WATER MANAGEMENT FOR SUSTAINABLE SAND-BASED CREEPING BENTGRASS PUTTING GREENS

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A THESIS

Submitted to
Michigan State University
In partial fulfillment of the requirements
For the degree of

MASTER OF SCIENCE

Crop and Soil Sciences

2012

ABSTRACT

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Irrigation scheduling is an essential component for developing best management practices for turfgrass. This study investigated the effects of three irrigation scheduling methods on water use, leachate quantity, and leachate quality for creeping bentgrass (*Agrostis stolinifera* L.) grown on a sand-based putting green. Data measured by this study include: irrigation volumes, irrigation frequency, leachate volumes, nitrate loading, phosphorus loading, rooting depth, root mass, putting green quality, percent green ground cover, localized dry spot incidence (LDS), and dollar spot occurrence. Annual irrigation volumes for 2010 show the 80% daily potential evapotranspiration (PET) treatment required the lowest volume (284.7 mm) while rooting depth adjusted irrigation (RDAI) and soil moisture dependent irrigation (TDR) required 340.7 mm and 421.9 mm, respectively. The TDR irrigation treatment resulted in the greatest annual leachate volumes in 2010 (397.9 mm) and 2011 (410.8 mm). In both 2010 and 2011 applying 80% daily PET resulted in the best quality putting green surface. The TDR and RDAI treatment had significantly ($p \leq 0.05$) more LDS than the 80% daily PET treatment from 10 Aug. – 18 Oct. 2010 while the TDR had significantly greater LDS incidence from 21 June – 5 Oct. 2011. Results show that more frequent irrigation applications at low volumes during dry months reduces irrigation and leachate volumes and the occurrence of LDS.

DEDICATED

To

My family, your support throughout the years made me who I am today.

ACKNOWLEDGEMENTS

I would like to thank Dr. Steinke for all the help and for teaching me how to be a turfgrass scientist. I would also like to thank Mark Collins and Frank Roggenbuck for giving me the opportunity to work at the Turfgrass Research Center. Without the learning experiences and your support over the years I would not have had the opportunity to pursue Turfgrass research.

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INTRODUCTION

Changes in water use legislation are occurring and affecting the availability and quality of water for turfgrass irrigation. California drought years in the mid-1970s resulted in the imposition of water restrictions. During this time turf managers realized that acceptable turfgrass quality could be maintained with reduced or even deficit irrigation (Doorenbos and Pruitt, 1984). Deficit irrigation has great potential in conserving water resources in temperate climate areas where rainfall occurs at fairly regular 10- to 14-day intervals since low irrigation volumes could be used to simply maintain minimum soil moisture levels between periodic rain events (Sass and Horgan, 2006). Human health and environmental quality concerns have caused many communities across North America to restrict the use of water moving towards more enviromentally sustainable turf areas (Cisar, 2004). It is necessary to come up with irrigation practices that conserve water and ultimately reduce the environmental impact of turf.

Environmental Stress:

Hot and dry climatic conditions make irrigation vital for plant health and survival. Drought suppresses growth and causes a loss of turf quality (White, 1996; Carrow and Duncan, 2003). Fu and Dernoeden (2009) found drought stress imposed by deep and infrequent irrigation led to a 16% reduction in root diameter compared with light and frequently irrigated creeping bentgrass. Allowing the soil volumetric moisture content to reach 4% significantly reduced lateral spread and caused a 70% reduction in root mass in three annual bluegrass (*Poa annua* L.) biotypes (Slavens et al., 2011). Huang et al. (1997) found that water stress not only affected root distribution and total root growth but also root viability. Persistent root growth of perennial grasses is a characteristic that greatly enhances the adaptation of a grass to semiarid and arid climates (Weaver and Zink, 1955). Huang and Gao (1998) reported that soil drying induced leakage of organic solutes from roots at different soil depths for all tall fescue (*Festuca arundinaceae*) cultivars, especially 'Rebel Jr.' and 'Bonsai'. The deleterious effects of combined drought and heat stress are associated with damage to cell membranes, photosynthesis, and antioxidant systems in perennial ryegrass and tall fescue (Jiang and Huang, 2001). Huang and Liu (2003) found that summer root decline in bentgrass occurred due to both the decreased production of new roots and the increasing death rate of older roots and that the decline could be associated with high soil temperatures. Optimum air temperatures range from 15 to 24°C for shoot growth and soil temperatures from 10 to 18°C for root growth for cool season grasses (Huang et al., 1998).

Deficit Irrigation:

DaCosta and Huang (2006) found creeping bentgrass irrigated at 80% of actual ET maintained acceptable quality throughout the summer in New Jersey. During the fall, acceptable turf quality was maintained at 40% actual ET replacement (Dacosta and Huang, 2006). Dacosta and Huang (2006) observed a significant decrease in creeping bentgrass quality when irrigated at 60 vs. 100% ET in the summer. Deficit irrigation may lead to decreased water use efficiency (WUE). In 2002, irrigating at 40% ET resulted in a 48% decline in WUE through August 2 (29-d of treatments) and an 82% decline by August 17 (47-d of treatments) compared with initial levels (DaCosta and Huang, 2006). During cooler parts of the year, irrigating on a deficit schedule may not affect soil water depletion patterns. In the fall treatment period of 2003, irrigating at 40, 60, or 80% ET caused no significant differences in soil water depletion among three species of bentgrass (DaCosta and Huang, 2006). This finding indicates a need for implementing different irrigation strategies based on the season, in order to conserve the maximum amount of water.

Plant water loss can be reduced under water deficit stress by leaf rolling or rapid stomatal closure and these mechanisms have been demonstrated in many grasses (Frank and Berdahl, 2001; Xu et al., 2006). There was as much as a 10-day delay in drought stress symptoms between different varieties of tall fescue (Karcher et al., 2008). This could have a significant impact on the supplemental irrigation requirements over an entire growing season, especially in humid regions, where periodic rain can significantly reduce or even eliminate the need for irrigation. In those cases, the delay of drought stress symptoms would delay the need for supplemental irrigation and provide additional chances for rainfall to occur.

Irrigation Frequency:

There is an ongoing debate within turfgrass culture whether light and frequent or deep and infrequent irrigation is best. Frequent irrigation of putting greens to prevent water stress has been shown to produce shallow rooted turf with reduced tolerance to environmental stress. Different irrigation timings and volumes affect turfgrass disease, growth, root production, and health (Jordan et al., 2003). Jordan et al. (2003) found that irrigating on a 4-day frequency as opposed to every day or every other day significantly increased shoot density and root length density of creeping bentgrass grown on a sand-based root-zone. Jordan et al. (2003) also recognized that overall turfgrass quality was identical when irrigating at these frequencies in Texas. Even with thicker fuller turf, visual quality ratings showed no differences due to varying irrigation frequencies. Irrigating every day was found to contribute to high soil temperatures and low soil aeration (Jordan et al., 2003). Irrigating less frequently could result in greater root uptake of water and increased drainage of excess irrigation water, which would have improved soil aeration and stimulated root growth (Jordan et al., 2003). Qian et al. (1997) proposed that plants irrigated less frequently produce larger root systems, ultimately resulting in higher turf quality. Fu and Dernoeden's (2009) findings show that creeping bentgrass grown in a sand-based rootzone and irrigated at visual signs of wilt stress produced a larger root system than light and frequently irrigated bentgrass. Fu and Dernoeden (2009) also found that light-frequent irrigated creeping bentgrass plots used twice the volume of water as the deep-infrequent plots both years of their study between 22 May and 31 August. The thatch mat layer was also thicker for the light-frequent irrigation treatment as compared to deep-infrequent irrigation (Fu and Dernoeden, 2009).

Frequent or excessive irrigation not only increases costs associated with water consumption, but can reduce environmental stress tolerance and predispose turf to injury from mechanical stresses, cyanobacteria, moss, and diseases (Beard, 1973; Dernoeden, 2002; Turgeon, 2008). Deep and infrequent irrigation at the time turf shows wilt is generally recommended in summer for cool-season grasses (Beard, 1973; Fry and Huang, 2004). Turfgrasses subjected to deficit irrigation can develop larger root systems and store more carbohydrates than well-watered plants (Jordan et al., 2003; Fry and Huang, 2004; Dacosta and Huang, 2006; Fu and Dernoeden, 2009). Jordan et al. (2005) stated that a reduction in irrigation frequency preconditions the plant to adapt to lower water potentials increasing the overall stress tolerance. Lateral spread of annual bluegrass increased 50% and inflorescence decreased 25% when irrigation frequency was reduced (Slavens et al., 2011). Biran et al. (1981) found that irrigating at the onset of temporary wilting decreased water consumption and overall growth by up to 35% in most grasses.

A decrease of the irrigation frequency causes an increase of the water stored in the root zone. A decrease of the water content in the immediate vicinity of the soil surface leads to reduced evaporation. Infrequent irrigation causes drainage to increase somewhat but remains low enough not to seriously threaten ground water quality (Mermoud et al., 2005). High soil moisture levels caused by prolonged periods of rainfall or irrigation can be responsible for large runoff and nutrient losses even on established dense turfgrass (Linde et al., 1995). Morvant, et al. (1998) found that although the amount of water applied in a daily-irrigated treatment was greater than in intermittently-irrigated treatment, the amount of leachate was greatly reduced by daily irrigation.

Sass and Horgan (2006) found that daily irrigation results in a large proportion of water ending up in the upper 5 cm of the soil. Water in this range is more subject to high rates of evaporation and thus is less useful to the grass. They also found that irrigating with low volumes of water limits the depth of infiltration and that a large volume of water never makes it past the thatch layer. Huang and Liu (2003) found that during the summer months creeping bentgrass roots are mainly in the upper 10 cm of the soil profile. Irrigating past this depth in the soil is also a way to waste water because it is unavailable to the plant.

Sensor-Based Irrigation Scheduling:

A common method used for direct measurement of soil VWC is time domain reflectometry (TDR), which utilizes electromagnetic wave pulses from metal probes transmitted through the soil (Walker et al., 2004). TDR accurately estimated soil water in hybrid bermudagrass irrigated every 6 days (Young et al., 1997). Irrigation can be effectively scheduled with soil moisture data by replacing the amount of water lost over a given amount of time. This could lead to more efficient use of irrigation and ultimately water savings. Fares and Alva (2000) demonstrated that capacitance sensors could be used to schedule irrigation of citrus trees in Florida by establishing set points in context with plant available soil water content using data collected from sensors.

Li et al. (2004) found that soil water content does not accurately reflect the amount of plant available water under partial irrigation at variable dosages. Also, only when the water was depleted from the last irrigation event was the turfgrass canopy conductance decreased (Li et al., 2004). Set moisture contents for timing irrigation is only possible when equal amounts of irrigation are applied in each run (Li et al., 2004). Finally, precise estimations of soil water depletion were found to be better than measuring soil water directly (Li et al., 2004).

Sand-Based Root-Zones:

The USGA specifications for putting green construction have existed since 1960. The latest specifications came about in 2004 and call for a predominately sand-based root zone. Sand-based putting greens have low moisture and nutrient holding capacities requiring special management strategies. A low moisture holding capacity requires careful water management to mitigate leaching of nutrients and irrigation water.

Research by Johnson et al. (2009) on sand root-zones showed that seashore paspalum lowers its transpiration rate when the soils fraction of transpirable water reached 0.10 to 0.17. Transpiration of seashore paspalum grown on organic topsoil diminished when the fraction of transpirable water reached between 0.25 and 0.31 (Johnson et al., 2009). Capillary barrier soil profiles contain coarse-textured sand or gravel underlying a finer-textured surface layer for the purpose of inhibiting downward water flow and increasing the water storage capacity of the finer-textured layer (Miller, 1973). Due to the capillary barrier, McCoy (2009) found that turfgrass water use during dry down periods occurs equally at all root-zone depths on USGA putting greens. This occurs due to the turfgrass using water at shallower depths during the day there by creating a moisture gradient, which at night pulls water from deeper depths and replenishes water in the upper soil layers (McCoy, 2009). USGA greens are also constructed to have high hydraulic conductivities, which aid them in using a perched water table to moderate moisture patterns (McCoy, 2009).

Nutrient Loading:

The hydrology of a soil may exert a strong effect on P transfer through subsurface pathways. At a simple level, the amount of rainfall will determine the P export from a soil of a given P status. Baker et al. (1975) found that P export varied considerably from year to year depending on the rainfall and, therefore, the amount of runoff. In addition, the response of the soil to rainfall can determine the P transferred, especially by the extent of preferential flow through the soil (Sims et al., 1998). Jensen et al. (1998) discovered that orthophosphate transfer only occurred through wide-aperture macropores in structured soils, despite water flow not being restricted to the same macropores. An increased soil moisture content enhances P solution reactions and improves the migration capability of phosphorus, especially on sand (Meissner et al., 1995).

Nitrate leached from putting greens has the potential to impair water quality on golf courses (Petrovic, 1990). Nitrate leaching through sand-based golf greens, which have a low capacity to retain nutrients and water, can be of particular concern (Brown et al., 1982). Studies have found that nitrate leaches faster through immature turf than mature stands due to very small root systems and little thatch accumulation. Rooting medium also affected the amount of nitrate that leached through the profile. Pure sands leached the most and profiles of sand amended with 10% organic matter and soil leached far less (Brauen and Stahnke, 1995). Pare et al. (2006) found that nitrate N accounted for >99% of the total mineral N found in leachates from simulated USGA greens. Bowman et al. (1998) found that delaying irrigation could reduce leaching. Lysimeters watered 1, 3, and 5 days after initial fertilizer application had different amounts of nitrate leach from their profiles.

Localized Dry Spot:

Environmental consequences of localized dry spot include decreased infiltration of irrigation water and precipitation, non-uniform wetting of soil profiles, increased run-off and evaporation, and increased leaching due to preferential flow (Dekker et al., 2001a). The development of water repellent soils is associated with organic matter coating soil particles while inducing hydrophobic properties on their surface area (Ma'shum and Farmer, 1985; Horne and McIntosh, 2000). Soil hydrophobicity can also be impacted by soil wetting and drying cycles (Dekker et al., 2001). Dekker et al. (2001b) found that soils have a critical soil water content; a volumetric water content below the critical level causes a soil to become non-wettable in the field. Soil water repellency reduces actual plant available water (PAW) because it "locks out" part of the soil's water holding potential. In severe cases soil water repellency can render soils non-usable for crop production as the soil is unable to accept or hold water necessary for plant growth (Hallett et al., 2001). In less severe cases, because water is not available in parts of the root zone, it can cause reduced plant performance (Cisar et al., 2001; Leinauer et al., 2007). It has been observed that even after extended wet periods, soil water repellency and preferential flow paths recur (Oostindie et al., 2005).

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Chapter 1

WATER MANAGEMENT FOR SUSTAINABLE SAND-BASED CREEPING BENTGRASS PUTTING GREENS

ABSTRACT

Irrigation scheduling is an essential component for developing best management practices for turfgrass. This study investigated the effects of three irrigation scheduling methods on water use, leachate quantity, and leachate quality for creeping bentgrass (*Agrostis stolinifera* L.) grown on a sand-based putting green. Data measured by this study include: irrigation volumes, irrigation frequency, leachate volumes, nitrate loading, phosphorus loading, rooting depth, and root mass. Annual irrigation volumes for 2010 show the 80% daily potential evapotranspiration (PET) treatment required the lowest volume (284.7 mm) while rooting depth adjusted irrigation (RDAI) and soil moisture dependent irrigation (TDR) required 340.7 mm and 421.9 mm, respectively. The TDR irrigation treatment resulted in the greatest annual leachate volumes in 2010 (397.9 mm) and 2011 (410.8 mm). The TDR irrigation treatment resulted in the greatest annual nitrate loading in 2011 (1.36 kg NO_3^- ha^{-1}) compared to the RDAI (0.32 kg NO_3^- ha^{-1}) and 80% daily PET (0.11 kg NO_3^- ha^{-1}) treatments. Annual phosphorus loading totals were significant ($p \leq 0.05$) in 2010 and 2011 with the TDR (0.091, 0.100 kg NO_3^- ha^{-1}) treatment resulting in three times more P loading than the 80% daily PET (0.017, 0.036 kg NO_3^- ha^{-1}) and RDAI (0.032, 0.032 kg NO_3^- ha^{-1}) treatments. Data show that reduced irrigation volumes along with more frequent applications during dry months minimizes the environmental impact of turfgrass by conserving water and reducing nutrient losses. However, utilizing a deep and

infrequent irrigation method would save water during months that receive regular precipitation by allowing precipitation to supply moisture rather than irrigation. Deep and infrequent irrigation results in an extended interval allowing for a greater chance to receive precipitation between irrigation applications.

INTRODUCTION

Increased water consumption accompanied by declining water quality throughout the world has increased interest in water conservation methods but implementation remains difficult due to a lack of defined management practices. Although putting greens represent merely 3% of total maintained turf area on golf courses in the United States, these areas represent the most input-intensive component of turfgrass environments (Lyman et al., 2007). As water resources become limited, turfgrass managers may need to rely on irrigation scheduling methods that simultaneously conserve water and reduce non-point source pollution.

Drought conditions during the mid-1970's resulted in the imposition of water restrictions and the realization that acceptable turfgrass quality could be maintained with reduced or deficit irrigation (Doorenbos and Pruitt, 1984). Human health and environmental quality concerns have also prompted North American communities to initiate water restrictions, a move aimed at decreasing water consumption and encouraging sustainable turf management (Cisar, 2004). It is not known what effects conservation-based irrigation strategies will have on the overall environmental impact of turfgrass management as few data are available detailing the impact of these strategies on water usage, water quality, or turfgrass response.

Irrigation philosophy (i.e. light and frequent or deep and infrequent) is a debate deeply engrained within turfgrass culture. Irrigation frequency has been shown to impact rooting depth, disease incidence, algae formation, and thatch production (Kackley et al., 1990; Davis and Dernoeden, 1991). Jordan et al. (2003) found five creeping bentgrass cultivars ('A-4', 'Crenshaw', 'Mariner', 'L-93', 'Penncross') irrigated every 4 d had improved quality, shoot density, and rooting depth compared to creeping bentgrass watered every 1-2 d. Jordan et al.

(2005) proposed that a reduction in irrigation frequency preconditions plants to adapt to lower water potentials, increasing their overall stress tolerance. Fu and Dernoeden (2009a) found light and frequently irrigated ‘Providence’ creeping bentgrass used twice the volume of water as deep and infrequently irrigated ‘Providence’ creeping bentgrass between 22 May and 31 Aug over two years of study. However, researchers also discovered that applying water daily to moisten the top 4 to 6 cm of root-zone resulted in excellent summer color and quality of ‘Providence’ creeping bentgrass (Fu and Dernoeden, 2009a).

Researchers have found that deep, infrequent irrigation can negatively impact the environment. Huang and Liu (2003) discovered that from July through Sept., the majority of creeping bentgrass root biomass was growing in the upper 10 cm of soil. Irrigating below the 10 cm root zone depth resulted in additional water losses to deep infiltration (Huang and Liu, 2003). Gerst and Wendt (1983) found that infrequent irrigation at high rates leached water past the root-zone of bermudagrass (Cynodon dactylon L.) and increased shoot growth rates. Irrigation in excess of evapotranspiration increased nitrate and phosphorus leaching in sand-based putting greens (Shuman, 2001). To further water conservation efforts, irrigation scheduling methods may need to consider plant rooting depth and soil physical properties (Stewart, 2004).

As water supplies decline, deficit irrigation may become more frequently practiced (Fereres and Soriano, 2007). Turfgrass subjected to deficit irrigation can develop larger rooting systems and increase carbohydrate reserves compared to well-watered plants (Jordan et al., 2003; Fu et al., 2004; Dacosta and Huang, 2006; Fu and Dernoeden 2008; Fu and Dernoeden, 2009b). Dacosta and Huang (2006) found that irrigating at 60% or 80% evapotranspiration (ET) did not significantly alter colonial (*Agrostis capillaris* L.), creeping, or velvet (*Agrostis canina* L.) bentgrass water use efficiency when compared to 100% ET replacement. Researchers also found that creeping bentgrass irrigated at 80% ET maintained acceptable quality throughout the summer but acceptable quality was maintained at 40% ET in the autumn. Frequency is also important when applying deficit irrigation. When irrigated at 50% ET, tall fescue (*Festuca arundinacea* Schreb.) turfgrass quality was improved with shorter irrigation intervals (2d) as compared to longer intervals (4,7, or 14 d) (Fry and Butler, 1989).

Alternative irrigation scheduling methods need to be assessed for their environmental impacts as improvements in water conservation could be offset by changes in non-point source pollution. Scheduling methods that maintain or improve turf quality may be deleterious to the environment. Numerous studies have documented the effects of irrigation volumes and frequencies on turf (Qian et al., 1997; Jordan et al., 2003; Fu and Dernoeden, 2009a, b). However, few turfgrass studies have examined the fate of water and nutrients applied to creeping bentgrass grown on sand-based putting greens under various irrigation scheduling regimes. Sand-based putting greens have high infiltration rates and inherently low water- and nutrient-holding capacities (Johnson et al., 2003). Data are lacking concerning the effects of irrigation scheduling methods on water use and nutrient fate on low-input sand-based putting greens in Michigan. The objective of the study was to compare three irrigation scheduling methods for their effects on water usage, leachate quantity, leachate quality, and rooting characteristics.

MATERIALS AND METHODS

A two-year field study was conducted between Jun. 2010 and Oct. 2011 at the Hancock Turfgrass Research Center in East Lansing, MI. ‘A-4’ creeping bentgrass was seeded into nine 11 m x 11 m plots on a sand-based putting green in Aug. 2008. Main plots were divided into three subplots with lysimeters installed in each subplot to quantify percolate volumes and nutrient losses. The particle size distribution of the 30.5 cm sand root zone and the 10.2 cm gravel layer both conformed to USGA specifications (USGA, 1993) (Table 1).

Three irrigation treatments were tested in this field investigation. The first irrigation treatment was defined as 80% replacement of potential evapotranspiration. Reference potential evapotranspiration data were collected from the Michigan Automated Weather Network website (http://www.agweather.geo.msu.edu/mawn), which provided data from a weather station located 5 m from the putting green. The PET estimation is a reference potential evapotranspiration and was based on the FAO Penman-Monteith Equation (Allen et al., 1998). Irrigation to replace the 80% PET occurred at 4 A.M the following morning. When precipitation exceeded 12.7 mm, irrigation was withheld for the next two days. The two-day interval with no irrigation was implemented due to daily PET rarely exceeding 7.6 mm in Michigan and 80% replacement of 7.6 mm over two days would be accounted for by 12.7 mm of precipitation.

Table 1. Particle size distribution for sand used to construct USGA specification putting green.

	mm									
Particle Size	>2.0	1.0-2.0	0.7-1.0	0.5-0.7	0.25-0.5	0.18-0.25	0.1-0.18	0.05-0.1	silt	clay
	--------------------%--------------------									
Distribution	0.1	9.8	10.7	16.5	39.2	14.4	6.5	0.5	1.6	0.7

The second irrigation treatment was referred to as rooting-depth adjusted irrigation (RDAI) and was dependent upon soil physical properties and rooting depth. The aim of this irrigation treatment was to maintain the root zone volumetric water content (VWC) between field capacity and one-half of the plant available water. The amended sand-based root zone used in this study was determined to have a 20% VWC at field capacity and a permanent wilting point (PWP) of 5% VWC. Field capacity was determined by placing a total of nine saturated soil cores in pressure plate extractors set at 0.1 atmospheres of pressure and allowed to equilibrate to account for the high sand content (Klute, 1986). The PWP was determined by allowing the turf to wilt and using a time domain reflectometry (TDR) probe (Field Scout TDR 300 Soil Moisture Meter, Spectrum Technologies, East Plainfield, IL) to measure the VWC at that point. A total of six areas were probed and averaged to estimate PWP. Water lost from the root-zone was based on reference PET. Rooting depth was measured by taking a core from each plot with a 10.2 x 2.5 x 17.8 cm soil profiler (Miltona Turf Products, N Maple Grove, MN) and gently shaking the core to remove excess sand from the roots. The core was placed on the coring device and measured from the soil surface to include approximately 80% of the available root mass.

The third irrigation treatment (TDR) consisted of using a TDR soil moisture probe to determine VWC. Irrigation was applied when soil moisture dropped to ≤ 10% VWC. Irrigation was then applied to bring the top 7.6 cm of root zone to 20% VWC.

Irrigation treatments were applied to each of the 9 main plots using four Toro TR-50 sprinkler heads (The Toro Company, Riverside, CA) positioned on the plot corners. Each sprinkler applied 7.6 liters per minute (LPM) for a total of 30.4 LPM during each irrigation event. Rain gauges used during irrigation system audits confirmed the rate of 0.254 cm/10 min of irrigation.

Lysimeters were installed Aug. 2008 into the 27 subplots on the sand-based putting green. The lysimeters were constructed from Rubbermaid® 265 liter stock water tanks (Rubbermaid Commercial Products LLC, Winchester, VA). Two 22.7 kg bags of Quikrete® were poured into the bottom of the Rubbermaid® tanks at a slight angle to allow water to flow towards the drain plug and prevent water stagnation at the bottom of the lysimeters. Lysimeters were plumbed with 3.8 cm schedule 40 PVC threaded couplings (Spears Manufacturing, Bolingbrook, IL) connected to 3.8 cm schedule 40 PVC pipe (Harvel, Easton, PA) and positioned to drain at a 2% slope towards the north end of the green into 18 individual catch basins. Catch basins consisted of two 265 L stock water tanks stacked on top of one another and bolted together at the rims. The top tank was then cut off at 20.3 cm from bottom and a lid was attached to the basin to prevent precipitation from entering. The basins were buried in the ground leaving 20.3 cm of tank above ground. The 3.8 cm drainage pipes ran into the basins and were fitted with 3.2 cm sump pump hose to ensure flow into 19 liter collection buckets located inside the basins.

Plots were mowed five times weekly during the growing season at a height of 3.2 mm using a Toro Greensmaster 3150-Q triplex greens mower (The Toro Company, Riverside, CA), with clippings removed. Sand topdressing was applied at a rate of 0.25 cm every other week throughout the growing season. Sand was brushed into the green and irrigation applied for a 5 min period to move sand into the thatch layer. The putting green was aerified on 15 Oct. 2010 with a Toro ProCore 648 with 0.95 cm diameter hollow tines at 5 cm spacing. Sand was top-dressed onto the green and brushed into the aerification holes.

Total fertilizer for each of the two growing seasons was 145.6 kg N ha^{-1} $year^{-1}$, 6.1 kg P_2O_5 ha^{-1}, and 94.8 kg K_2O ha^{-1}. Plots were fertilized with 24 kg N ha^{-1} on 19 May, 6 Oct., 12 kg N ha^{-1} on 9 Sept. and 21 Sept., and 37 kg N ha^{-1} on 1 Nov. 2010 using a 19-0-15 (N-P-K) granular fertilizer (2.37% urea, 9.74% WSN, 6.89% WIN, K as K_2O, 15% potassium sulfate, 2.0% K-mag, 7.7% S, 0.05% Cu, 1.05% Fe, 0.05% Mn, 0.05% Zn, Andersons Golf Products, Maumee, OH). In 2011, plots were fertilized with 24 kg N ha^{-1} on 16 May, 14 Sept., 14 Oct., and 37 kg N ha^{-1} on 1 Nov. 2011. Nitrogen was applied as a foliar spray on 24 Jun., 30 Jun., 12 July, 26 July, 10 Aug., 25 Aug. 2010 and 6 Jun., 22 Jun., 6 July, 20 July, 8 Aug., and 22 Aug. 2011 using an 18-3-4 (N-P-K) liquid fertilizer (2.0% amoniacal nitrogen, 1.5% nitrate nitrogen, 14.5% urea nitrogen, 3.0% available phosphoric acid, 4.0% soluble potash, 0.12% chelated copper, 1.0% chelated iron, 0.1% chelated manganese, 0.1% chelated zinc, Grigg Brothers, Albion, ID) at a rate of 6.1 kg N ha^{-1}. Granular treatments were applied and irrigated with 1.3 mm water to avoid fertilizer burn.

Fungicides were applied curatively to avoid turf loss. Chlorothalonil [1,3-benzenedicarbonitrile,2,4,5,6-tetrachloroisophthalonitrile] (54.7 kg ha^{-1}) was applied on 15 July 2010 and (47.34 kg ha^{-1}) on 27 July, 10 Aug, and 22 Sept 2010. Chlorothalonil [1,3-benzenedicarbonitrile,2,4,5,6-tetrachloro-isophthalonitrile] was applied (54.74 kg ha^{-1}) on 20 July, 8 Aug, and 22 Aug in 2011. Boscalid (BASF) [3-pyridinecarboxamide, 2-chloro-N-(4'-

chloro(1,1'-biphenyl-2-yl)] was applied (0.55 kg ha^{-1}) on 13 Aug 2011 to control dollar spot (*Sclerotinia homeocarpa* F.T Bennet).

Irrigation volumes were measured and determined by an irrigation audit consisting of 6 rain gauges placed within each main plot and running irrigation for 20 min. Irrigation volumes collected during 20 min. were averaged between the six rain gauges. The average volume was then divided in half to determine the irrigation application rate per 10 min. The irrigation system was determined to applied 2.54 mm water per 10 minute interval.

Leachate volumes were measured and subsamples analyzed for total dissolved N and orthophosphate. Lysimeters were emptied after every precipitation or irrigation event that generated leachate. A sub-sample of leachate was collected from each of the three subplots in 125 ml Nalgene® bottles and mixed to create a representative sample for each of the 9 main plots. Leachate was analyzed at the Michigan State University Soil Testing Laboratory (East Lansing, MI). Soluble phosphorus was measured according to EPA-600/R-93/100, Method 365.1 (USEPA, 1993). Nitrate-nitrogen was measured by soil nitrate analysis by cadmium reduction (Huffman and Barbarick, 1981). The volume of leachate collected from each subplot multiplied by the nutrient concentration data from each sample were used to calculate total nutrient load for the season.

Root length was determined by removing one soil core per sub-plot measuring 10.2 cm x 2.5 cm x 17.8 cm (Miltona Turf Products, N Maple Grove, MN). The soil core was removed and shaken for 15 s over a plastic bucket to remove loose sand from root tissue. The sand-free root sample was placed back onto the soil profiler with roots fully extended. Root length was measured to the point where approximately 80% of the total root mass extended. This rooting depth was also used for calculating irrigation quantities in the RDAI treatment.

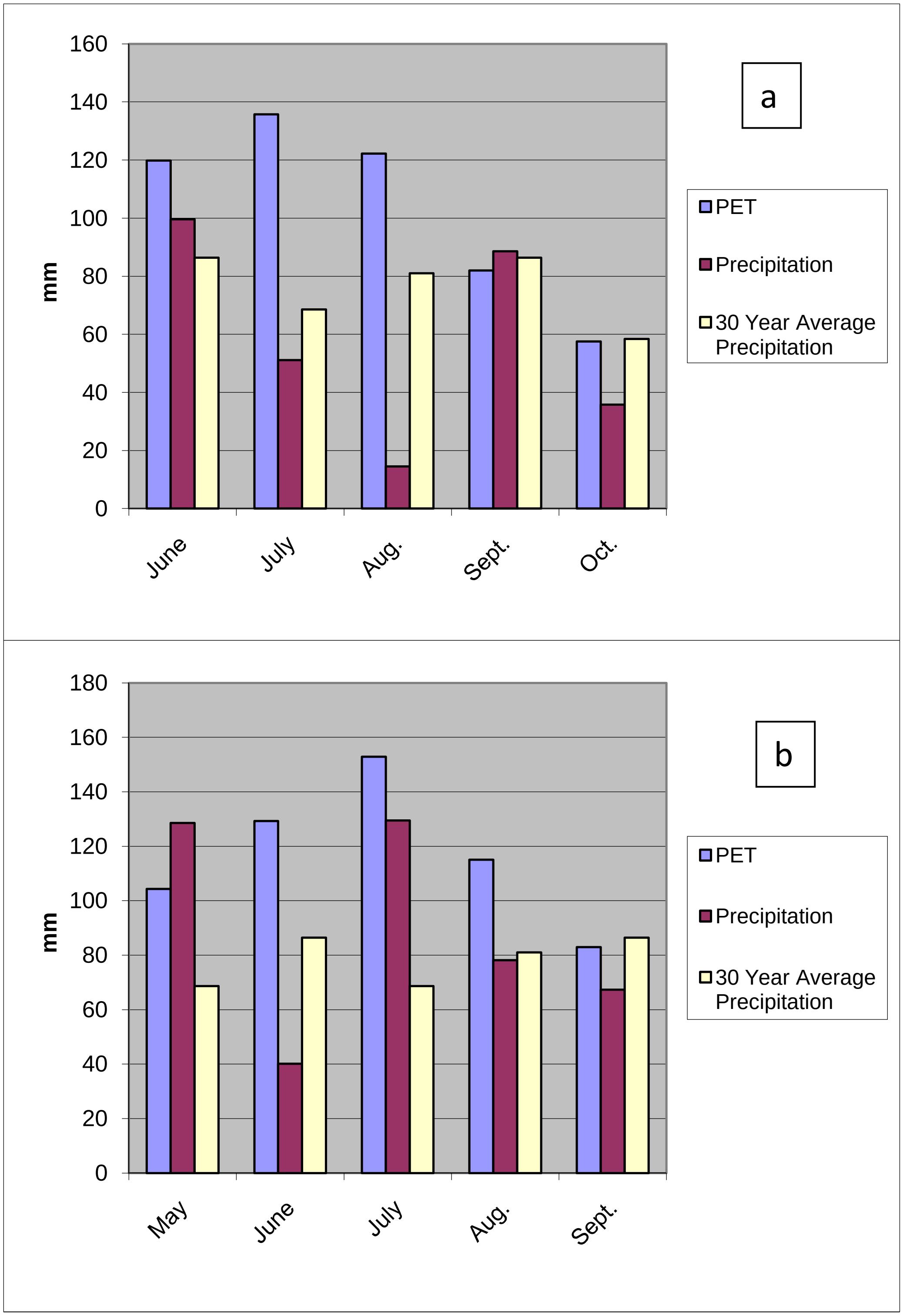
The experiment was a completely randomized design with 3 subplots within each of 9 main blocks to add power during statistical analysis. All data were subjected to analysis of variance using the SAS 9.2 (SAS institute Inc., Cary, NC) mixed model procedure. Mean differences were separated using Fisher's Least Significant Difference.

RESULTS AND DISCUSSION

Environmental Data

Differing climatic conditions between each year of the two-year study provided an opportunity to examine three irrigation scheduling methods during different weather patterns (Fig. 1). Months were classified as wet or dry depending precipitation relative to the 30-yr mean precipitation for that month in East Lansing, MI. The 30-yr mean May through Oct. precipitation for East Lansing, MI was (69, 86, 69, 81, 86, and 58 mm) for each of these months, respectively. In 2010, June and Sept. precipitation exceeded the 30-yr monthly means, classifying these months as wet. The July and Aug. 2010 precipitation totals were below 30-yr monthly means by 18 and 66.5 mm, respectively, thus classifying these months as dry. Oct. 2010 received 35.8 mm of precipitation which was below the 30-yr monthly mean classifying Oct. as a dry month. In May 2011 (wet month), plots received twice the 30-yr monthly mean precipitation, replacing more moisture than lost to PET. June 2011 (dry month) received 40.1 mm of precipitation which was below the 30-yr monthly mean of 86 mm. July 2011 received 10.4 mm of precipitation for the first 26 days (dry month) but received 114.6 mm of precipitation in the final four days resulting in above average precipitation for the month. August 2011 (dry month) received 78.2 mm of precipitation which was slightly less than the 30-yr monthly mean but was not sufficient to account for PET. Sept/Oct 2011 weather data were combined due to the experiment ending 5 October. Sept. through 5 Oct. 2011 was classified as dry due to receiving 67.3 mm of precipitation, which was below the 30-yr monthly mean. Spring-time conditions over both years were considered wet due to precipitation exceeding 30-yr monthly means. During each summer, plots experienced at least two consecutive months of dry weather, July/Aug. 2010 and June/July 2011. Autumn of 2010 was classified as wet in Sept. and dry in Oct. and autumn of 2011 was classified as dry.

Fig. 1. Potential evapotranspiration (PET), precipitation, and the 30-year monthly mean precipitation for East Lansing, MI, 2010a, 2011b. For interpretation of the references to color in this and all other figures, the reader is referred to the electronic version of this thesis.



Irrigation Volumes

Irrigation volume data show significant ($p \leq 0.05$) differences 9 out of 10 months, and for the 2010 annual total volumes (Table 2). Irrigation treatments differed in June 2010 where the TDR treatment required the least water (31.2 mm) followed by the 80% daily ET (49.0 mm) and the RDAI (67.3 mm). July through Sept. 2010 irrigation volumes resulted in TDR > RDAI > 80% daily PET (Table 2). The RDAI irrigation treatment utilized the least amount of water in Oct. 2010. Total annual irrigation volumes for 2010 were significantly different ($p \leq 0.05$) with the TDR treatment using 421.9 mm of irrigation, followed by the RDAI and 80% daily PET treatments with 340.7 and 284.7 mm, respectively. For 2011, the TDR irrigation treatment required the lowest irrigation volume during May, but June and July data show the 80% daily PET irrigation treatment required less water than the RDAI and TDR. Sept/Oct 2011 irrigation volume data show the RDAI and TDR treatments required the least amount of water. No treatment differences were observed for the total annual irrigation volumes for 2011.

Irrigation volumes over both years resulted in two trends depending on whether the month was relatively wet or dry and if PET values were high or low. June 2010 and May 2011 resulted in the TDR irrigation treatment using the least water and the 80% daily PET using less than the RDAI. When irrigation treatments were initiated each year, soil moisture was high, PET was low, and plots received timely precipitation. These climatic conditions resulted in the TDR treatment requiring one and two irrigation cycles for June 2010 and May 2011, respectively (Table 4). The 80% daily PET treatment required irrigation following any day that PET losses exceeded precipitation, leading to irrigation applications to relatively wet soils. RDAI volumes were dependent on rooting depth and PET losses. When timely precipitation was not received and rooting depth was shallow, 100% PET was applied more frequently leading to greater irrigation volumes than the TDR. This finding was in line with Fu and Dernoeden (2009b) that found light frequently irrigated creeping bentgrass plots used twice the volume of water as deep, infrequently irrigated plots.

Irrigation volume data from July to Oct. 2010 and June to July 2011, show that the TDR irrigation treatment required more water than either the 80% daily PET or RDAI. Both of these periods were characterized as dry with high PET losses requiring supplemental irrigation for plant health and survival. Over 70% of soil moisture fluctuation occurs in the top 4 cm of soil (Sass and Horgan, 2006). The TDR treatment scheduled deep irrigation when the top 7.6 cm of soil dried out. This portion of soil dries out faster than the lower soil profile due to a greater root density (Carrow, 1996). Relying on soil moisture in the top 7.6 cm to schedule deep-infrequent irrigation may have resulted in greater irrigation volumes and frequencies than the plant required. Precise estimations of soil water depletion were found to be better than measuring soil water directly (Li et al., 2004). The RDAI irrigation treatment took rooting depth as well as PET data into account when scheduling irrigation, thus avoiding over application. The 80% daily ET treatment required the least water due to lower application volumes than PET predicted and did not depend on precipitation to realize water savings. July-Sept. 2010 and June-July 2011 data show the 80% daily PET treatment used approximately 80% of the irrigation that the RDAI utilized, resulting in significantly ($p \leq 0.05$) lower irrigation volumes.

The RDAI treatment conserved more water than the 80% daily PET treatment in Oct. 2010 due to low PET and timely rainfall. Low PET in Oct. 2010 extended the irrigation interval for the RDAI treatment resulting in increased opportunities to receive precipitation. Sept/Oct 2011 irrigation volume data show the TDR used the least water, while the 80% daily PET used the greatest volume. Despite ample precipitation, the 80% daily PET treatment was irrigated 20 times while the RDAI and TDR treatments were irrigated two and one times, respectively (Table 4). During months that received precipitation on a regular basis, the 80% daily PET treatment applied water unnecessarily between precipitation events.

Annual irrigation volumes for 2010 were greatest for the TDR treatment primarily due to over estimating the amount of irrigation to apply and applying too frequently during the summer months. The TDR treatment also used more water due to irrigation being scheduled prior to natural rainfall events. If the soil reached 10% VWC during the day, irrigation was scheduled for the following morning regardless of the weather forecast, which sometimes resulted in irrigation being applied at night within proximity of precipitation events. The RDAI treatment ranked second for 2010 annual irrigation volumes primarily due to applying 100% PET when water savings were not realized during periods with minimal precipitation, where as the 80% daily PET treatment saved water by applying 80% PET. Annual irrigation volumes for 2011 were not significant due to the TDR treatment using the least irrigation during the spring and autumn, while the 80% daily PET treatment used the least irrigation during dry periods. The RDAI treatment was intermediate in water use during most months. Alternating scheduling methods has the potential to result in greater water savings than utilizing one scheduling method over the course of a year.

Table 2. Total water volume applied to creeping bentgrass putting greens under three irrigation methods, 2010-11, East Lansing, MI.

	2010					
Irrigation Method	June	July	Aug.	Sept.	Oct.	Yearly Total
	---------------------------mm---------------------------					
80 % daily PET†	49.0	86.6	90.4	36.1	22.6	284.7
RDAI‡	67.3	100.1	110.8	47.1	15.4	340.7
TDR¶	31.2	150.7	142.2	71.1	26.7	421.9
LSD (0.05)	8.4	4.0	28.0	10.3	2.2	23.3

	2011					
Irrigation Method	May	June	July	Aug.	Sep/Oct	Yearly Total
	---------------------------mm---------------------------					
80% daily PET†	34.8	86.1	97.5	50.3	44.5	313.2
RDAI‡	44.7	111.8	117.6	50.2	27.8	352.1
TDR¶	34.3	122.6	105.0	57.2	17.8	336.8
LSD (0.05)	0.02	19.7	15.7	NS	11.1	NS

† 80% daily potential evapotranspiration
‡ Rooting depth adjusted irrigation
¶ Time domain reflectometry based deep and infrequent irrigation

Leachate Volumes

Leachate volume data show significant ($p \leq 0.05$) differences four of five months in 2010, three of five months in 2011, and for both 2010 and 2011 annual total volumes (Table 3). June 2010 leachate volume data show the TDR irrigation treatment produced less leachate than the 80% daily PET and RDAI treatments. July through Sept. 2010 leachate volume data resulted in TDR > RDAI ≥ 80% daily PET. Total annual leachate volumes for 2010 showed the same trend as July-Sept. with the TDR treatment producing more leachate than the RDAI and 80% daily ET treatments. June through Aug. 2011 leachate volume data show a trend of TDR > RDAI ≥ 80% daily PET, which was similar to the dry months of 2010. Total 2011 annual leachate volume data resulted in the TDR irrigation treatment producing the most leachate (411 mm) and the 80% daily PET and RDAI being similar, producing 249 and 223 mm, respectively (Table 3).

Leachate volume data followed a pattern where dry months resulted in significance ($p \leq 0.05$) and wet months or months with low PET did not. June and Oct. 2010 and May, Aug., and Sept/Oct. 2011 were relatively wet months where irrigation was rarely required. When precipitation was the primary source of moisture and irrigation volumes were similar among plots, leachate volumes were similar. June 2010 leachate results can be attributed to irrigation and precipitation being applied to soils near field capacity for the 80% daily PET and RDAI irrigation treatment. The TDR treatment applied irrigation once June 2010 (Table 4), which resulted in the lowest leachate volumes. Aug. 2011 leachate volume data can be explained by the TDR treatment keeping the majority of the 30.5 cm soil profile near field capacity resulting in precipitation in excess of field capacity to be drained from the profile. The RDAI and 80% daily PET treatment were only irrigated to supply moisture to the depth of the root-zone, which allowed precipitation to be stored below the root-zone instead of forcing leachate through the profile. Morvant, et al. (1998) found that although the volume of water applied in a daily irrigated treatment was greater than in an intermittently-irrigated treatment, the amount of leachate was greatly reduced by daily irrigation. During dry periods, July-Aug. 2010 and June-July 2011, the 80% daily PET and RDAI irrigation treatments resulted in the lowest leachate volumes. The 80% daily PET and RDAI aimed to diminish the amount of irrigation that traveled past the root-zone, resulting in less overall leachate.

Leachate for the 80% daily PET and RDAI treatments primarily occurred during or after large precipitation events. The TDR treatment resulted in leachate directly after irrigation and after precipitation events, resulting in the largest volumes. The TDR treatment produced the greatest annual leachate volumes across 2010 and 2011. The TDR treatment resulted in greater annual leachate volumes due to greater volumes being collected during dry months when the 80% daily PET and RDAI treatment produced little leachate. Scheduling irrigation to reduce water from draining below the root-zone resulted in lower volumes leaching from the sand-based putting green.

Table 3. Total leachate volume from creeping bentgrass putting greens under three irrigation methods, 2010-11, East Lansing, MI.

2010

Irrigation Method	June	July	Aug.	Sept.	Oct.	Yearly Total
	--------------------	--------------------	mm	--------------------	--------------------	--------------------
80% daily PET†	68.5	56.8	25.4	102.3	9.2	262.3
RDAI‡	59.1	64.9	48.7	98.0	10.4	281.2
TDR¶	40.5	120.1	84.2	141.1	12.2	397.9
LSD (0.05)	7.2	46.7	38.2	28.8	NS	104.2

2011

Irrigation Method	May	June	July	Aug.	Sept/Oct	Yearly Total
	--------------------	--------------------	mm	--------------------	--------------------	--------------------
80% daily PET†	62.2	38.5	27.0	63.7	57.6	249.0
RDAI‡	62.3	39.9	29.3	53.7	38.2	223.4
TDR¶	63.7	104.3	87.3	105.5	50.0	410.8
LSD (0.05)	NS	41.1	45.8	42.7	NS	153.7

† 80% daily potential evapotranspiration
‡ Rooting depth adjusted irrigation
¶ Time domain reflectometry based deep and infrequent irrigation

Irrigation Frequency

Irrigation frequencies were significantly different ($p \leq 0.05$) for all 10 months of the study (Table 4). The 80% daily PET treatment was the most frequently irrigated while the TDR was the least frequently irrigated. During periods of wet weather (Sept-Oct 2010 and Aug.-Sept/Oct. 2011), there were no differences in irrigation frequency between the RDAI and TDR treatments. Precipitation allowed the RDAI and TDR treatments to forego irrigation for extended periods, where as the 80% Daily PET treatment would resume irrigation 2 d after precipitation events ≥ 12.5 mm. When PET was low (June, Sept-Oct. 2010, May, Aug-Sept/Oct. 2011), the TDR treatments top 7.6 cm did not dry out as quickly, allowing for longer intervals between irrigation. During times of high PET, the RDAI treatment had higher irrigation frequencies than the TDR due to the small amount of plant available water used to schedule the RDAI treatment. Moisture was extracted throughout the rooting depth for both the RDAI and TDR. However for the TDR, the top 7.6 cm of the soil profile had to dry down to 10% VWC leading lower to irrigation frequencies. The RDAI treatment calculated water loss using PET, which during hot months resulted in more frequent irrigation. Frequent irrigation, as in the 80% daily PET treatment, may increase costs associated with water consumption and reduce the plants environmental stress tolerance predisposing the turf stand to injury from mechanical stresses, cyanobacteria, moss, and diseases (Dernoeden, 2002; Turgeon, 2008).

Table 4. Irrigation frequency from creeping bentgrass putting greens under three irrigation methods, East Lansing, MI.

2010						
Irrigation Method	June	July	Aug.	Sept.	Oct.	Yearly Total
	----------Irrigation Applications----------					
80% daily PET‡	13.0	24.0	28.0	14.0	9.0	88.7
RDAI¶	4.0	6.0	8.0	3.0	1.0	22.0
TDR¥	1.0	4.0	4.7	3.0	1.0	13.7
LSD (0.05)	NS†	NS†	0.7	NS†	0.7	7.7
2011						
Irrigation Method	May	June	July	Aug	Sep/Oct	Yearly Total
	----------Irrigation Applications----------					
80% daily PET‡	11.0	21.0	24.0	15.0	20.0	91.0
RDAI¶	4.0	9.0	8.3	4.0	2.3	27.7
TDR¥	2.0	5.7	5.7	3.0	1.0	17.3
LSD (0.05)	NS†	0.7	1.1	1.2	0.7	2.2

†Statistical analysis could not be run due to extremely small mean standard error.
‡ 80% daily potential evapotranspiration
¶ Rooting depth adjusted irrigation
¥ Time domain reflectometry based deep and infrequent irrigation

Nitrate Loading

Total dissolved nitrogen was significant ($p \leq 0.05$) two of six months in 2010 and three of five months and the annual total in 2011 (Table 5). The TDR treatment resulted in a four-fold increase in the amount of dissolved nitrogen leaching through the putting green profile during Oct. 2010. TDR nitrate loading was greater for June, July, and Sep/Oct 2011 by a factor of 4, 10, and 10, respectively, as compared to the other treatments. Annual 2011 nitrate loading data show the TDR treatment leached more than 12 and 4 times the amount of nitrate as the 80% daily PET and RDAI irrigation treatments, respectively.

All irrigation treatments maintained similar leachate NO_3^- concentrations during the course of the study. Since concentrations did not differ, leachate volumes were the driving factor for overall NO_3^- loading. Shuman (2001) noted that irrigation in excess of ET rates enhanced nitrate and phosphorus leaching in sand-based putting greens. The TDR treatment did not take PET into account when applying irrigation and resulted in water applications exceeding PET. Nitrate is weakly adsorbed in sand-based systems and large flushes of water may result in preferential flow and increased nutrient leaching. Decreasing irrigation rates per application with increased frequency is the most practical approach for preventing preferential flow and subsequent nutrient losses from soil (Barton and Colmer, 2006). High soil moisture levels caused by prolonged periods of rainfall or irrigation can be responsible for large runoff and nutrient losses even on established dense turfgrass (Linde et al., 1995). Sep/Oct nitrate loading data were likely significant due to a granular fertilizer application of 24.4 kg N ha^{-1} on 14 Sept. 2011 followed by 53.1 mm of precipitation before the conclusion of the experiment on 5 October 2011.

All treatments produced similar amounts of leachate from September 1-October 5, 2011. Although the TDR only had irrigation applied once during this time, this treatment had larger NO_3^- concentrations resulting in increased NO_3^- loads. All treatments received the same fertility, which raises the question as to why the TDR treatment leached more nitrate. Localized dry spot was more prevalent on TDR plots during Sept. resulting in large patches of senesced turfgrass. When turfgrass is either dormant or senesced it can contribute to nutrient loading through vegetative losses (Steinke et al., 2007), resulting in increased nutrient leaching. Differences in microbial populations may also be the cause nitrate loading differences. Clein and Schimel (1994) found that a single short drying-rewetting event reduced microbial activity in Alaskan birch litter by greater than 25% over a two month laboratory incubation. The TDR treatment resulted in multiple drying-rewetting cycles over the course of the growing season, and may have reduced the amount of active microbes in the soil by the end of the season as compared to the 80% Daily PET and RDAI treatments. Some studies suggest that increased nitrate availability in the summer is due to root death caused by heat and drought stress leading to reduced nutrient uptake (Geron et al., 1993). Soil nitrate levels drop in the spring and fall due to increased root growth and uptake (Hull and Liu, 2005). Yearly loading totals were greatest for the TDR and RDAI treatments due to large flushes of water moving through the sand profile, resulting in greater nitrate leaching. The 80% Daily PET treatment only leached following large precipitation events which may have allowed for increased plant uptake of nitrate between events and less NO_3^- available to leach.

Leachate from any treatment rarely had NO_3^- concentrations greater than 10 ppm, which is the maximum concentration set for drinking water by the EPA (U.S. Environmental Protection

Agency, 2012). Brauen and Stahnke (1995) found that applying 195.3 kg NO_3^- ha^{-1} to turf grown on straight sand resulted in minimal nitrate leaching. Researchers also noted that NO_3^- accumulation in leachate was reduced during the second fall after establishment due to a more developed root system and higher organic matter content. Annual nitrate leaching totals for 2011 were considerably less than 2010. Denitrification is increased in soils with a pH above 8.0 and could be the cause of low NO_3^- loading values (Bremner and Shaw, 1958). The pH of the sand-based putting green used in this study was 8.1 as indicated by a soil test from Sept. 2011. Soil moisture status may also affect denitrification. Bremner and Shaw (1958) found that soils with moisture levels greater than 60% of total moisture holding capacity resulted in increased denitrification. The 80% daily PET treatment kept soil moisture near field capacity, potentially causing increased denitrification and reducing the concentration of NO_3^- in leachate. However, relying on denitrification to reduce nitrate leaching should not be a goal since applied nitrogen is not beneficially utilized. In order to reduce nitrate leaching and optimize nitrogen use efficiency, turf managers may need to consider irrigating with lower water volumes in combination with longer periods between individual irrigation events. Extending the time between irrigation events may allow the roots and soil to immobilize the N and reduce the amount of soluble N in soil solution (Bowman et al., 1998).

Table 5. Effect of three irrigation methods on total dissolved nitrogen in leachate from creeping bentgrass putting greens, 2010-11, East Lansing, MI.

2010

Irrigation Method	June	July	Aug.	Sept.	Oct.	Nov.	Yearly Total
	------------------------ kg NO_3^- ha^{-1} ------------------------						
80% daily PET†	0.35	0.05	0.19	0.72	0.04	0.01	1.35
RDAI‡	0.40	0.45	0.44	0.81	0.07	0.02	2.20
TDR¶	0.50	0.14	0.60	0.75	0.32	0.02	2.33
LSD (0.05)	NS	NS	NS	NS	0.17	0.01	NS

2011

Irrigation Method	May	June	July	Aug.	Sep/Oct	Yearly Total
	---------------------- kg NO_3^- ha^{-1} ----------------------					
80% daily PET†	0.01	0.02	0.02	0.05	0.01	0.11
RDAI‡	0.03	0.05	0.03	0.13	0.09	0.32
TDR¶	0.02	0.08	0.21	0.12	0.93	1.36
LSD (0.05)	NS	0.04	0.11	NS	0.51	0.59

† 80% daily potential evapotranspiration
‡ Rooting depth adjusted irrigation
¶ Time domain reflectometry based deep and infrequent irrigation

Phosphorus Loading

Phosphorus loading data were significant ($p \leq 0.05$) five of six months in 2010, two of five months in 2011, and for the annual totals over both years (Table 6). June 2010 data show the RDAI and TDR irrigation treatments resulted in greater soluble P losses than the 80% daily PET. July-Sept. 2010 P loading data show that the TDR treatment resulted in five to ten times more soluble P than the RDAI and 80% daily PET treatments. In Oct. 2010, the TDR irrigation treatment leached eight times more soluble P than the 80% daily PET treatment. Cumulative P loading for 2010 show the TDR treatment produced over five and three times more soluble P leaching than the 80% daily PET and RDAI treatments, respectively. In June-July 2011, the TDR treatment leached up to ten times more soluble P than the other treatments which was similar to the results from summer 2010. Annual soluble P loading for 2011 resulted in the TDR treatment leaching three times more soluble P than the other two treatments.

The risk of soil P leaching is considered to be minimal, though the risk of downward P movement increases on sand and sandy loam textured soils (Reddy et al., 1978; Gilliam et al., 1985; Mansell et al., 1985). Sandy soils subject to P loss due to reduced cation exchange capacity, low organic matter, and increased rates of water percolation (Harris et al., 1996; Johnson et al., 2003). Increased soil moisture enhances P solution reactions and improves the migration capability of phosphorus, especially on sandy soils (Meissner et al., 1995). Phosphorus loading treatment differences for 2010 were influenced by leachate volume differences. In June 2010, the TDR and RDAI treatments leached the most P largely due to preferential flow caused by large irrigation volumes at or near soil field capacity. Preferential flow paths may be responsible for the majority of the subsurface P transfer. Dissolved reactive P losses in subsurface drainage water can be substantial when conditions for leaching are favorable or promoted or when preferential flow is present (Duxbury and Perverly, 1978; Geohring et al., 2001; Jamieson et al., 2003). Jensen et al. (1998) found that orthophosphate transfer only occurred through wide-aperture macropores in structured soils, despite water flow not being restricted to the same macropores.

Baker et al. (1975) found that P export varied considerably from year to year depending on the intensity of precipitation and surface runoff. During June through Aug. 2011, P loading totals were higher than that of June-Aug. 2010. During the span from 1 Sept – 5 Oct 2011, little P was leached from any treatment. A soil test taken 4 Oct. 2011 revealed 11 ppm of available phosphorus which is considered low (Carrow et al., 2001). Low phosphorus levels may explain why no phosphorus leached the last month of the study. Decaying plant matter could have been a source of soluble P during the study. Steinke et al. (2007) found that P leached from dead vegetation was a significant source of P found in run-off. The TDR treatment incurred large areas of blighted turf which may have been a source of P in the present study. Annual 2011 total phosphorus loading differences could be attributed to the significant differences June-July since no other monthly loading totals were significant.

Table 6. Effect of three irrigation methods on loading of soluble P in leachate from creeping bentgrass putting greens, 2010-11, East Lansing, MI.

2010

Irrigation Method	June	July	Aug.	Sept.	Oct.	Nov.	Yearly Total
	--------------------------kg soluble P ha^{-1}--------------------------						
80% daily PET†	0.000	0.002	0.000	0.013	0.001	0.001	0.017
RDAI‡	0.010	0.001	0.000	0.016	0.004	0.001	0.032
TDR¶	0.007	0.011	0.021	0.040	0.008	0.003	0.091
LSD (0.05)	0.004	0.008	0.018	0.012	0.006	NS	0.036

2011

Irrigation Method	May	June	July	Aug.	Sep/Oct	Yearly Total
	---------------------kg soluble P ha^{-1}------------------------					
80% daily PET†	0.011	0.002	0.004	0.019	ND	0.036
RDAI‡	0.011	0.003	0.004	0.014	ND	0.032
TDR¶	0.015	0.027	0.027	0.031	ND	0.100
LSD (0.05)	NS	0.016	0.019	NS	NS	0.050

† 80% daily potential evapotranspiration
‡ Rooting depth adjusted irrigation
¶ Time domain reflectometry based deep and infrequent irrigation

Root Depth

Root depth was significant ($p \leq 0.05$) on one of five dates in 2010 (Table 7). The 80% Daily PET and RDAI treatments produced the greatest rooting depths on 2 Nov. 2010, each maintaining a 15.0 cm root zone. Rooting depth was significant on two of six dates in 2011. The TDR treatment produced the greatest rooting depth on 1 Aug. 2011 while the RDAI and TDR treatment both resulted in greater rooting depths by mid-September.

Turfgrasses subjected to deficit irrigation can develop larger root systems and store more carbohydrates than well-watered plants (Jordan et al., 2003; Fry and Huang, 2004; Dacosta and Huang, 2006; Fu and Dernoeden 2008; Fu and Dernoeden, 2009a,b). Root respiration decreases in many plants during periods of water stress, ‘Volkamer’ lemon (*Citrus volkameriana* Tan.) has 30-50% lower root respiration under water stress than well watered plants (Bryla et al., 1997, 2001). Reducing root-zone temperature has also shown to increase root growth, export of cytokinin from roots, leaf photosynthesis, chlorophyll content, protein synthesis, and shoot growth in several species (Skene and Kerridge, 1967). Increased photorespiration and high root zone temperatures are the main causes of summer root die-back. Excessive growth occurs when turf is watered frequently, and growth is maintained through carbohydrate reserves. Thus, watering frequently may have caused a reduction in rooting depth in the 80% daily PET treatment due to increased shoot growth and decreased photosynthate assimilation.

Data for 2 Nov. 2010 may be explained by decreasing temperatures and low PET values in combination with a saturated root-zone. Periods of freezing nights and thawing days are more apt to cause damage to turfgrass than constant freezing temperatures (Bell, 2011). Beard (1973) found that temperatures from 10-18 C were optimal for root growth of cool-season grasses. Night time soil temperatures began to fall below 10 C consistently after 15 October 2010. If aeration does not become limited, periods of high soil moisture reduces the number and depth of roots (Madison and Hagan, 1962). In Nov. 2010, the TDR treatment had higher soil moisture levels than the other two treatments, possibly causing the reduction in rooting depth. Low soil temperature combined with phosphorus deficiency could have accelerated root mortality in the TDR treatment resulting in the shallowest rooting depth.

Jordan et al. (2003) found that irrigating on a 4-day frequency as opposed to every day or every other day significantly increased shoot density and rooting density of creeping bentgrass grown on a sand-based root-zone. With high PET throughout June and July 2011, the RDAI treatments interval between irrigation and precipitation was once every 2-3 d, which may not have been great enough to result in rooting potential differences. Rooting depths for all treatments decreased from 1 Aug. – 29 Sept. 2011 which may be explained by supraoptimal soil temperatures causing increased root mortality.

Table 7. Rooting depth of creeping bentgrass putting greens under three irrigation methods, 2010-11, East Lansing, MI.

	2010				
Irrigation Method	July 2	Aug. 2	Sept. 15	Oct. 15	Nov. 2
	---------------------------cm----------------------------				
80% daily PET†	11.9	10.2	10.4	11.9	15.0
RDAI‡	13.2	11.9	12.4	12.7	15.0
TDR¶	13.0	13.0	12.4	14.2	12.4
LSD (0.05)	NS	NS	NS	NS	1.5

	2011					
Irrigation Method	May 16	July 1	Aug. 1	Sept. 1	Sept. 15	Sept. 29
	------------------------------------cm------------------------------------					
80% daily PET†	12.1	14.0	14.5	13.0	11.9	10.0
RDAI‡	12.7	15.1	14.0	14.5	15.4	11.4
TDR¶	12.8	14.3	16.9	15.0	13.3	12.7
LSD (0.05)	NS	NS	2.0	NS	2.6	NS

† 80% daily potential evapotranspiration
‡ Rooting depth adjusted irrigation
¶ Time domain reflectometry based deep and infrequent irrigation

Root Mass

No significant treatment effects for root mass occurred in 2010 or 2011. Root mass of all treatments increased throughout 2010. The 80% daily PET increased from 810 mg per core to 990 mg per core, RDAI root mass increased from 650 mg per core to 1,140 mg per core, and the TDR root mass increased from 880 mg per core to 1,120 mg per core. In 2011, all three irrigation treatments caused root mass to increase from spring into summer, but all treatments underwent similar declines in root mass from summer to autumn and ended the year at similar root mass levels as spring.

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Chapter 2

WATER MANAGEMENT FOR OPTIMAL PERFORMANCE OF SAND-BASED CREEPING BENTGRASS PUTTING GREENS

ABSTRACT

Irrigation scheduling can impact turfgrass shoot and root development, disease incidence, and putting green aesthetics. Determining the optimal irrigation interval and volume is essential to providing exceptional quality creeping bentgrass (*Agrostis stolinifera* L.) grown on sand-based putting greens. This study investigated the effects of three irrigation scheduling methods on irrigation volumes and frequency, rooting depth, putting green quality, percent green ground cover, localized dry spot incidence (LDS), and dollar spot occurrence. Annual irrigation volumes for 2010 show the 80% daily potential evapotranspiration (PET) treatment required the least water volume (284.7 mm) while the rooting depth adjusted irrigation (RDAI) and soil moisture dependent irrigation (TDR) treatments required 340.7 mm and 421.9 mm, respectively. In both 2010 and 2011 applying 80% daily PET resulted in the best quality putting green surface. The TDR and RDAI treatment had significantly ($p \leq 0.05$) more LDS than the 80% daily PET treatment from 10 Aug. – 18 Oct. 2010 while the TDR had significantly greater LDS incidence from 21 June – 5 Oct. 2011. Data show the TDR treatment resulted in significantly ($p \leq 0.05$) less dollar spot on six of seven dates in 2010 and two of five dates in 2011. Results show that more frequent irrigation applications at low volumes during dry months reduces the occurrence of LDS. Basing irrigation programming on rooting depth during months with low PET demand and adequate precipitation may simultaneously serve as a water-conservation method and best management practice for creeping bentgrass putting greens.

INTRODUCTION

Creeping bentgrass (*Agrostis stononifera* L.) is an excellent turfgrass for putting green surfaces and dominates putting green acreage across much of the United States. Advances in creeping bentgrass germplasm and irrigation availability have lead to the high-input putting greens used across much of North America. Careful water management of creeping bentgrass should be a top priority for turfgrass managers as water restrictions for amenity landscapes may soon impact putting surfaces regardless of aquifer or reservoir status. Currently, due both to a lack of options for irrigation scheduling and readily available access to a continuous water supply, little incentive exists for superintendents to utilize non-traditional irrigation methods because of readily available access to water.

Turfgrass irrigation is a balance between meeting the moisture needs of the plant yet not exceeding the soil's water holding capacity and excluding oxygen from the root zone. Water restrictions may require turf managers to find ways to maintain acceptable turf quality through reduced irrigation (Los Angeles Department of Water and Power, 2010; San Antonio Water System, 2011). Water management may influence shoot and root development, disease incidence, algae formation, and thatch production (Kackley et al., 1990; Davis and Dernoeden, 1991). Madison and Hagan (1962) found irrigating every 20 days enhanced Kentucky bluegrass (*Poa pratensis* L.) rooting compared to irrigating every two days. Bennett and Doss (1960) reported rooting of cool-season forage grasses was increased by allowing the upper 60 cm of soil to dry-out to 15% versus 70% available soil moisture. More recent literature (Jordan et al., 2003) has determined that creeping bentgrass rooting depth and density were improved by irrigating every four days rather than every one or two days. Biran et al. (1981) found that delaying irrigation until the onset of temporary wilting decreased water consumption and growth up to 35% in ‘Alta’ tall fescue (*Festuca arundinacea* Schreb.) and ‘Pennfine’ perennial ryegrass (*Lolium perenne* L.). However, the quality of ‘Alta’ tall fescue and ‘Pennfine’ perennial ryegrass were both improved when watered every two or three days as compared to three times every two weeks (Biran et al., 1981). As economic concerns and water restrictions force golf course managers to consider lower-input maintenance approaches, data pertaining to putting green water management will be required to move the industry further towards increased sustainability.

Greater degrees of deficit irrigation may become a standard best management practice as water supplies become limited (Fereres and Soriano, 2007). Dacosta and Huang (2006) found that irrigating at 60% or 80% ET did not significantly alter colonial (*Agrostis capillaris* L.), creeping (*A stolonifera* L.), or velvet (*A canina* L.) bentgrasses water use efficiency when compared to 100% ET replacement. Irrigating creeping bentgrass at 80% evapotranspiration (ET) three times per week throughout the summer led to acceptable turfgrass quality. Acceptable turfgrass quality was maintained at 40% ET during the autumn (Dacosta and Huang, 2006). Irrigation frequency may also contribute towards turfgrass quality when applying deficit irrigation. When tall fescue was irrigated at 50% ET, improved turfgrass quality was obtained with shorter irrigation intervals (2d) as compared to longer intervals (4,7, or 14d) (Fry and Butler, 1989). In a green house study, Ervin et al. (2009) observed that creeping bentgrass irrigated at 70 or 85% ET every five days resulted in similar turf quality as compared to 100% ET replacement. Deficit irrigation has the potential to conserve water in areas where precipitation occurs at regular 10- to 14-day intervals due to low irrigation volumes maintaining minimum soil moisture levels between precipitation events. Natural rainfall, rather than irrigation, would serve as the impetus to fully recharge the root zone (Sass and Horgan, 2006).

Data validating the effects of conservation-based irrigation scheduling methods on sand-based creeping bentgrass putting greens in Michigan are critical for developing science-based approaches to water conservation. The objective of the study was to compare three irrigation scheduling methods for their effects on turfgrass quality, disease occurrence, localized dry spot incidence, and rooting characteristics.

MATERIALS AND METHODS

A two-year field study was conducted between Jun. 2010 and Oct. 2011 at the Hancock Turfgrass Research Center in East Lansing, MI. Penn ‘A-4’ creeping bentgrass was seeded into nine 11m x 11m plots on a sand-based putting green in Aug. 2008. Main plots were divided into three subplots with lysimeters installed in each subplot to quantify percolate volumes and nutrient losses. The particle size distribution of the 30.5 cm sand root zone and the 10.2 cm gravel layer both conformed to USGA specifications (USGA, 1993) (Table 1).

Three irrigation treatments were tested in this field investigation. The first irrigation treatment was defined as 80% replacement of potential evapotranspiration. Reference potential evapotranspiration data were collected from the Michigan Automated Weather Network website (http://www.agweather.geo.msu.edu/mawn), which provided data from a weather station located within a 5 m distance of the putting green. The PET estimation is a reference potential evapotranspiration and was based on the FAO Penman-Monteith Equation (Allen et al., 1998). Irrigation to replace the 80% PET occurred at 4 A.M. the following morning. When precipitation events exceeded 12.7 mm, irrigation was withheld for two days. This occurred because daily PET rarely exceeds 7.6 mm in Michigan and 80% replacement of 7.6 mm over two days would be accounted for by 12.7 mm of precipitation making irrigation unnecessary.

Table 8. Particle size distribution for sand used to construct USGA specification putting green.

	mm									
Particle Size	>2.0	1.0-2.0	0.7-1.0	0.5-0.7	0.25-0.5	0.18-0.25	0.1-0.18	0.05-0.1	silt	clay
	---%---									
Distribution	0.1	9.8	10.7	16.5	39.2	14.4	6.5	0.5	1.6	0.7

The second irrigation treatment was referred to as rooting-depth adjusted irrigation (RDAI) and was dependent upon soil physical properties and rooting depth. The aim of this irrigation treatment was to maintain the root zone volumetric water content (VWC) between field capacity and one-half of the plant available water. The amended sand-based root zone used in this study was determined to have a 20% VWC at field capacity and a permanent wilting point (PWP) of 5% VWC. Field capacity was determined by placing a total of nine saturated soil cores in pressure plate extractors set at 0.1 atmospheres of pressure and allowed to equilibrate to account for the high sand content (Klute, 1986). The PWP was determined by allowing the turf to wilt and using a time domain reflectometry (TDR) probe (Field Scout TDR 300 Soil Moisture Meter, Spectrum Technologies, East Plainfield, IL) to measure the VWC at that point. A total of six areas were probed and averaged to estimate PWP. Water lost from the root-zone was based on reference PET. Rooting depth was measured by taking a core from each plot with a 10.2 x 2.5 x 17.8 cm soil profiler (Miltona Turf Products, N Maple Grove, MN) and gently shaking the core to remove excess sand from the roots. The core was placed on the coring device and measured from the soil surface to include approximately 80% of the available root mass.

The third irrigation treatment consisted of using a TDR soil moisture probe to determine VWC. Irrigation was initiated when soil moisture dropped to ≤ 10% VWC. Irrigation was then applied to bring the top 7.6 cm of root zone to 20% VWC.

Irrigation treatments were applied to each of the 9 main plots using four Toro TR-50 sprinkler heads (The Toro Company, Riverside, CA) positioned on the plot corners. Each sprinkler applied 7.6 liters per minute (LPM) for a total of 30.4 LPM during each irrigation event. Rain gauges used during irrigation system audits confirmed the rate of 0.25 cm per 10 min of irrigation.

Plots were mowed 5 times weekly during the growing season at a height of 3.2 mm using a Toro Greensmaster 3150-Q triplex greens mower (The Toro Company, Riverside, CA), with clippings removed. Sand topdressing was applied at a rate of 0.25 cm every other week throughout the growing season. Sand was brushed into the green and irrigation applied for a 5 min period to move sand into the thatch layer. The putting green was aerified on 15 Oct. 2010 with a Toro ProCore 648 with 0.95 cm diameter hollow tines at 5 cm spacing. Sand was top-dressed onto the green and brushed into the aerification holes.

Total fertilizer for each of the two growing seasons was 145.6 kg N ha^{-1} $year^{-1}$, 6.1 kg P_2O_5 ha^{-1}, and 94.8 kg K_2O ha^{-1}. Plots were fertilized with 24 kg N ha^{-1} on 19 May, 6 Oct., 12 kg N ha^{-1} on 9 Sept. and 21 Sept., and 37 kg N ha^{-1} on 1 Nov. 2010 using a 19-0-15 (N-P-K) granular fertilizer (2.37% urea, 9.74% WSN, 6.89% WIN, K as K_2O, 15% potassium sulfate, 2.0% K-mag, 7.7% S, 0.05% Cu, 1.05% Fe, 0.05% Mn, 0.05% Zn, Andersons Golf Products, Maumee, OH). In 2011, plots were fertilized with 24 kg N ha^{-1} on 16 May, 14 Sept., 14 Oct., and 37 kg N ha^{-1} on 1 Nov. 2011. Nitrogen was applied as a foliar spray on 24 Jun., 30 Jun., 12 July, 26 July, 10 Aug., 25 Aug. 2010 and 6 Jun., 22 Jun., 6 July, 20 July, 8 Aug., and 22 Aug. 2011 using an 18-3-4 (N-P-K) liquid fertilizer (2.0% amoniacal nitrogen, 1.5% nitrate nitrogen, 14.5% urea nitrogen, 3.0% available phosphoric acid, 4.0% soluble potash, 0.12% chelated copper, 1.0% chelated iron, 0.1% chelated manganese, 0.1% chelated zinc, Grigg Brothers, Albion, ID) at a rate of 6.1 kg N ha^{-1}. Granular treatments were applied and irrigated with 1.3 mm water to avoid fertilizer burn.

Fungicides were applied curatively to avoid turf loss. Chlorothalonil [1,3-benzenedicarbonitrile,2,4,5,6-tetrachloroisophthalonitrile] (54.7 kg ha^{-1}) was applied on 15 July 2010 and (47.34 kg ha^{-1}) on 27 July, 10 Aug, and 22 Sept 2010. Chlorothalonil [1,3-benzenedicarbonitrile,2,4,5,6-tetrachloro-isophthalonitrile] was applied (54.74 kg ha^{-1}) on 20 July, 8 Aug, and 22 Aug in 2011. Boscalid (BASF) [3-pyridinecarboxamide, 2-chloro-N-(4'-chloro(1,1'-biphenyl-2-yl)] was applied (0.55 kg ha^{-1}) on 13 Aug 2011 to control dollarspot (*Sclerotinia homeocarpa* F.T Bennet).

Irrigation volumes were measured and determined by an irrigation audit consisting of 6 rain gauges placed within each main plot and running irrigation for 20 min. Irrigation volumes collected during 20 min. were averaged between the six rain gauges. The average volume was then divided in half to determine the irrigation application rate per 10 min. The irrigation system was determined to applied 2.54 mm water per 10 minute interval.

Turfgrass quality was visually rated every two weeks June-Oct 2010 and May-Oct. 2011, with 1 = completely necrotic, dead turf; 6 = minimally acceptable putting green turf; and 9 = optimal density, uniformity, and color. Ball roll was measured on each subplot using a Pelzmeter (PelzGolf, Independent Golf Research, Inc., Spicewood, TX). Ball roll measurements were taken on 8 July, 26 Aug., and 29 Sept. 2010; and 14 June, 18 July, and 29 Aug. 2011. Three golf balls were rolled from north to south and three golf balls were rolled from south to north. The ball roll distances were averaged to determine the green speed of the plot.

Localized dry spot (LDS) was rated every two weeks June-Oct 2010 and May-Oct. 2011 as a visual estimate of the percentage within each subplot affected with LDS.

Dollar spot incidence was evaluated on 21, 29 Jun, 13, 26 July, 5 Aug., 7, 23 Sept. 2010 and on 3, 21 June, 19 July, 8 Aug. and 9 Sept. 2011. Dollar spot incidence was evaluated by counting the number of infection centers within a 1m x 1m quadrat placed randomly on each subplot avoiding areas with severe LDS coverage. Infection centers were defined as areas at least 2 cm in diameter, and infection centers that coalesced into larger blighted areas were recorded as a single infection center.

Root length was determined by removing one soil core per sub-plot measuring 10.2 cm x 2.5 cm x 17.8 cm (Miltona Turf Products, N Maple Grove, MN). The soil core was removed and shaken for 15 s over a plastic bucket to remove loose sand from root tissue. The sand-free root sample was placed back onto the soil profiler with roots fully extended. Root length was measured to the point where approximately 80% of the total root mass extended. The rooting depth was also used for calculating irrigation quantities in the RDAI treatment.

Digital images were taken with a Canon EOS Digital Rebel XT (Canon U.S.A., Inc., Lake Success, NY). Aperture was set at 24, quality was set to RAW, isospeed was set at 800, and the camera was in auto-depth mode. The camera was fitted on a light box apparatus to ensure identical light intensity for every image. Images were then transferred from the flash card to a desktop computer, reformatted to JPEG, and resized to 800 x 600 pixels. The images were analyzed for percent green ground cover using a macro in SigmaScanPro 5 (Systat Software, Inc., Chicago, IL). The hue range was set to 55-90 and the saturation range was set to 10-90. Digital images were collected on 23 June, 28 June, 15 July, 3 Aug., 10 Aug., 16 Aug., 23 Aug., 1 Sept., 9 Sept., 14 Sept., 23 September, 30 Sept., and 12 Oct. 2010; and 4 May, 24 May, 8 June, 21 June, 6 July, 25 July, 10 Aug., 25 Aug., and 4 Sept. 2011.

The experiment was a completely randomized design with 3 subplots within each of 9 main blocks to add power during statistical analysis. All data were subjected to analysis of variance using the SAS 9.2 (SAS institute Inc., Cary, NC) mixed model procedure. Mean differences were separated using Fisher's Least Significant Difference.

RESULTS AND DISCUSSION

Environmental Data

Climatic conditions varied slightly between each year of the two-year study providing an opportunity to examine the effects of three irrigation scheduling methods under multiple climate scenarios (Table 9). Months were classified by the necessity for supplemental irrigation, which was affected by potential evapotranspiration (PET) and precipitation relative to the 30-yr monthly mean precipitation. Precipitation received during June and Sept. 2010 exceeded the 30-year monthly means and was nearly sufficient to account for PET losses, classifying these months as non-dependent on irrigation. July, Aug., and Oct. 2010 (dependent on irrigation) received less precipitation than PET and the respective 30-year means. In May 2011 (non-dependent), plots received twice the 30-yr monthly mean precipitation, replacing more moisture than lost to PET. June 2011 (irrigation dependent) received 40.1 mm of precipitation which was below the 30-yr monthly mean and one-third of PET. July 2011 received 10.4 mm of precipitation for the first 26 days but received 114.6 mm of precipitation in the final four days resulting in above average precipitation for the month, (irrigation dependent). August 2011 (irrigation dependent) received 78.2 mm of precipitation but was not sufficient to account for PET. Due to the experiment ending 5 Oct. 2011, Sept/Oct 2011 weather data were combined and classified as irrigation-dependent. Spring conditions over both years were not dependent upon irrigation due to precipitation exceeding PET losses. During each summer, plots experienced at least two months of dry weather (July/Aug. 2010 and June/July/Aug. 2011). Autumn 2010 was classified as non-dependent on irrigation while autumn 2011 was classified as dependent on irrigation.

Table 9. Potential evapotranspiration, 30-year monthly mean precipitation, and monthly precipitation for East Lansing, MI, 2010-11.

Environmental data	2010 June	July	Aug.	Sept.	Oct.	Season Total
	-----mm-----					
PET†	119.8	135.7	122.2	82.0	57.5	517.2
30-yr mean precipitation	86.4	68.6	81.0	86.4	58.4	380.8
Precipitation	99.6	51.1	14.5	88.6	35.8	289.6

Environmental data	2011 May	June	July	Aug.	Sept/Oct	Season Total
	-----mm-----					
PET†	104.3	129.3	152.9	115.1	83.0	584.6
30-yr mean precipitation	68.6	86.4	68.6	81.0	86.4	391.0
Precipitation	128.5	40.1	129.5	78.2	67.3	443.6

† Potential evapotranspiration

Irrigation Volumes

Irrigation volumes showed significant ($p \leq 0.05$) differences 9 out of 10 months during the two-year study and for the 2010 total annual volumes (Fig. 1). Irrigation treatments differed in June 2010 where the TDR treatment used the least water (31.2 mm) followed by the 80% daily ET (49.0 mm) and the RDAI (67.3 mm). July through Sept. 2010 irrigation volumes resulted in TDR > RDAI > 80% daily PET (Fig. 1). The RDAI irrigation treatment utilized the least amount of water in Oct. 2010. Total annual irrigation volumes for 2010 were significantly different with the TDR treatment using 421.9 mm of irrigation, followed by the RDAI and 80% daily PET treatments requiring 340.7 and 284.7 mm, respectively.

The TDR irrigation treatment used the lowest irrigation volume May 2011. June and July 2011 data show the 80% daily PET irrigation treatment used less water than the RDAI and TDR. Sept/Oct 2011 irrigation volume data show the RDAI and TDR treatments required the least water. No treatment differences were observed for the total annual irrigation volumes for 2011.

Irrigation volumes over both years resulted in two trends. June 2010 and May 2011 resulted in the TDR irrigation treatment using the least water and the 80% daily PET using less than the RDAI. When irrigation treatments were first initiated each year, soil moisture was high, PET was low, and plots received timely precipitation. Moist soil conditions during June 2010 and May 2011 only required the TDR treatment to apply irrigation one and two times, respectively (Table 3). The 80% daily PET treatment required irrigation following any day that PET losses exceeded precipitation, leading to unnecessary irrigation applications to relatively wet soils. RDAI irrigation was dependent on rooting depth and PET losses. If timely precipitation was not received and rooting depth was shallow, 100% PET was applied more frequently leading to high irrigation volumes for the RDAI treatment.

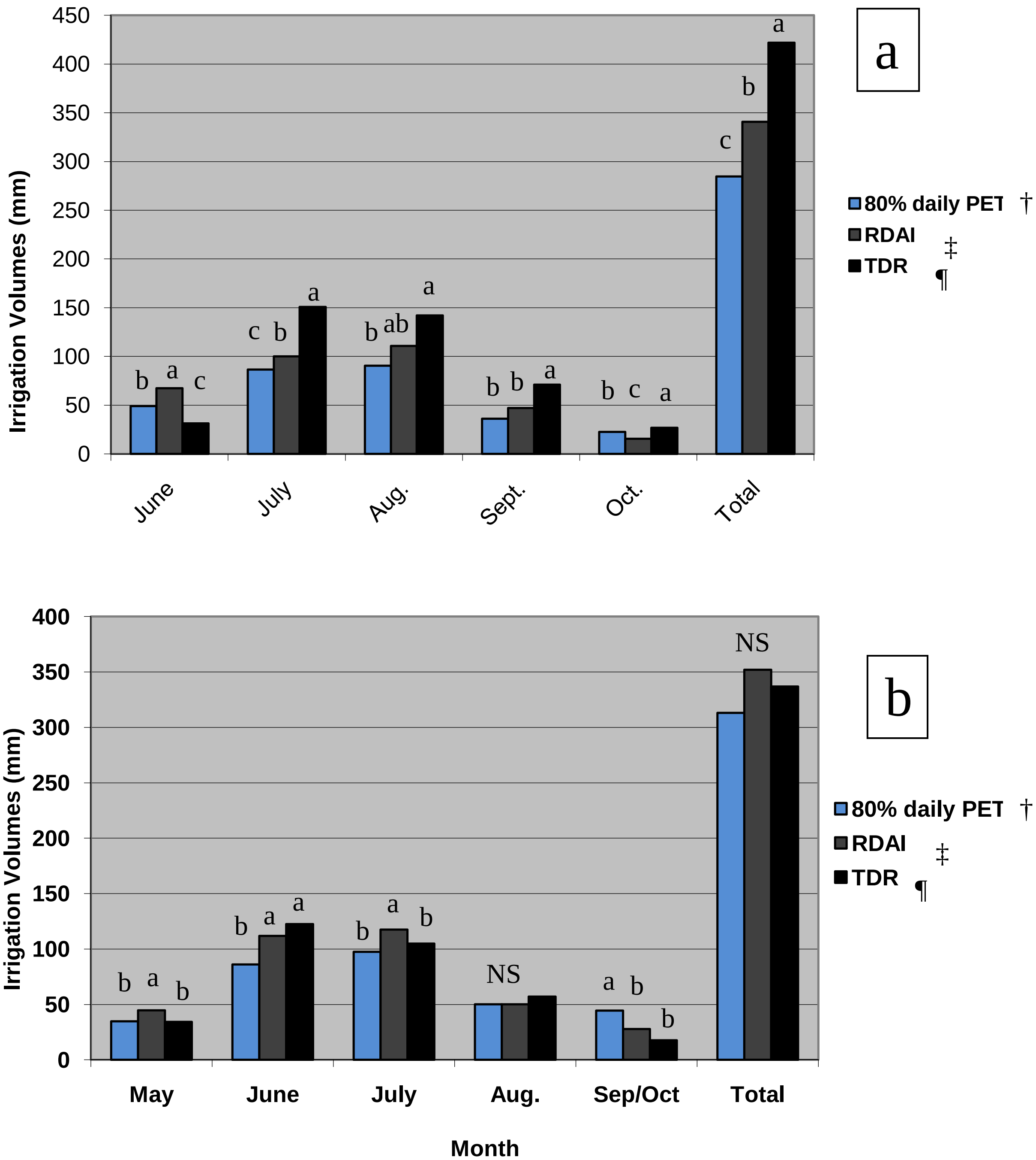
Data from July/Aug. 2010 and June/July 2011 show the TDR irrigation treatment used greater irrigation volumes than the 80% daily PET and RDAI. July/Aug. 2010 and June/July 2011 were months that received little precipitation and incurred high PET losses making supplemental irrigation critical to plant health and survival. Over 70% of soil moisture fluctuation occurs in the top 4 cm of soil (Sass and Horgan, 2006). The TDR treatment scheduled deep irrigation when the top 7.6 cm of soil dried out. This portion of soil dries more quickly than the lower soil profile due to a higher rooting density (Carrow, 1996). Relying on soil moisture in the top 7.6 cm to schedule deep-infrequent irrigation may result in greater irrigation volumes and frequencies than the plant requires. Precise estimations of soil water depletion have been found to be better than measuring soil water directly (Li et al., 2004). The RDAI irrigation treatment accounted for rooting depth and PET data when scheduling irrigation thereby avoiding over application. The 80% daily ET treatment used the least water because it applied less water than PET predicted and did not depend on precipitation to realize water savings. July/Aug. 2010 and June/July 2011 data show the 80% daily PET treatment used approximately 80% of the irrigation that the RDAI utilized resulting in significantly ($p \leq 0.05$) lower irrigation volumes.

Sept. 2010 and Aug. 2011 were months that received timely precipitation to account for PET losses and supplemental irrigation was not required for plant survival. During Sept. 2010, the TDR treatment required greater irrigation volumes than the other two treatments, but no differences were observed Aug. 2011.

The RDAI treatment conserved more water than the 80% daily PET treatment in Oct. 2010 due to low PET and timely rainfall. Low PET in Oct. 2010 extended the irrigation interval for the RDAI treatment resulting in a greater number of opportunities to receive precipitation. The RDAI and TDR treatments were each irrigated once during Oct. 2010, but the TDR applied greater volumes. Sept/Oct 2011 irrigation volume data resulted in the TDR using the least water, while the 80% daily PET used the greatest volumes. Despite ample precipitation Sept/Oct 2011, the 80% daily PET treatment was irrigated 20 times while the RDAI and TDR treatments were irrigated two and one times, respectively (Table 3). During months that received precipitation on a regular basis, the 80% daily PET treatment applied water unnecessarily between precipitation events.

Annual irrigation volumes for 2010 were greatest for the TDR treatment primarily due to over estimating irrigation volumes and frequencies during the summer months. The TDR treatment used more water due to irrigation being scheduled prior to natural rainfall events. Regardless of the weather forecast if the soil reached 10% VWC during the day, irrigation was scheduled for the following morning. This method did result in irrigation being applied at night within proximity of precipitation events. The RDAI treatment ranked second in 2010 annual irrigation volumes primarily due to applying 100% PET when water savings were not realized during periods with minimal precipitation. Yearly irrigation volumes for 2011 were insignificant due to the TDR treatment using the least irrigation during the spring and autumn, while the 80% daily PET treatment used the least irrigation during dry periods. The RDAI treatment used an intermediate amount of irrigation during most months. Alternating scheduling methods could result in greater water savings than utilizing one scheduling method over the course of a year.

Fig. 2. Total water volume applied to creeping bentgrass putting greens under three irrigation methods, 2010a-11b, East Lansing, MI.



† 80% daily potential evapotranspiration
‡ Rooting depth adjusted irrigation
¶ Time domain reflectometry based deep and infrequent irrigation

Irrigation Frequency

Irrigation frequencies were significantly different ($p \leq 0.05$) 6 of 10 months during the study (Table 10). The 80% daily PET treatment was the most frequently irrigated while the TDR was the least frequently irrigated. During periods of wet weather (Sept-Oct 2010 and Aug.-Sept/Oct. 2011), there were no differences in irrigation frequency between the RDAI and TDR treatments. Precipitation allowed the RDAI and TDR treatments to forego irrigation for extended time periods where as the 80% Daily PET treatment would resume irrigation 2 d after precipitation events ≥ 12.7 mm. When PET was low (June, Sept-Oct. 2010, May, Aug-Sept/Oct. 2011), the TDR treatments top 7.6 cm of soil did not dry as quickly allowing for longer intervals between irrigation. During periods of high PET, the RDAI treatment had greater irrigation frequencies than the TDR due to the small amount of plant available water used to schedule the RDAI irrigation. Moisture was extracted throughout the rooting depth for both the RDAI and TDR. However the top 7.6 cm of soil for the TDR had to dry down to 10% VWC leading to lower irrigation frequencies. The RDAI treatment calculated water loss using PET, which during hot months led to more frequent irrigation. Frequent irrigation, as in the 80% daily PET treatment, may increase costs associated with water consumption and reduce the plants environmental stress tolerance predisposing the turf stand to injury from mechanical stresses, cyanobacteria, moss, and diseases (Dernoeden, 2002; Turgeon, 2008).

Table 10. Irrigation frequency from creeping bentgrass putting greens under three irrigation methods, East Lansing, MI.

2010

Irrigation Method	June	July	Aug	Sept	Oct	Yearly Total
	-----------------Irrigation Applications-------------------					
80% daily PET‡	13.0	24.0	28.0	14.0	9.0	88.7
RDAI¶	4.0	6.0	8.0	3.0	1.0	22.0
TDR¥	1.0	4.0	4.7	3.0	1.0	13.7
LSD (0.05)	NS†	NS†	0.7	NS†	0.7	7.7

2011

Irrigation Method	May	June	July	Aug	Sep/Oct	Yearly Total
	-----------------Irrigation Applications-------------------					
80% daily PET‡	11.0	21.0	24.0	15.0	20.0	91.0
RDAI¶	4.0	9.0	8.3	4.0	2.3	27.7
TDR¥	2.0	5.7	5.7	3.0	1.0	17.3
LSD (0.05)	NS†	0.7	1.1	1.2	0.7	2.2

†Statistical analysis could not be run due to extremely small mean standard error.
‡ 80% daily potential evapotranspiration
¶ Rooting depth adjusted irrigation
¥ Time domain reflectometry based deep and infrequent irrigation

Rooting Depth

Root depth was significant ($p \leq 0.05$) on one of five dates in 2010 and two of six dates in 2011 (Table 11). The 80% Daily PET and RDAI treatments produced the greatest rooting depths on 2 Nov. 2010, each maintaining a 15.0 cm root zone. The TDR treatment produced the greatest rooting depth on 1 Aug. 2011. On 15 Sep. 2011 the RDAI and TDR treatment both resulted in a greater rooting depth than the 80% daily PET treatment.

Turfgrasses subjected to deficit irrigation can develop larger root systems and store more carbohydrates than well-watered plants (Jordan et al., 2003; Fry and Huang, 2004; Dacosta and Huang, 2006; Fu and Dernoeden 2008; Fu and Dernoeden, 2009). Liu and Huang (2000) found that high carbohydrate availability (i.e., glucose and sucrose) during heat stress was an important physiological trait associated with heat-stress tolerance in creeping bentgrass. Ample carbohydrate reserves are important because high temperatures reduce photosynthesis and increase respiration in creeping bentgrass (Carrow, 1996). When watered frequently, excessive turf growth is maintained through carbohydrate reserves. However, reducing root-zone temperatures through frequent irrigation has been shown to increase root growth, export of cytokinin from roots, leaf photosynthesis, chlorophyll content, protein synthesis, and shoot growth in several species (Skene and Kerridge, 1967).

Root respiration in many plants decreases during periods of water stress. Bryla et al. (1997, 2001) found ‘Volkamer’ lemon (*Citrus volkameriana* Tan.) had 30-50% lower root respiration under water stress than well watered plants. Jordan et al. (2003) found a 4-day irrigation frequency significantly increased shoot density, root depth, and root density of creeping bentgrass grown on a sand-based root-zone. With high PET throughout June and July

2011, the RDAI treatment interval between irrigation and precipitation was once every 2-3 d. This interval may not have been great enough to result in rooting depth differences. Rooting depths for all treatments decreased from 1 Aug. – 29 Sept. 2011 which may be explained by elevated soil temperatures causing increased root mortality.

Table 11. Rooting depth of creeping bentgrass putting greens under three irrigation methods, 2010-11, East Lansing, MI.

	2010				
Irrigation Method	July 2	Aug. 2	Sept. 15	Oct. 15	Nov. 2
	----------------------------cm----------------------------				
80% daily PET†	11.9	10.2	10.4	11.9	15.0
RDAI‡	13.2	11.9	12.4	12.7	15.0
TDR¶	13.0	13.0	12.4	14.2	12.4
LSD (0.05)	NS	NS	NS	NS	1.5

	2011					
Irrigation Method	May 16	July 1	Aug. 1	Sept. 1	Sept. 15	Sept. 29
	------------------------------------cm------------------------------------					
80% daily PET†	12.1	14.0	14.5	13.0	11.9	10.0
RDAI‡	12.7	15.1	14.0	14.5	15.4	11.4
TDR¶	12.8	14.3	16.9	15.0	13.3	12.7
LSD (0.05)	NS	NS	2.0	NS	2.6	NS

† 80% daily potential evapotranspiration
‡ Rooting depth adjusted irrigation
¶ Time domain reflectometry based deep and infrequent irrigation

Putting Green Quality

Quality ratings were significant ($p \leq 0.05$) on 10 of 18 dates in 2010 and 14 of 14 dates in 2011 (Table 12). Putting green quality data show no treatment differences until 19 July 2010, when the 80% daily PET produced the best quality putting surface and the TDR treatment produced the lowest quality putting surface. Beginning 2 Aug. 2010, and through the remainder of the year the 80% daily PET treatment produced the greatest quality putting green surface. Data in 2011 also show the 80% daily PET irrigation treatment created the highest quality putting surface on all 14 observation dates. The RDAI irrigation treatment was similar to the 80% daily PET treatment on 8 observation dates but the TDR treatment always resulted in the lowest 2011 putting green quality.

Multiple factors influence turfgrass quality including disease incidence, localized dry spot (LDS) coverage, turf density, and turf color (Walsh et al., 1999; Miller J., 2007). Beginning 19 July 2010, the TDR treatment displayed the greatest amount of LDS, leading to consistently low quality ratings. On 2 Aug. 2010, the RDAI treatment displayed similar levels of localized dry spot as the TDR and the greatest levels of dollar spot incidence leading to lower quality ratings. Despite recommendations for deep-infrequent irrigation (Qian et al., 1997), continuously applying water to ensure a moist 4- to 6 cm root-zone each morning resulted in improved summer quality for creeping bentgrass (8.0) compared to 6.8 for deep-infrequent irrigation (Fu and Dernoeden, 2009). Daily irrigation in this study resulted in the least LDS incidence leading to better quality turfgrass.

Drought stress induced by hydrophobic soil conditions on the TDR and RDAI treatments was the main cause of low quality ratings over both years. Drought suppresses growth and causes a loss of turf quality (White, 1996; Carrow and Duncan, 2003). Fu and Dernoeden (2009a) found drought stress imposed by deep and infrequent irrigation resulted in a 16% reduction in root diameter compared with light and frequently irrigated creeping bentgrass. A water deficit may also inhibit the ability to maintain physiological functions. Ribas-Carbo et al. (2005) found that even a 3-5 day cessation of watering resulted in an 80-100% decline in light-saturated net photosynthesis in controlled environment-grown soybean (*Glycine max*) leaves.

Table 12. Creeping bentgrass putting green quality under three irrigation methods, 2010-11, East Lansing, MI.

2010

Irrigation Method	Jun 15	Jun 29	Jul 8	Jul 13	Jul 19	Jul 22	Jul 26	Aug 2	Aug 10	Aug 16	Aug 23
	----------------------------------Quality (1-9)----------------------------------										
80% daily PET†	6.8	7.1	6.3	5.2	5.3	4.8	4.9	5.3	5.3	4.8	4.9
RDAI‡	7.1	7.4	6.1	5.2	5.2	4.9	5.1	4.8	4.6	4.3	4.0
TDR¶	7.3	7.1	6.1	5.1	5.0	4.7	5.0	4.7	4.5	4.4	3.8
LSD (0.05)	0.4	0.3	NS	NS	0.3	NS	NS	0.4	0.4	0.4	0.5

Irrigation Method	Aug 30	Sep 7	Sep 13	Sep 20	Sep 27	Oct 4	Oct 11
	------------------------Quality (1-9)------------------------						
80% daily PET†	5.3	3.5	4.7	4.3	4.7	5.1	5.1
RDAI‡	4.3	3.9	4.3	4.3	4.3	4.8	4.7
TDR¶	3.5	3.8	3.9	4.6	4.3	4.3	4.6
LSD (0.05)	0.7	0.4	0.5	NS	0.4	0.5	0.4

† 80% daily potential evapotranspiration
‡ Rooting depth adjusted irrigation
¶ Time domain reflectometry based deep and infrequent irrigation

Table 12 (cont'd)

Irrigation Method	Apr 12	May 6	May 23	Jun 2	Jun 13	Jun 27	Jul 14	Jul 27	Aug 12	Aug 18	Aug 25	Sep 9	Sep 22	Oct 5
	2011													
	--Quality (1-9)---													
80% daily PET†	7.6	7.1	7.9	7.9	8.2	7.9	7.8	8.3	8.0	8.1	7.4	7.2	7.1	7.6
RDAI‡	6.7	6.5	6.9	6.9	7.2	6.8	6.9	7.1	6.7	6.7	6.8	6.5	6.4	6.6
TDR¶	5.9	6.0	6.7	6.6	6.7	6.2	6.0	5.6	5.8	5.5	5.7	5.1	5.2	5.7
LSD (0.05)	1.1	0.8	0.6	1.2	0.9	1.3	1.5	0.8	1.0	1.4	1.4	0.9	1.1	0.9

† 80% daily potential evapotranspiration
‡ Rooting depth adjusted irrigation
¶ Time domain reflectometry based deep and infrequent irrigation

Percent Green Ground Cover

Digital imaging for percent green ground cover was not significant on twelve of thirteen dates in 2010 and seven of eight dates in 2011 (Table 13). Dollar spot reduced the percent green ground cover of the 80% Daily PET and RDAI treatments while the TDR treatment incurred the most LDS symptoms. Both of these factors together may have resulted in the lack of significance.

Table 13. Percent green ground coverage from creeping bentgrass putting greens under three irrigation methods, 2010-11, East Lansing, MI.

2010

Irrigation Method	23 Jun	28 Jun	15 Jul	3 Aug	10 Aug	16 Aug	23 Aug	1 Sep	9 Sep	14 Sep	23 Sep	30 Sep	12 Oct
	---% Green Ground Coverage--												
80% daily PET†	95.4	95.4	90.7	93.6	93.8	94.5	94.6	93.3	88.1	93.8	95.6	93.5	94.1
RDAI‡	95.9	95.2	90.4	92.7	94.3	92.7	94.4	93.2	89.6	93.6	95.8	93.2	93.4
TDR¶	95.4	94.4	89.0	91.4	93.6	92.8	92.9	90.5	87.8	93.3	95.2	93.0	94.4
LSD (0.05)	NS	NS	NS	1.7	NS	NS	NS	NS	NS	NS	NS	NS	NS

2011

Irrigation Method	24 May	8 Jun	21 Jun	16 Jul	25 Jul	10 Aug	21 Aug	5 Sep
	-----------------% Green Ground Coverage----------------------							
80% daily PET†	98.5	98.7	93.6	96.2	99.2	98.8	97.4	89.1
RDAI‡	96.5	99.3	95.9	96.1	99.2	98.0	95.1	93.5
TDR¶	96.0	97.8	84.8	87.7	88.2	85.4	85.9	87.0
LSD (0.05)	NS	NS	NS	6.7	NS	NS	NS	NS

† 80% daily potential evapotranspiration
‡ Rooting depth adjusted irrigation
¶ Time domain reflectometry

Green Speed

Green speed was not significant ($p \leq 0.05$) on any sampling date in 2010 or 2011. This corroborates findings from Lodge et al. (1991) which did not find significant differences in ball roll distance over three different irrigation regimes.

Localized Dry Spot Incidence

LDS data were significant ($p \leq 0.05$) on 14 of 17 dates in 2010 and 8 of 11 sampling dates in 2011 (Table 14). TDR plots displayed the greatest LDS incidence on 6 July 2010 and the greatest LDS coverage during the period from 22 July - 10 Aug. 2010. Between 23 Aug. - 7 Sept. 2010, plots differed in LDS coverage according to TDR ≥ RDAI > 80% daily PET. From 20 Sept. - 11 Oct. 2010, the TDR and RDAI irrigation treatment had more LDS than the 80% daily PET treatment. On 18 Oct. 2010, all treatments differed with the TDR having the most and the 80% daily PET having the least LDS coverage. The TDR irrigation treatment had the most LDS coverage from 21 June – 9 Sept. 2011.

LDS is a condition that can occur on all soil textures but is especially problematic on sandy soils. Extended periods of hot, dry weather are most conducive to the formation of hydrophobic soils (Panina, 2010) and may result in decreased infiltration of irrigation water and precipitation, non-uniform wetting of soil profiles, increased run-off and evaporation, and increased leaching due to preferential flow (Dekker et al., 2001a). Dekker et al. (2001b) found soils have critical soil volumetric water contents, below which causes a soil to become non-wettable in the field. Both the RDAI and TDR treatments allowed the upper soil profile to dry out considerably between irrigation applications below the critical soil water content (approximately 8% VWC). The RDAI treatment experienced decreased rooting depths July –

Aug. 2010 along with increased PET losses leading to a higher irrigation frequency. Increased irrigation frequency helped to alleviate LDS on the RDAI plots. The 80% Daily ET plots received regular irrigation to maintain a moist upper soil profile and resulted in minimal LDS.

In Sept. 2010, timely precipitation resulted in only three irrigation applications for the RDAI and TDR plots. Carrow (1996) found that high rooting density in the surface 3-10 cm of soil enhanced wilt possibly due to rapid depletion of the surface soil water. Precipitation that withheld irrigation may not have been sufficient to wet below 3-10 cm causing the RDAI soil profile to dry out and increase LDS symptoms. Greater irrigation volumes applied to the TDR treatment along with precipitation wetted the soil profile to greater depths reducing LDS symptoms by 13 Sept. 2010. Due to low PET extending irrigation intervals, LDS was enhanced in all irrigation treatments Oct. 2010. Low PET values resulted in extremely small volumes of daily water application causing insufficient rewetting of the soil profile to avoid increases in LDS in the 80% daily PET treatment. Under daily shallow irrigation, a large proportion of the irrigation volume applied remains in the upper 5 cm of soil and is subject to high rates of evapotranspiration (Sass and Horgan, 2006).

The lack of significance in May 2011 was due to high soil moisture during the winter and early spring decreasing LDS by 50% or more across all plots. Leading up to June 21, increasing temperatures and rapid soil drying increased LDS incidence. Finishing the 2010 season with the greatest LDS, LDS symptoms were more pronounced in the TDR treatment on 21 June 2011. Even after extended wet periods, soil water repellency and preferential flow paths can reoccur (Oostindie et al., 2005). The expression and extent of a soils water repellency depends mainly on soil water content (King, 1981; Dekker and Ritsema, 1994; de Jonge et al., 1999; Regalado and Ritter, 2005) and the soil’s wetting and drying history (Doerr and Thomas, 2000). The TDR treatment had a history of severe wetting and drying cycles in 2010 causing it to be more affected by LDS in 2011. Dekker et al. (2001) observed that not only drying but the temperature at which the drying took place influences the severity of water repellency in soils. There was a 12 d period 30 May - 10 June 2011 where little precipitation occurred and temperatures steadily rose to 34 C. The temperature at which the TDR's soil dried could have induced more severe LDS symptoms. Hot, dry periods during June/July 2011 caused increased LDS across TDR plots.

Due to large precipitation events occurring at the end of July and maximum air temperatures dropping below 30 C during the day and below 20 C at night, LDS symptoms declined slightly by 8 Aug 2011. Despite the reduction in LDS, the TDR treatment displayed the greatest amount of symptoms 8 Aug. 2011. By 17 Aug 2011, LDS increased over all treatments by 3.0, 4.4, and 5.5% for the 80% daily PET, RDAI, and TDR treatments, respectively. The increased LDS over all treatments could be explained by frequent light precipitation events that acted to postpone irrigation, but were not enough to completely rewet the upper soil profile. On 25 Aug 2011, the TDR treatment resulted in the most LDS coverage and LDS increased on RDAI and 80% daily ET plots. LDS may have increased on the 80% daily PET and RDAI plots due to increased organic matter accumulation. Organic matter content was not measured in this study, but observations during root length sampling revealed a large dark layer of OM. Large levels of OM can act to increase the severity of LDS. The development of water repellent soils is associated with organic matter coating soil particles while inducing hydrophobic properties on their surface area (Ma'shum and Farmer, 1985; Horne and McIntosh, 2000). Organic matter is greatest in the thatch layer under turfgrasses, leading to LDS forming near the soil surface. This organic layer was observed in the 80% daily PET and RDAI treatments, but not in the TDR treatment.

LDS was observed to increase across all plots by 9 Sept. 2011, but data show that the TDR treatment resulted in the greatest amount of LDS. Only 4 mm of precipitation was received over three events and PET was relatively low leading up to 9 Sept. 2011. When PET was low, similar to autumn 2010, the 80% Daily ET treatment required very small amounts of irrigation. Weeks of extremely light irrigation applications may have allowed the soil to dry to its critical VWC (8%) and result in the formation of LDS on 80% daily PET plots. The RDAI treatment is also governed by PET estimates, which when coupled with increased rooting depths, acted to increase the irrigation interval enough to allow the top layer of soil to dry out, inducing LDS formation. The TDR treatments LDS incidence remained relatively constant throughout the late summer and autumn of 2011.

Table 14. Percent localized dry spot coverage (LDS) from creeping bentgrass putting greens under three irrigation methods, 2010-11, East Lansing, MI.

	2010									
Irrigation Method	6 July	13 July	19 July	22 July	26 July	2 Aug	10 Aug	16 Aug	23 Aug	30 Aug
	---% LDS---									
80% daily PET†	3.4	2.6	2.0	2.9	2.0	2.7	3.8	2.6	4.8	4.4
RDAI‡	1.2	2.0	1.9	3.8	2.2	2.9	10.0	7.1	14.4	15.6
TDR¶	8.9	7.9	6.4	13.8	7.3	10.0	18.7	12.0	26.7	27.2
LSD (0.05)	4.9	NS	NS	6.6	4.5	6.1	9.0	NS	8.9	11.3

	2010						
Irrigation Method	7 Sept	13 Sept	20 Sept	27 Sept	4 Oct	11 Oct	18 Oct
	---% LDS---						
80% daily PET†	3.6	4.1	4.4	8.9	10.0	12.8	6.7
RDAI‡	12.2	11.7	18.9	32.2	34.4	36.7	31.1
TDR¶	22.2	16.1	21.7	30.0	33.3	32.8	38.3
LSD (0.05)	7.4	6.7	8.7	7.3	10.2	10.5	7.0

† 80% daily potential evapotranspiration
‡ Rooting depth adjusted irrigation
¶ Time domain reflectometry

Table 14 (cont'd)

	2011										
Irrigation Method	6 May	21 June	5 July	11 July	19 July	8 Aug	17 Aug	25 Aug	9 Sept	22 Sept	5 Oct
	--% LDS--										
80% daily PET†	2.8	3.9	6.7	5.0	2.8	2.2	5.2	8.6	15.6	24.4	21.1
RDAI‡	10.0	8.3	11.7	12.2	12.2	12.0	16.4	18.9	20.6	28.3	21.7
TDR¶	10.6	22.8	30.0	36.1	36.7	30.6	36.1	35.0	41.7	43.9	40.0
LSD (0.05)	NS	7.1	16.5	14.8	13.8	14.7	13.3	16.9	16.3	NS	NS

† 80% daily potential evapotranspiration
‡ Rooting depth adjusted irrigation
¶ Time domain reflectometry based deep and infrequent irrigation

Dollar Spot Incidence

Dollar spot (*Sclerotinia homeocarpa* F.T Bennet) incidence was significant ($p \leq 0.05$) on six of seven dates in 2010 and two of five dates in 2011 (Table 15). Dollar spot was most severe on the 80% daily PET and RDAI irrigation treatments from 21 June – 5 Aug. 2010. On 7 Sept. 2010 the RDAI had the most and the TDR had the least dollar spot incidence. On 23 Sept. 2010 the 80% daily PET treatment had the most and the TDR treatment had the least dollar spot. From 8 Aug. – 9 Sept. 2011 the TDR treatment had the least dollar spot incidence.

Disease models have been developed to predict dollar spot incidence (Mills and Rothwell, 1982; Hall, 1984). Mills and Rothwell (1982) state there is more of a risk of dollar spot when mean daily temperatures exceed 25 C and relative humidity is above 90% during any three days in any seven day period. Hall (1984) found increased dollar spot risk following: (i) two consecutive days with rainfall and a mean temperature > 22 C; or (ii) three consecutive days with rainfall and a mean temperature > 15 C. Dollar spot incidence began early in 2010 due to warm wet weather in June. Relative humidity in June 2010 was between 81 and 94 percent, while maximum temperatures were between 21 and 31 C. Moderate night time temperatures (9-20 C) increased the likelihood of disease occurrence (Hall, 1984). From 21 June – 26 July 2010, the 80% Daily ET and RDAI treatments produced more dollar spot than the TDR treatment. This finding could be due to more irrigation being applied to 80% daily PET and RDAI treatments than to the TDR treatment resulting in longer periods of leaf wetness. Higher dollar spot infection was observed at irrigation ≥ 80% Ep (Class A pan evaporation) in ‘Tifway’ bermudagrass (Cynodon dactylon L.) (Qian, 1999). The 80% Daily ET and RDAI treatment were irrigated 31 and 9 times from 1 June – 26 July 2010, and replaced 80% and 100% PET, respectively. Since irrigation was applied at 4am, the leaf blades may have been exposed to prolonged wetness. Extended periods of leaf wetness are thought to increase the severity of foliar pathogens (Williams et al., 1996). Williams et al. (1996) found the severity of dollar spot on creeping bentgrass was significantly reduced when leaf surface moisture was displaced by mowing or poling.

The TDR treatment may have produced the least dollar spot due to inhospitable soil conditions for the pathogen to thrive by facilitating severe wetting and drying cycles which have been shown to decrease microbial communities. Sparse rainfall events across large landscapes (i.e. Alaskan taiga) have been known to place additional stress on soil microbial communities (Clein and Schimel, 1994). Water potential 'upshock' associated with rewetting a dry soil can also negatively impact a large fraction of the microbial community (Bottner, 1985; Kieft et al., 1987). Prolific localized dry spot coverage on the TDR treatment may have contributed to the decreased occurrence of dollar spot as well.

Table 15. Dollar spot incidence from creeping bentgrass putting greens under three irrigation methods, 2010-11, East Lansing, MI.

	2010						
Irrigation Method	21 June	29 June	13 July	26 July	5 Aug.	7 Sept.	23 Sept.
	--------------------------------infection centers/m^2------------------------------------						
80% daily PET†	47.2	52.1	56.6	61.4	26.6	93.6	135.7
RDAI‡	41.7	42.7	55.2	66.7	33.9	98.7	126.4
TDR¶	21.0	25.1	30.2	40.4	29.9	65.1	94.2
LSD (0.05)	18.8	17.0	19.8	15.5	NS	29.6	34.2

	2011				
Irrigation Method	3 June	21 June	19 July	8 Aug.	9 Sept.
	----------------------infection centers/m^2----------------------------				
80% daily PET†	1.0	3.8	16.7	84.3	103.3
RDAI‡	1.2	2.2	20.4	74.8	66.9
TDR¶	2.0	3.7	10.0	37.9	34.3
LSD (0.05)	NS	NS	NS	34.4	66.4

† 80% daily potential evapotranspiration
‡ Rooting depth adjusted irrigation
¶ Time domain reflectometry based deep and infrequent irrigation

CONCLUSIONS

<u>Chapter one</u>: Environmental study

Data from this study indicate that alternating irrigation scheduling throughout the growing season could lead to water savings and reduced environmental impact. Applying light and frequent irrigation at a deficit conserves water during months that do not receive regular precipitation. During months that receive regular rainfall, deep and infrequent irrigation could conserve water by utilizing precipitation to recharge soil moisture between irrigation applications. Data show that leachate volumes, nitrate loading and orthophosphate loading is minimized by light and frequent irrigation and enhanced by deep and infrequent irrigation that does not take rooting depth and soil moisture holding capacity into account. The RDAI treatment applied water volumes only to the depth of the active root zone resulting in reduced leachate and nutrient loads, but no water savings during dry months.

Implementing an integrated water management plan, where irrigation scheduling methodology changes with seasonal conditions would result in the greatest water savings and minimal nutrient loading. Times in which PET losses are high require low volumes of water at short intervals in order to keep the upper soil profile moist while also reducing leachate. However, times of low PET demand or high humidity can benefit from applying greater water volumes at extended irrigation intervals, but moisture status must be monitored to ensure the upper soil profile remains above the critical VWC to avoid hydrophobic conditions. Further investigation into deficit irrigation and seasonally dependent optimal irrigation frequency for sand-based putting greens could lead to even greater water savings and improved nutrient retention.

<u>Chapter two</u>: Putting green performance study

Data from this study indicate that alternating irrigation scheduling throughout the growing season may result in water savings and enhanced putting green quality. Applying light and frequent irrigation at a deficit conserves water and reduces the occurrence of LDS during months that do not receive regular precipitation. During months that receive regular rainfall, deep and infrequent irrigation allows precipitation to recharge soil moisture between irrigation applications. Deep and infrequent irrigation based on soil moisture status resulted in reduced dollar spot infection but increased irrigation volumes, leachate volumes, and LDS occurrence requiring wetting agents. Deep and infrequent irrigation based on rooting depth resulted in minimal irrigation volumes in the autumn and reduced LDS during the summer.

Implementing an integrated water management plan, where irrigation scheduling methodology changes with seasonal conditions would result in the greatest water savings while also producing an acceptable quality putting green surface. Times in which PET losses are high require low volumes applied at short intervals in order to keep the upper soil profile moist while reducing water usage. Times of low PET demand or high humidity can benefit from applying greater water volumes at extended irrigation intervals, but moisture status must be monitored to ensure the upper soil profile remains above the critical VWC to avoid hydrophobic conditions. Further investigation of differing irrigation scheduling methods on varying soil types could advance scientific understanding of plant-soil-water relationships and result in water savings and enhanced turfgrass quality.

APPENDIX

Table 16. Soil nutrient test results for USGA putting green.

P	K	Mg	Ca	Organic Matter	CEC
---------------------------ppm----------------------------------				-------%---------	meq / 100 g
11	48	42	1046	0.8	5.7

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