stress at least one day before the unassisted human eye. As shown in Figures 3.1 and 3.2 this was achieved in all species. Since measurements were done in the middle of the day and irrigation is performed on most fairways (low mowing height) during the night, to maximize the benefit stress should be detected 1.5 days in advance to allow irrigation scheduling without increasing water used or decrease days between irrigation. In both years this was possible for the species typically used for fairways, creeping bentgrass, Kentucky bluegrass and perennial ryegrass, with better results in 2010 perhaps due to familiarity with the glasses. The higher water use species in this study, annual bluegrass, strong and slender creeping red fescue and Chewings fescue had higher number of days in advance that stress was detected than days between irrigations especially at the lower mowing height (Figures 3.3 and 3.4) suggesting they were under stress during most of the trial. The glasses would be more effective in anticipating irrigation timing for the grasses that required less water or more days between irrigations.
Figure 3.1 Days in advance of detecting water stress using the early detection glasses for 2009.

Figure 3.2 Days in advance of detecting water stress using the early detection glasses for 2010.
Figure 3.3 Days in between irrigation inputs in 2009.

Figure 3.4 Days in between irrigation inputs in 2010.
The glasses may be particularly effective used by individuals to spot areas of turf that may need irrigation soon, including sports field managers. It may be possible to target irrigate areas of golf courses such as slopes by visualizing stress in advance and prevent overirrigation of the majority of a golf course.

**Conclusion**

Stress conditions could be detected one to two days before they were visible to the unaided eye with the stress detection glasses. The glasses can spot wilting caused by drought or broken sprinklers. They could be an important tool for turf managers to help in scheduling and utilization by inexperienced crew members for early detection of stress. The glasses were tested across a broad range of species and were effective with the different turf canopies and variation in color present in the different species.

**References Cited**


Brock, R.J., 2005. Stress Detection Glasses, History and Additional Information. (unpublished)


CHAPTER 4

EVALUATION OF THE EFFECTIVENESS OF TIME DOMAIN REFLECTOMETRY
ON A NATIVE SILT CLAY SOIL

Abstract

A portable Time Domain Reflectometer (TDR) system was used in conjunction with other methods to determine if it could reliably determine the volumetric water content (VWC) at which irrigation was required for ten cool season turfgrass species grown under different mowing and fertility regimes. It was determined with the native silt clay loam soil the 7.6 cm and 20 cm supplied probes were not robust enough to be used in this type of system. The 3.8 cm probes were utilized to monitor VWC in the top soil surface area at the end of dry down cycles. For most species the probes could reliably measure the %VWC at which irrigation was required to maintain a functional turf surface. For most species at the typical recommended mowing height, if maturity was achieved, this was at approximately 30% VWC.

Introduction

Turfgrasses, like all other agronomic, horticultural, and landscape vegetation, require water and nutrients for growth and survival. Without adequate water and nutrition, turfgrass will likely be forced into dormancy becoming brown, and ultimately desiccated, and in severe instances may even die (Murphy, 2002). A loss of ground cover by turfgrasses can have significant negative impacts on the aesthetics and functionality of the plant stand as well as the environment. In fact, previous research has routinely found that bare soils, stones, and other hard surfaces are heat sinks that can result in a buildup of maximum daytime temperatures ranging to more than 21°C higher than a transpiring turfgrass sward (Beard, 1973). In addition, temperatures in urban areas can average 3.2°C higher than nearby rural environments as a direct result of the transpiration of water from turfgrass leaves (Beard and Kenna, 2008). Therefore, irrigation inputs are at times desirable to maintain the functional benefits of a healthy, actively growing turfgrass stand in areas where rainfall cannot meet the water demand of plants. Moreover, as freshwater availability throughout the world is becoming increasingly limited and more costly, freshwater conservation in turfgrass culture has become extremely important to a viable future (Githinji et al., 2009).
It is increasingly important for turfgrass managers to carefully monitor the soil water status of the site and make adjustments in irrigation practices in response to water stress (Dettman-Kruse et al., 2008). Knowing how much water the turfgrass can receive from the soil will aid to develop an irrigation schedule to meet the turfgrass water needs (Githinji et al., 2009). While various irrigation scheduling and assessment techniques have proven to be effective compared to a set irrigation schedule or relying on the experience of a turfgrass manager there are limitations associated with each technique.

Over the last decade, a number of relatively accurate and precise devices to measure soil water content have been commercially developed. Although these devices have been used successfully in agricultural research and crop production systems, non-destructive soil water content meters have not been widely adopted in the turfgrass industry until recently. These devices are portable, relatively inexpensive, and can provide a turfgrass manager the ability to rapidly assess soil water content.

Time domain reflectometry (TDR) has been used to monitor water content in many agricultural settings yet TDR is a relatively new method of measuring soil water content in turfgrass and has been developed for its ease in taking multiple water-content samples with no disturbance to the soil profile (Young et al., 1997; Young et al., 2000). Professional turfgrass managers might find these devices useful as TDR can provide accurate readings of the irrigation needs of turfgrass (Young et al., 2000). TDR measures the propagation velocity of a high-frequency voltage impulse sent down two or more parallel metal probes in the soil (Kome, 1993). TDR-measured diurnal changes in water content can be attributed mostly to plant-root uptake (Young et al., 2000). TDR measurements have been reported to give soil-water content estimates accurate to ±2% and have shown good correlation with gravimetric determinations (Keeley and Koski, 1997).

Young et al. (1997) used weighing lysimeters to validate the use of vertically installed TDR probes for measuring ET of daily irrigated plants. When water accumulation at the bottom of the lysimeter was accounted for, comparisons between TDR and micrometeorological readings were within 8.5% and the TDR-measured water contents were statistically similar to gravimetrically determined water contents.
Kome (1993) reported that the maximum VWC was in the 0-5 cm layer except during dry down periods. The top layer also showed the greatest variation in volumetric soil moisture during the course of their experiment. The dynamic nature of this layer can be attributed to the high density of functional roots absorbing the moisture in addition to the high organic matter content and its vulnerability to fluctuations in atmospheric conditions such as rainfall, wind speed, radiation, temperature and relative humidity (Kome, 1993).

High variability in VWC data is considered to result from a combination of factors including soils with a high percentage of clay present because they strongly attenuate the TDR signal (Keeley and Koski, 1997). For studies in high clay-content soils, Keeley and Koski (1997) recommend a maximum waveguide length of 30 cm to alleviate this problem but they also note long waveguides also increase the possibility of air-gap formation around the waveguides during installation.

Research of TDR has shown that VWC can be assessed with reasonable accuracy for a wide variety of soils (Seyfried and Murdock, 2004). Although the use in high clay content soils often leads to an underestimation of VWC, TDR is generally regarded as the best available electronic technique for the measurement of VWC (Seyfried and Murdock, 2004).

The goal of this research was to evaluate the effectiveness of time domain reflectometry to accurately assess soil volumetric water content on a native silt clay soil with ten different cool season turfgrass species being grown under different mowing and fertility regimes.

**Materials and Methods**

The research plot area (11 m x 37 m) is located on the 2.83 hectare turfgrass research parcel at the OSU Lewis-Brown Horticulture Farm (44° 33’ 4” latitude and 123° 12’ 51” longitude) in Corvallis, OR. The native soil plot consists of a Chehalis and Malabon silty clay loam with a pH of 6.3. Preliminary soil test results indicate no fertility gradient and adequate potassium and phosphorous levels.

Prior to year one initiation the perennial ryegrass (*Lolium perenne*) area was treated twice with glyphosate (N-phosphonomethyl-glycine) herbicide at a 2% solution two weeks apart to kill existing plant vegetation. When the existing vegetation was fully necrotic the area was incrementally mown down to a height of 1.6 cm and all foliage and debris was removed.
Specialized equipment was then used to remove the remaining organic matter and the site was lightly graded to a (~1-2%) slope and leveled with minimal disruption to provide adequate surface drainage throughout the plot area and preserve soil structure. Second year establishment required no grading, otherwise establishment methods were identical to year one. The plots were reestablished over the previous plots so the species sprayed out varied in the second year.

Nine of the experimental units were established from seed while one was established from sod as a result of no proven commercially available seed. Three replications of each species plot (3.66 m x 3.66 m) were seeded on 23 April 2009 and 17 April 2010. Three top performing cultivars, each one from a different seed company, were blended prior to seeding to provide a better representation of each species (Table 4.1). Each cultivar was chosen by breeders from the respective seed companies for its ability to adequately perform under low-water and limited nitrogen inputs with respect to its individual genus. Due to lack of available seed, annual bluegrass (*Poa annua var. reptans*) plots were sodded on 7 May 2009 and 11 May 2010 using a greens source composite from western Canada.

Upon completion of seeding, the plots were covered with a single-layer woven polyethylene seeding blanket to aid in maintaining temperatures conducive to germination. In addition, the seeding blanket reduced seed movement and contamination from one plot to the next as a result of potential heavy rainfall events. The seeding blanket was removed on 11 May 2009 and 13 May 2010. For both years two separate 41.65 kg N/ha (urea) applications were made to the seedbed prior to seeding. Upon germination 9.8 kg N/ha (urea) was applied on 7-10 day intervals until 2 weeks prior to the initiation of the study thus equating to 132.3 kg N/ha. Following seeding plots were irrigated 3-5 times daily for 3 minutes using an in-ground irrigation system until all plots had adequately germinated. At that time, all plots received 100% ET replacement until the trial start date of 15 July.

The experiment is characterized by ten species as horizontal treatments and two mowing heights (16 mm and 51 mm) as vertical treatments and a subplot treatment of two nitrogen fertility levels (0 kg/ha and 49 kg/ha). This strip-split-plot design was selected to allow for ease of mowing operations and to accommodate all of the treatments and factors in a
predetermined area of the research parcel. Each replication contained a total of 40 experimental units (sub-sub plots) measuring 0.91 m by 0.91 m.

Table 4.1 List of turfgrass species and cultivars used for establishment.

<table>
<thead>
<tr>
<th>Species</th>
<th>Seeding Rate (kg/ha)</th>
<th>Cultivars</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kentucky bluegrass <em>Poa pratensis</em> L.</td>
<td>146.4</td>
<td>Prosperity, Langara, Touche</td>
</tr>
<tr>
<td>Creeping Bentgrass <em>Agrostis stolonifera</em> L.</td>
<td>73.2</td>
<td>Crystal Blue Links, 007, MacKenzie</td>
</tr>
<tr>
<td>Colonial Bentgrass <em>Agrostis capillaris</em> L.</td>
<td>73.2</td>
<td>Alistair, SR 7150, SR 7100</td>
</tr>
<tr>
<td>Velvet Bentgrass <em>Agrostis canina</em> L.</td>
<td>73.2</td>
<td>Greenwich, SR 7200, Vesper</td>
</tr>
<tr>
<td>Perennial Ryegrass <em>Lolium perenne</em> L.</td>
<td>292.8</td>
<td>Silverdollar, Express II, Zoom</td>
</tr>
<tr>
<td>Tall Fescue <em>Festuca arundinacea</em> Schreb.</td>
<td>292.8</td>
<td>Coronado TDR, SR 8650, Mustang 4</td>
</tr>
<tr>
<td>Slender Creeping Red Fescue <em>Festuca rubra</em> L. spp. <em>littoralis</em></td>
<td>195.1</td>
<td>Seabreeze GT, Shoreline</td>
</tr>
<tr>
<td>Chewings Fescue <em>Festuca rubra</em> L. ssp. <em>commutata</em></td>
<td>195.1</td>
<td>Treasure II, SR 5130, Windward</td>
</tr>
<tr>
<td>Strong Creeping Red Fescue <em>Festuca rubra</em> L. spp. <em>rubra</em></td>
<td>195.1</td>
<td>Shademaster III, Garnet</td>
</tr>
<tr>
<td>Annual Bluegrass <em>Poa annua</em> var. <em>reptans</em></td>
<td>Sod</td>
<td>Northwest Greens Type</td>
</tr>
</tbody>
</table>

Upon adequate germination all plots were mowed at 16 mm to encourage lateral growth and encourage stand density for approximately 75 days. Clippings were routinely removed during all mowing operations to discourage stand contamination. Once established (approximately 75 days) each block was randomly split into two different mowing heights (16 mm and 51 mm). These mowing heights are representative of a golf course fairway (16 mm) and a home lawn (51 mm). The plots maintained at 16 mm were mowed three times per week (M, W, and F) while plots maintained at 51 mm were mowed once per week (Tue). All plots were mowed in the morning with the same, striping, rear-roller drive rotary mower (Hayter 56 model,
Seago International). This mower was used for its rear-drive roller to evenly distribute the weight of the unit and the associated rapid height of cut adjustment.

In addition, the main plots were randomly split into two separate nitrogen fertility levels stripped across the mowing height treatments. The low nitrogen plots received 0 kg/ha additional nitrogen during the course the study and the high nitrogen plots received an initial application one week prior to treatment initiation consisting of 49 kg N/ha with a granular Andersons 30-0-0 Contec DG SGN 150 (2.31% Ammoniacal N, 3.52% Urea N, 16.76% WIN, and 7.43% WSN).

Irrigation was applied to keep a functioning turfgrass stand with recuperative potential without allowing the entire subplot to enter dormancy or turn brown. As indicated above, all plots were initially irrigated uniformly replacing 100% of ET with an automated irrigation system utilizing Rainbird 5000 series rotor heads until one week prior to the trial start date of 15 July 2009 and 15 July 2010. Twenty-four hours prior to the initiation of the trial all plots were irrigated with 2.54 cm to bring them all to field capacity and allowed to drain. Once the trial was initiated 15 July 2009 and 2010, the automated irrigation system was turned off.

Daily each individual subplot (0.91 m x 0.91 m area) was evaluated for soil moisture content in the morning (0900h) at a 3.8 cm depth using the Spectrum Field Scout TDR 300 Soil Moisture Meter (Spectrum Technologies, Inc., Plainfield, IL).

Keeley and Koski (1997) indicate up to 20 replicate samples were necessary to obtain an accurate estimate of VWC in a 305 m by 5 m plot containing a high clay-content soil. Therefore based off of their work, it was determined 0.0006639 moisture readings per plot would be acceptable for the 0.91 m by 0.91 m plots used thus one reading per plot was taken.

It should also be noted the original intent of the study was to use 7.6 cm and 20 cm soil moisture probes to adequately represent the active root zone of all species and treatments. However, only a few days into the trial in 2009 it was discovered the 20 cm tines would not hold up to the heavy soils. As the subsurface began to dry the tines began to bend easily and eventually broke completely. Within a few days of this, the 7.6 cm tines also began to bend and eventually broke. At a replacement cost of $50.00 per set of tines and the time required to recalibrate the instrument it was deemed unacceptable to continue with the 7.6 and 20 cm tine
lengths. Therefore it was determined to only utilize the 3.8 cm tines for the moisture meter measurements.

In addition to taking soil moisture readings, plots were evaluated daily during the hottest part of the day between 1200h and 1400h and assessed on overall functionality (playability) and rated on a numerical scale (0-2; 0 = no water stress, 1 = some water stress, 2 = water stressed with a need to irrigate). The rating scale took into consideration; % cover (density), % dormant turfgrass, % stressed (fired) turfgrass, and overall stand need for irrigation inputs. Immediately following visual inspections, evaluations were then made using Stress Detection Glasses. The Stress Detection Glasses utilize technology developed by NASA that filters overpowering light in the center of the visual spectrum so the fringe spectra becomes more apparent indicating early plant stress. Weekly digital images were also taken and evaluated using SigmaScan Pro™ software in an attempt to legitimize visual assessments over the concern of the subjectivity of the ratings. At this time all plots (images) were also visually rated utilizing a 1 to 9 visual rating scale based on turf quality, turfgrass density, and uniformity; where 1 equals dead turf; 9 equals ideal turf; and 5 equals minimally acceptable quality. Results of the various assessment methods to determine stress will be reported separately.

Once an individual subplot was rated a 2, irrigation was applied by hand at a rate of 7.62 mm through a Precision™ Rainbow low flow nozzle equipped to deliver 37-53 LPM attached to a flow and batch meter. This amount of water was used because the intent was to deliver enough water to allow for adequate recharging of the various root-zones without running off of the plots. The amount applied each time was the same but the amount of root-zone replacement varied from 41% replacement of a reference ET to 89% of a reference ET. Water use was correlated with the rating scale and based on volumetric water content (VWC) readings taken daily at 3.8 cm with the TDR soil moisture probe (data not shown). Each time irrigation inputs were applied to a respective subplot, data was recorded. Environmental conditions such as high and low daily temperatures, reference ET rates, and precipitation due to rainfall were monitored and recorded using a Campbell-Scientific on-site weather station located within 50 meters of the research site. In conjunction with this, general soil temperature data at the surface, 5 cm, 10 cm, and 15 cm depths was routinely monitored and recorded throughout the study using an adjacent onsite data logger located within 15 meters of
the trial site. The trial ran for the same 45 day period in 2009 and 2010 in an attempt to gather as much data as possible during an expected and naturally cyclic period of no precipitation.

**Results and Discussion**

Hutto et al. (2006) indicate soil moisture status is usually expressed on a percent basis by weight (gravimetric soil moisture content) or by volume (volumetric soil water content, VWC). VWC is defined as the volume of water within a given volume of soil and may also be expressed as the depth of water for a specific unit depth of soil (Hutto et al., 2006).

In 2009 all species under high mowing required irrigation at approximately 30 %VWC (Figure 4.1). The lower water users, both bunch and spreading types, including tall fescue, perennial ryegrass creeping bentgrass, Kentucky bluegrass and velvet bentgrass, also required water at 30% VWC at the lower mowing height in 2009. The higher water use group, including the fine fescues and annual bluegrass, required water when they dropped to 35 to 40% VWC under low mowing.

In 2010 the lower water use group under high mowing again required water between 25 to 30% VWC (Figure 4.2). All species under low mowing required irrigation at between 35 to 45% VWC. The plots were generally not as mature in 2010 as in 2009 due to a colder, wetter spring. However the mowing height was not changed until approximately 11 days before the start of the experiment so this major difference was not anticipated. The root systems of grasses are less likely to develop with high levels of water and perhaps all species had reduced root development due to the extensive rainfall before the start of the experiment. Under low mowing all species could not develop a more extensive root system under the conditions of the experiment, while the high mowing plots could continue to allocate more photosynthate to the root system during the experiment. Scheduling irrigation using VWC would be more difficult with newly established turfgrass mown at fairway height than at higher heights. Variability of establishment conditions seem to influence the root development and ability to extract water more at low mowing heights.

To monitor VWC at greater depths in high clay content soils with a portable meter more robust probes would need to be developed. Even with different potential rooting depths in 2009 the same water content was achieved in all species at the time irrigation was ruled
Figure 4.1 Volumetric water content at time of irrigation input for 2009 trial period.

Figure 4.2 Volumetric water content at time of irrigation input for 2010 trial period.
necessary. These results suggest that buried probes may be reliably used with automated systems shortly after full establishment is achieved in many turf species.

**Conclusion**

The findings demonstrate that although variation in the amount of water required between turfgrass species under the conditions of this study most species responded in a similar way to reductions in VWC after maturity. Clay soils are usually at field capacity at about 45% VWC and considered at wilt point at 22%. Probes measuring VWC could be utilized to schedule irrigation with a set point of 30% VWC for home lawns and sports field (high mow) and fairways (low mow) for the primary turfgrass species used in these situations including Kentucky bluegrass, creeping bentgrass and perennial ryegrass.

**References Cited**


CHAPTER 5

GENERAL CONCLUSION

With increased regulatory and environmental pressures mounting throughout the country regarding the utilization of non-saline or freshwater in conjunction with nitrogen, these findings will enable legislators and turfgrass managers alike to make more informed decisions. Without data for newly developed varieties of the commonly used cool-season turfgrasses it becomes increasingly more difficult for individuals to make informed decisions regarding functionality. With many unsubstantiated claims regarding water use of various turfgrasses, this data will help to substantiate what quantity of water inputs is actually necessary to keep these specific species alive and functioning indefinitely.

In addition, the findings from this data allows for informed decisions regarding necessary inputs and resources required to achieve a functioning and acceptable stand of turfgrass. Ultimately this research should allow end users to use as a measuring point from which they can base their decision making process regarding the most critical cultural inputs, water, nitrogen, and mowing.

Stress conditions could be detected one to two days before they were visible to the unaided eye with the stress detection glasses. The glasses can spot wilting caused by drought or broken sprinklers. They could be an important tool for turf managers to help in scheduling and utilization by inexperienced crew members for early detection of drought stress. The glasses were tested across a broad range of species and were effective with the different turf canopies and variation in color present in the different species.

Lastly, the findings demonstrate that although variation in the amount of water required between turfgrass species under the conditions of this study most species responded in a similar way to reductions in VWC after maturity. Clay soils are usually at field capacity at about 45% VWC and considered at wilt point at 22%. Probes measuring VWC could be utilized to schedule irrigation with a set point of 30% VWC for home lawns and sports field (high mow) and fairways (low mow) for the primary turfgrass species used in these situations including Kentucky bluegrass, creeping bentgrass and perennial ryegrass.


