HYDROLOGICAL AND BIOGEOCHEMICAL INVESTIGATIONS OF IRRIGATION AND NUTRIENT MANAGEMENT EFFECTS ON SURFACE RUNOFF FROM ST. AUGUSTINEGRASS LAWNS

A Dissertation

by

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ABSTRACT

St. Augustinegrass (*Stenotaphrum secundatum* (Walt.) Kuntze) performance under conservation irrigation is poorly described. Further, the effect of summer drought stress on the lawn ecosystem could have unforeseen implications for storm water runoff quantity and quality. To address these concerns, two field studies were conducted in College Station, TX, to examine the relationships between St. Augustinegrass health, conservation irrigation management, and surface runoff chemistry. In experiment 1, turf performed adequately when receiving water at 60% of historical average ET_o, but substantial overwatering occurred during the wettest year. Experiment 2 was conducted at a state-of-the-art surface runoff capture and measurement facility with the objectives of estimating effective rainfall in lawns, quantifying NO_3-N losses due to irrigation and fertility management, and investigating relative partitioning among N species in runoff. Commonly used effective rainfall coefficients did not result in accurate estimates of effective rainfall. Rather, methods which accounted for initial abstraction and subsequent rainfall independently were more accurate. Reduced runoff volumes associated with deficit irrigation equated to a short-term reduction in NO_3-N exports. However, the resultant accumulation of N in fertilized sites led to higher NO_3-N concentrations over time. Nitrate-N concentration was typically below 5 mg L^{-1} but peaks in excess of 20 mg L^{-1} were measured during late winter in one year. Aside from this atypical peak, the largest portion of total dissolved N (TDN) was in the organic form (DON), while NH_4-N was typically the smallest portion. Overall, deficit irrigation practices appear to be effective methods for conserving water if occasional turf attrition can be tolerated. Under deficit irrigation, reduced fertility appears warranted for mitigating potential N pollution over time. Dissolved organic N as an export from turf has largely been ignored by previous research. These data suggest DON could be the primary species of N leaving turf sites, and further study of the quality of N within this pool is warranted.

DEDICATION

…to my family as we move on to a new journey in a strange land.

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NOMENCLATURE

N	Nitrogen
TDN	Total Dissolved Nitrogen
NO_3-N	Nitrate - Nitrogen
NH_4-N	Ammonium - Nitrogen
DON	Dissolved Organic Nitrogen
DIN	Dissolved Inorganic Nitrogen
DON:TDN	Dissolved Organic Nitrogen : Total Dissolve Nitrogen Ratio
NIT:AMM	Nitrate – Nitrogen : Ammonium – Nitrogen Ratio
WEON	Water Extractable Organic Nitrogen
WEIN	Water Extractable Inorganic Nitrogen
IA	Initial Abstraction
RR	Runoff Ratio
FAO-56	Food and Agriculture Organization of the United Nations Irrigation and Drainage Paper No. 56
PM	Penman – Monteith Reference ET Method
ET	Evapotranspiration
ET_o	Reference ET
ET_c	Crop ET
$ET_{c\ adj}$	Adjusted Crop Coefficient
ET_{Def}	ET Deficit

K_c	Crop Coefficient
K_{er}	Effective Rainfall Coefficient
K_s	Stress Coefficient
K_{as}	Allowable Stress Coefficient
MDIL	Maximum Deficit Irrigation Level
R_{eff}	Effective Rainfall
TXETN	Texas ET Network
SCS – CN	Soil Conservation Service – Curve Number
ANOVA	Analysis of Variance
LSD	Least Significant Difference

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CHAPTER I

INTRODUCTION AND LITERATURE REVIEW

Problem Statement

Residential water demand management continues to be a primary concern among major water purveyors in Texas. During the summer, peak water use is largely driven by landscape irrigation. To regulate demand during these peak use periods, purveyors commonly impose water restrictions which limit the frequency at which consumers can irrigate. Specific restrictions are selected for their ease of implementation and effectiveness at spreading peak demand across the water system. Despite not directly addressing water conservation, restrictions are assumed to enhance annual water savings. Major shortfalls exist in our understanding of plant – soil water relationships in Texas lawn irrigation management. St. Augustinegrass (*Stenotaphrum secundatum* (Walt.) Kuntze) turf response to specific conservation irrigation volumes and frequencies are poorly understood. Soil moisture conditions have a well understood effect on water infiltration and therefore surface runoff. The effect of varying turf densities on runoff volumes is less well documented. Irrigation management which alters soil moisture and presumably turf canopy conditions are likely to impact on-site water retention and storm water contaminant loading in a conflicting manner.

Literature Review

St. Augustinegrass in Texas

St. Augustinegrass is a fast-growing, stoloniferous perennial grass adapted to warm, coastal regions of the U.S. St. Augustinegrass is relatively inexpensive to produce; easy to install; provides a quality lawn under medium management levels; is effectively clipped with a rotary mower; demonstrates good shade, salt, and heat tolerances; and is adapted to soils across the state Duble, 2001). St. Augustinegrass is adapted to most irrigated landscapes in Texas but has limited adaptation to northern regions of the state due to poor cold tolerance and western regions due to aridity (Chalmers and McAfee, 2010). In Texas, the majority of residential lawns are planted with St. Augustinegrass. According to an economic analysis of Texas sod production, about 60% of sod sales across the state are St. Augustinegrass and 82% of farms surveyed had some acreage planted to St. Augustinegrass (Falconer and Niemeyer, 2006). Available cultivars in the state include the following in order of number of production farms: ‘Raleigh’, ‘Palmetto’, ‘Floratam’, ‘Texas Common’, ‘Delmar’, ‘Sapphire’, ‘Amerishade’, and ‘Captiva’ (Turfgrass Producers of Texas, 2013). Among those producing St. Augustinegrass, ‘Raleigh’ is grown on 91% of sod farms (Falconer and Niemeyer, 2006).

Plant Water Use

Plant water use is defined as the amount of water required for plant growth plus water lost through transpiration and evaporation from plant and soil surfaces (Beard, 1973). Only 1 to 3% of water is used for metabolic activities, therefore the overwhelming majority of water is transpired (Beard, 1973). Transpiration under well-watered conditions is largely described by the cohesion-tension theory which explains water uptake as a metabolically passive process driven by a water potential gradient decreasing from the soil, to plant roots, up through the plant, to the atmosphere (Taiz and Zeiger, 2006). The theory suggests water moves as a continuous column of water from the roots through the xylem. Transpiration is caused by two fundamental processes: evaporation of water from inter-cellular surfaces and diffusion of vapor out of the leaves. Evaporation is driven by the energy balance and diffusion by the vapor pressure gradient between intercellular spaces and the environmental conditions outside the leaf. The vapor pressure inside the leaf is often considered to be at saturation for the leaf temperature. Stomata are the gateways for the majority of transpirational water loss in plants. Diurnal patterns of stomatal control result in opening during the day and closure at night. Transpiration rates differ among turfgrass genotypes due to variations in rooting, leaf area, cuticle thickness, osmotic pressure of leaf cells, leaf morphology, leaf orientation, leaf internal resistances, stomatal variations, and leaf rolling capability (Beard, 1973). These differences can be described in terms of resistances to the physical processes of evaporation and diffusion.

The combination of transpiration and surface evaporation is termed evapotranspiration (ET). Due to the difficulty in separating evaporation from transpiration in the field, water balance measurements typically do not differentiate between the two and simply account for total ET. Most commonly, ET rate is described in terms of a water depth per unit time such as mm d^{-1} or in. wk^{-1}. Previous studies have compared ET rates among various species and cultivars under well-watered conditions (Biran, 1981; Kim and Beard, 1988; Atkins et al., 1991; Green et al., 1990a; Salaiz et al., 1991). Others have measured ET under conditions which include periodic drying cycles or moderate drought stress (Green et al., 1990b; Devitt et al., 1992; Carrow, 1995; Pannkuk et al., 2010). Methods for quantifying turfgrass ET in the field have included the use of mini-lysimeters (Aronson et al., 1987; Kim and Beard, 1988; Green et al., 1990a, 1990b; Bowman and Macaulay, 1991; Atkins et al., 1991; Green et al., 1991; Salaiz et al., 1991), large lysimeters (Stewart and Mills, 1967; Kneebone and Pepper, 1982; Devitt et al., 1992), changes in soil moisture as measured by sensors (Carrow, 1995; Pannkuk et al., 2010), direct measurement using closed chambers (Peacock and Dudeck, 1985), and eddy correlation methods (Jia et al., 2009; Peterson, 2013). Results of ET studies indicate substantial inter- and intra-specific variation exists among turfgrasses (Biran et al., 1981). Cool-season turfgrasses typically have higher ET rates than warm-season turfgrasses (Biran et al., 1981). Published St. Augustinegrass ET rates have ranged from 3.7 mm d^{-1} to 8.1 mm d^{-1} (Kim and Beard, 1988; Atkins et al., 1991; Augustin, 1984). Discrepancies among published rates are due to differing management and environmental conditions. A field study using mini-lysimeters described ‘Texas

Common' St. Augustinegrass as having medium-low ET rates (Kim and Beard, 1988). In desert conditions, St. Augustinegrass had the highest transpiration rate among warm-season turfgrasses (Kneebone and Pepper, 1982). Environmental parameters can affect turfgrass ET non-uniformly among genotypes; that is, relative rankings of inter- and intra-specific comparisons are not always consistent across environments. (Atkins et al., 1991)

Increased water use rates have been associated with management practices such as raising mowing heights (Shearman and Beard, 1973; Biran et al., 1981; Feldhake et al., 1984; Johns et al., 1983; Kim, 1983), mowing frequently (Shearman and Beard, 1973), increasing nitrogen fertility (Shearman and Beard, 1973; Kneebone and Pepper, 1982; Kim, 1983; Feldhake et al., 1984; Barton et al., 2009), and irrigating frequently (Shearman and Beard, 1973; Biran, 1981). Increasing K fertility has been shown to reduce ET rates unless high levels of N and P are applied; under such high fertility levels, K fertilizers increased ET rates (Ebdon et al., 1999). Environmental stresses such as compaction and irrigation water sodicity may reduce ET rates (Sills and Carrow, 1983; Pannkuk et al., 2010).

Drought Stress

If transpiration exceeds water absorption by roots, a plant undergoes a water deficit which can also be termed drought stress (Beard, 1973). Internal water deficits can cause a number of physiological and morphological responses within the turfgrass plant including increased rooting, decreased shoot density, decreased leaf number, thinner leaves, increased cuticle thickness, decreased succulence, decreased photosynthetic rate, and decreased protein content (Beard, 1973). The first visible indication of a water deficit in turf is ‘foot-printing’ which describes the delayed return of leaves to their original upright position after foot traffic. Foot-printing indicates a reduction in leaf water potential and poor turgor pressure at the cellular level. A color change may also be observed which gives turf a blue-gray appearance. The second visible indication of a water deficit is wilting (the drooping, rolling, or folding of leaves resulting from a loss of turgidity). Initially, wilting occurs during mid-day or during peak evaporative conditions and is not expressed the following morning due to nocturnal turgor recovery (DiPaola, 1977). If water deficits are not corrected, leaf firing (senescence) can occur in many turfgrasses. Leaf firing refers to chlorosis of leaf tips that progresses down the leaf margins under drought conditions (Carrow, 1996). Eventually, many grasses are able to survive loss of green cover and become dormant (Steinke et al., 2010). Upon re-wetting of the soil, new shoots can emerge and promote recovery. The duration of drought is positively related to turfgrass recuperative rates (Steinke et al., 2013). Drought stress has been quantified using the following parameters: visual turf quality, visual leaf wilting, visual leaf firing (Carrow, 1996), digital image analysis (Steinke et al., 2010), chlorophyll fluorescence, verdure or leaf dry mass, leaf area index, leaf water potential, relative leaf water content, canopy temperature (Huang et al., 1998), carbon exchange rate, diffusive resistance, transpiration rate (Peacock and Dudeck, 1984), nonstructural carbohydrate content, chlorophyll content, electrolyte leakage (Fernandez and Love, 1993), protein concentration, water soluble carbohydrate content (DaCosta and Huang, 2006a), canopy spectral reflectance (Jiang and Carrow, 2005), clipping yield (DiPaola, 1977), and antioxidant formation (Jiang and Huang, 2001).

The severity of the stress is influenced by the duration of drought, evaporative demand of the atmosphere, and water retention characteristics of the soil (Beard, 1989). A plant’s ability to function or survive under drought conditions is termed drought resistance. Three mechanisms contribute to a plant’s drought resistance: drought escape, drought avoidance, or drought tolerance (Beard, 1989). Escape refers to plants which complete their lifecycle prior to the onset of drought conditions and rely on the next generation to emerge when favorable conditions return. For turfgrasses, avoidance and tolerance are more desirable mechanisms. Drought avoidance refers to the ability of a plant to exclude internal water deficits by reducing ET rates or enhancing root functionality and depth. Drought tolerance refers to turgor maintenance, desiccation tolerance, or dormancy capability despite the onset of tissue damaging internal water deficits. Water consumption rates are not consistent predictors of drought resistance (Gibeault et al., 1989; Beard, 1989; Ervin and Koski; 1998) although lower ET rates are associated with enhanced drought avoidance (Zhou et al., 2012). Drought resistance has been quantified by exposing turfgrasses to prolonged dry down periods. Chlorophyll fluorescence and digital image analysis for percent cover have been used to select for drought resistant species to be used along roadsides (Ow et al., 2011). Huang et al. (1997) studied warm-season turfgrass shoot responses under soil drying at upper and/or lower sections of the rootzone. They measured species differences in canopy temperature, leaf chlorophyll content, relative water content, and dry matter production and speculated that genotype differences were related to root plasticity. In Georgia, ‘Meyer’ zoysiagrass demonstrated poor drought resistance which was associated with sparse deep rooting (Carrow, 1996). Among *Zoysia* spp., rooting depth and mass were correlated with drought resistance (Marcum et al., 1995). Similar conclusions have been drawn for cool-season turfgrasses (Ervin and Koski, 1998; Suplick-Ploense and Qian, 2005). Drought tolerance and recovery of several warm-season turfgrasses and tall fescue were well correlated with osmotic adjustment during drought (Qian and Fry, 1997). A number of other papers have described leaf water relations as related to drought resistance (White et al., 1992; Lehman et al., 1993; Huang et al., 1998; White et al., 2001).

Reports on St. Augustinegrass drought resistance suggest substantial variation among genotypes. Beard (1989) described St. Augustinegrass as having ‘Good’ drought resistance but was worst among warm-season grasses. Carrow (1996) reported that ‘Raleigh’ St. Augustinegrass had high drought tolerance as defined by resistance to wilting and leaf firing. Among warm-season turfgrasses in the same study, drought resistance was strongly related to rooting depth. A field study using a linear gradient irrigation system similarly ranked warm-season turfgrasses (Qian and Engelke, 1999). Sifers et al. (1990) reported high intra-specific variation in leaf firing among St. Augustinegrasses; namely, ‘Floratam’ was highly drought resistant, while ‘Raleigh’ showed poor drought resistance. Other studies have similarly found ‘Floratam’ to have high drought resistance relative to other St. Augustinegrasses (Steinke et al., 2010).

The Need for Supplemental Irrigation

When cumulative ET exceeds effective rainfall, supplemental irrigation is required to prevent drought stress and maintain healthy turf. In Central and West Texas, such conditions typically exist from late spring through late summer although global sea surface temperature anomalies and tropical systems can have significant effects on seasonal rainfall across the state (Texas Water Development Board, 2012).

State-wide, Texas expects its population to increase 82% by 2060 with the majority of this growth occurring in metropolitan centers (Texas Water Development Board, 2012). Urban landscape irrigation most commonly uses municipal potable water supply, and the growing urban and suburban populations are placing stress on existing water supplies. During peak irrigation months, outdoor water use may represent 40 to 60% of residential water consumption and increase per capita use by two to three fold compared to winter season lows Vickers, 1991; White et al., 2004). Residential water consumption may increase by 33% during the summer in cities east of the Mississippi (Kjelgren et al., 2000). In more arid regions, summer outdoor water use was estimated as 48% of annual consumption (Kjelgren et al., 2000). A report released by the Texas Water Development Board estimated that 31% of residential water consumption is dedicated to outdoor uses (Hermitte and Mace, 2012). Thus, decreases in outdoor water use (i.e. landscape irrigation) would produce substantial reductions in total water consumption. Considering that turf represents a significant acreage of residential landscapes, understanding minimum water requirements and proper irrigation scheduling for common lawn grasses should be a primary objective of turfgrass research.

Irrigation Scheduling

Irrigation scheduling contains two components: event frequency and event volume. Event frequency can be selected through a number of methods including convenience (fixed interval), visual plant cues, soil moisture sensing, or soil water budget estimation. Calendar-based/fixed interval irrigation scheduling is fairly common because it is easy to implement and requires little attention from the lawn manager, especially when automatic in-ground irrigation is installed (Bremer et al., 2012). In addition, many water purveyors mandate irrigation restrictions based on calendar scheduling. Calendar-based irrigation is potentially inefficient due to scheduling patterns that may not reflect plant water needs. For example, irrigation run times and frequencies are often unchanged regardless of the season (Bremer et al., 2012). Calendar-based methods can be improved by using historical ET, real-time ET, or soil moisture sensors to set run times each week so that irrigation applied does not exceed soil field capacity (Pope and Fipps, 2000; White et al, 2004).

Plant cues can include both visual cues and measured plant parameters. Visual cues such as foot-printing or wilting can be used to predict the next irrigation event. Wilt-based irrigation requires an understanding of plant – soil water interactions since wilting can occur despite adequate soil moisture (Beard, 1973). Applying irrigation when ‘the grass looks dry’ is a common method among homeowners who lack in-ground irrigation systems (Bremer et al., 2012). At the first sign of wilting, untrained irrigators may prematurely apply irrigation without knowledge of the potential for nocturnal turgor recovery (DiPaola, 1977). Plant parameters such as canopy temperature and reflectance have also been used to schedule turf irrigation (Mantell and Stanhill, 1966; Throssell et al., 1987; Horst et al., 1989; Carrow, 1993; Jalali-Farahani et al., 1993; Jalali-Farahani et al., 1994; Emekli et al., 2007; Jiang et al., 2009; Johnsen et al., 2009). These methods require active monitoring of plant parameters which may be impractical for novice irrigators or most residential lawn settings. Wilt-based irrigation has been shown to maintain good quality turf at reduced irrigation volumes (Biran et al., 1981; Lewis et al., 2012).

Soil moisture sensor-based irrigation is among the most water conserving methods in the literature (Youngner et al., 1981; Aronson et al., 1987; Qualls et al., 2001; Cardenas-Lailhacar et al., 2010a, b; Haley and Dukes, 2011; Cardenas-Lailhacar and Dukes, 2012). Irrigation is applied such that soil moisture cycles between field capacity and some critical moisture content prior to reaching the permanent wilting point (Evett et al., 2012). The critical value for determining when to apply irrigation is often described as a percentage of plant available water (PAW) and is termed management allowed depletion (MAD). Soil MAD implies that within PAW exists a finite amount of readily available water (RAW), and under a given set of meteorological conditions, plant health will be reduced if the MAD level is exceeded. Since soil hydraulic properties vary across sites, estimating PAW requires assuming values for soil field capacity, permanent wilting point, and effective root zone depth. Science-based recommendations for MAD have not been published for St. Augustinegrass lawns, but a MAD of 50% PAW is commonly used (Allen et al., 1998). The use of a single MAD has been criticized due to the variation in soil tension associated with similar MAD volumetric water contents (Richards and

Marsh, 1961). Rather, MAD should be adjusted to reflect local plant – soil water conditions. Alternatively, critical soil moisture contents can be based on plant physiological responses such as transpiration rate. Cathey et al. (2011) studied warm-season turfgrass irrigation interval using several target transpiration rates (defined as normalized transpiration ratio or NTR) to set irritation frequency. In their study, 'Floratam' St. Augustinegrass began to wilt at 0.5 NTR and fired at 0.3 NTR, but recovered to acceptable turf levels within 7 days of well watered conditions. For wetter climates, tensiometer interruption-based irrigation successfully maintained bermudagrass (*Cynodon dactylon* X *C. transvaalensis*) turf using an event trigger of -0.1 bar at the 5 and 10 cm depth (Augustin and Snyder, 1984). In Mediterranean climates, tensiometers installed at 15 and 30 cm depths were used to trigger irrigation events at -0.65 bar for several warm and cool-season turfgrasses (Youngner et al., 1981). Granular matrix soil moisture sensors (resistance-based) reduced irrigation applied to various Colorado turf sites by an average of 73% of calculated ET (Blaney-Criddle equation) (Qualls et al., 2001). Blonquist et al. (2006) reported that time domain transmission (TDT) sensors buried at a 10cm depth could be used to maintain Kentucky bluegrass (*Poa pratensis* L.) using a soil MAD of 50% to trigger irrigation events. In the study, use of the TDT sensor resulted in similar water savings as meteorological-based ET estimation methods. Others have reported that a trigger of 80% field capacity was adequate to maintain St. Augustinegrass grown on Florida sandy soils (Cardenas-Lailhacar and Dukes, 2012). In their study, superior water savings were measured under fully automated soil moisture sensing systems when compared to those only used to adjust run times on calendar-based schedules. In general, soil moisture sensing systems have been most effective in wet climates where substantial overwatering can occur due to poor accounting of rainfall (Cardenas-Lailhacar et al., 2010a, b). Although the potential for water savings exist, soil moisture sensing systems have not gained the popularity of other methods. This has been largely attributed to initial costs of sensors, but technology costs have been decreasing which suggests popular use may increase (Cardenas-Lailhacar and Dukes, 2012). Soil moisture sensing system efficacy can vary with manufacturer and technology (Cardenas-Lailhacar and Dukes, 2012). For example, in Florida sandy soils, TDT sensors demonstrated significant water savings compared to granular matrix resistance sensors (Cardenas-Lailhacar and Dukes, 2012). Proper siting of single sensor systems can be difficult without extensive knowledge of local edaphic properties and variation across irrigation zones (Blonquist et al., 2006). Establishment of soil moisture thresholds and proper installation can also affect system performance (McCready et al., 2009; Greenwood et al., 2010). To achieve maximum water savings, soil moisture sensors require site specific calibrations (Greenwood et al., 2010). Monitoring and replacement of failing sensors can create long-term maintenance problems, particularly if multiple sensors are installed across the landscape (Greenwood et al, 2010).

Perhaps the ideal method for irrigation scheduling utilizes soil water budgets and estimated values of ET to account for all water inputs and outputs using formulas similar to equation 1:

$$SM = SM_0 + P + I - ET - RO - D \qquad \text{(Eq. 1.1),}$$

where SM is the existing soil moisture, SM_0 is the initial soil moisture for the given time period, P is the total precipitation, I is the irrigation applied, RO is runoff from rainfall or irrigation events, and D is deep drainage.

Soil water budget systems for irrigation scheduling require accurate estimates of soil water depletion due to ET which is typically estimated from meteorological data. ET-based irrigation has been shown to reduce water consumption while sustaining turf quality compared to less scientifically-based methods (Devitt et al., 1992). When used in conjunction with rain sensor interrupters, ET-based methods have been as efficient as soil moisture sensing methods (McCready et al., 2009). Evaporation from an open pan has been used to estimate turfgrass ET (Youngner et al., 1981; Gibeault et al., 1989; Carrow, 1996; Qian and Engelke, 1999). Although pan ET can provide a reasonable estimate, it is labor intensive and sensitive to wind fetch and speed (Allen et al., 1998). Over the last twenty years, standardized versions of meteorological-based estimates of ET have gained popularity due to their accuracy across multiple climates and automated capabilities (Allen et al., 1998). Meteorological-based methods have been further advanced due to increased availability of real-time data (Texas ET Network, California Irrigation Management Information System [CIMIS], Arizona Meteorological Network [AMET]).

ET_o – K_c Methods

Potential ET (PET) refers to ET from a theoretical crop of uniform height having complete green density under non-limiting soil moisture, thus representing the evaporative demand of the atmosphere (Penman, 1956). Several methods for estimating PET from meteorological data have been developed, but the Penman-Monteith combination model is generally recognized as the most accurate and is the basis for FAO (Food and Agriculture Organization of the United Nations) and ASCE (American Society of Civil Engineers) standards (Howell and Evett, 2004). Penman-Monteith PET takes into account vegetation canopy resistances that can be difficult to measure and have substantial diurnal variability. Therefore, empirically derived parameters are used to calculate reference ET (ET_o) for a specific reference crop. The FAO developed a standardized ET_o model (FAO-56 PM) assuming a cool-season grass reference crop maintained at a height of 0.12 m (Allen et al., 1998). The resulting crop is assumed to have a fixed surface resistance of 70 s m^{-1} which describes an occasionally dry surface that might occur under weekly irrigation (Allen et al., 1998). The FAO-56 PM ET_o is most applicable to crops of similar height and morphology as the reference crop, therefore the model should be a good fit for turfgrasses. Scalar adjustments to ET_o can be used to estimate a desired crop ET (ET_c) using Equation 2,

$$ET_c = ET_o \text{ x } K_c \qquad \text{(Eq. 1.2),}$$

where ET_c is the daily ET for the crop of interest and K_c is the corresponding crop coefficient.

Crop coefficients can have substantial inter-seasonal and inter-monthly variability (Gibeault et al., 1989). Crop coefficient variability may be more intuitive for annual crops which increase in height and leaf area as the plant matures from seedling emergence to harvest. In warm-season turfgrasses, crop coefficients can be lower for early spring until full canopy cover is achieved. During most of the growing season, variations are less dramatic and a single crop coefficient is usually adequate. Crop coefficients can be calculated by measuring plant actual ET (ET_a) and using Equation 3:

$$K_c = ET_a / ET_o \qquad \text{(Eq. 1.3)},$$

where ET_a and ET_o can represent daily or aggregated values averaged over the course of a growing season. Reported K_c's for warm-season turfgrasses maintained as lawns are listed in Table 1.1.

Several previous investigations of turfgrass ET may have violated the assumption of well-watered conditions. This is problematic when trying to compare across publications or sites since management levels are rarely identical. Such values, although confounded with soil moisture stress, can be useful since turf managers are rarely maximizing plant yield. Comparisons are further obscured because of different methodologies for measuring ET_a and calculating ET_o

Table 1.1. Reported crop coefficients (K_c's) for warm-season lawns.

Species	Cultivar	K_c	ET$_a$ Method	ET$_o$ Method	Climate	Scheduling Method	Reference
St. Augustine	Raleigh	0.68 / 0.72	TDR	Pan / FAO – 24 Penman	Georgia	56% soil MAD	Carrow, 1995
Zoysia[†]	Meyer	0.68 / 0.81					
Bermuda[‡]	Common	0.59 / 0.68					
Hybrid Bermuda	Tifway	0.57 / 0.67					
St. Augustine	Nortam	0.44	Linear Gradient Irrigation	Pan	Dallas	3 d wk^{-1}	Qian and Engelke, 1999
Buffalo[§]	Prairie	0.26					
Hybrid Bermuda	Tifway	0.35					
Zoysia	Meyer	0.68					
St. Augustine		0.63 / 0.52	Lysimeter	Sunken Pan	California	15 cb / 65 cb	Youngner et al., 1981
Zoysia		0.49	Lysimeter	Pan	Arizona	Maintained perched water table at 40 to 45 cm depth	Kneebone and Pepper, 1982
St. Augustine		0.43					
Bermuda	seeded	0.65					
Buffalo Bermuda		0.75	Linear Gradient Irrigation	FAO PM	New Mexico	2 to 3 d wk^{-1}	Smeal et al., 2003
Warm-season		0.75		FAO-56 PM			Allen et al., 1998
Warm-season		0.6		FAO-56 PM	Texas	1 d wk^{-1}	Pope and Fipps, 2000
St. Augustine	Raleigh	0.52 / 0.34	FDR	FAO-56 PM	San Antonio / College Station	1 -2 d wk^{-1}	Pannkuk et al., 2010
Bermuda		0.6	Lysimeter	Pan	Hawaii		Ekern, 1966
Bermuda	Common	0.55	Lysimeter	Penman	Nevada		Devitt et al., 1992
Warm-season		0.6		FAO-24 Penman	California		Gibeault et al., 1989

[†] *Zoysia japonica* Steud.

[‡] *Cynodon dactylon* (L.) Pers.

[§] *Bouteloua dactyloides* (Nutt.) Columbus

Irrigation Frequency

The effects of irrigation frequency have been studied for a number of turfgrasses including annual bluegrass (*Poa annua* L.) (Slavens et al., 2011), zoysiagrass (Qian and Fry, 1996; Sinclair et al., 2011), Kentucky bluegrass (Madison and Hagan, 1962), tall fescue (*Lolium arundinaceum* [Schreb.] Darbysh.) (Biran, 1981; King and Bush, 1985; Richie et al., 2002), bermudagrass (Biran, 1981; Sinclair et al., 2011), St. Augustinegrass (DiPaola, 1977; Biran, 1981; Peacock and Dudeck, 1984,1985; Sinclair et al., 2011), kikuyugrass (*Pennisetum clandestinum* Hochst. ex Chiov.) (Mantell, 1966), bahiagrass (*Paspalum notatum* Flugge) (Sinclair et al., 2011), seashore paspalum (*Paspalum vaginatum* Sw.) (Biran, 1981), centipedegrass (*Eremochloa ophiuroides* [Munro] Hack.) (Biran, 1981), perennial ryegrass (*Lolium perenne* L.) (Biran, 1981), and creeping bentgrass (*Agrostis palustris* Huds.) (Madison, 1962; Shearman and Beard, 1973; Jordan et al., 2003).

Infrequent irrigation has often been associated with enhanced turf quality (Richie et al., 2002; Jordan et al., 2003), greater rooting (Doss et al., 1960; Madison, 1962; Madison and Hagan, 1962; Qian and Fry, 1996; Jordan et al., 2003), reduced verdure and chlorophyll (Madison, 1962), reduced pest pressures (Davis and Dernoeden, 1991), and reduced clipping yield (Mantell, 1966; Biran, 1981). Tall fescue genotypes were compared under daily irrigation versus two moisture stress regimes: intermittent or prolonged (Silcock and Wilson, 1981). They reported increased water use efficiency (defined as g dry matter / g water consumed) under the prolonged stress regime but reduced water use efficiency under intermittent stress. Increased rooting has been attributed to greater oxygen diffusion rates and reduced susceptibility to compaction (Qian and Fry, 1996). Periodic water stress such as incurred through infrequent irrigation has been shown to pre-condition plants for future stresses including additional water stress or heat stress (King and Bush, 1985; Qian and Fry, 1996; Jiang and Huang, 2001). For example, during an extended dry period, pre-conditioned zoysiagrass demonstrated greater leaf water potentials, growth rates, water depletion from deep soil depths, and turf quality during an extended dry down (Qian and Fry, 1996). Infrequently watered tall fescue seedlings used less water and had greater leaf extension rates than daily watered plants upon exposure to extended drying cycles (King and Bush, 1985). According to Shearman and Beard (1973), infrequent irrigation pre-conditioning caused higher water use rates in creeping bentgrass, but these results may have been confounded due to significant reductions in turf cover under daily irrigation. More recent studies have found irrigation frequency did not affect sod root development of zoysiagrass, bermudagrass, bahiagrass, or St. Augustinegrass (Sinclair et al., 2011).

Irrigation interval research on St. Augustinegrasses has been limited to primarily ‘Floratam’, which has been shown to have above average drought tolerance (Steinke et al., 2010). Studies using a rhizotron found ‘Floratam’ St. Augustinegrass increased rooting during initial stages of drought similar to what might be expected during infrequent irrigation scheduling (DiPaola, 1977). Although continued drought caused root growth to stop, a recovery period where irrigation was resumed resulted in greater rooting in previously water stressed plants than non-stressed plants. Studies conducted on loam soils in Florida found that ‘Floratam’ St. Augustinegrass could be irrigated on six day intervals with no effect on turf quality or rooting length (Peacock and Dudeck, 1984, 1985). The same study indicated six day intervals decreased carbon exchange rates and ET due to increasing stomatal resistance, but measured parameters returned to normal levels within 24 hours of irrigation. Unfortunately, their results are difficult to extrapolate to alternate locations due to a lack of meteorological data, soil hydraulic properties, or soil moisture content reported in the paper. In addition, a critical interval was never achieved leaving the reader to speculate that a longer interval might have resulted in acceptable turf. The ideal soil moisture content, day interval, or soil MAD has yet to be adequately describe for many turfgrasses including St. Augustinegrass.

Deficit Irrigation and Allowable Stresses

Applying irrigation at volumes less than ET_c is a common water conservation practice which attempts to maintain a target turf quality while reducing irrigation volumes. The Irrigation Association uses the term ‘allowable stress’ to describe deficit irrigation coefficients (K_{as}) that can be applied to $ET_{c\ adj}$ (www.irrigation.org). Many turfgrasses will demonstrate acceptable turf quality under deficit irrigation, although the maximum deficit irrigation level (MDIL) that sustains acceptable turf varies with species (Feldhake et al., 1984; Fry and Butler, 1989; Green et al., 1990b; Richie et al., 2002; Fu et al., 2004; Henry et al., 2005; DaCosta and Huang, 2006a; DaCosta and Huang, 2006b; Cereti et al., 2009). Published MDIL’s are summarized in Table 1.2. Sustained MDIL-based deficit irrigation typically results in reduced plant ET (Green et al., 1990b; DaCosta and Huang, 2006a), reduced vertical growth rates (Green et al., 1990b; Fu et al., 2007; Cereti et al, 2009), increased water use efficiency (Fu et al., 2007), and increased canopy temperature (Feldhake et al., 1984). Deficit irrigation applied to maintain turf quality did not affect total rooting in tall fescue or bermudagrass (Cereti et al., 2009). Others have found increased rooting due to deficit irrigation in tall fescue (Fu et al., 2007). Studies conducted under a rainout shelter found deficit irrigation reduced tall fescue growth rates, net photosynthesis, and respiration but had no effect on zoysiagrass growth or physiological parameters (Fu et al., 2007). In the same study, tiller density was not affected in either species. Others have investigated the effects of MDIL-based deficit irrigation on turfgrass leaf sucrose content, leaf water relations, canopy reflectance, and plant-carbon-water interactions (Fu et al., 2004; DaCosta and Huang, 2006a,b; Fu et al., 2010).

Table 1.2. Published maximum deficit irrigation levels (MDIL) for maintaining acceptable quality of various turfgrasses.

Species	Cultivar	MDIL	Location	Reference
Kentucky bluegrass	Merion	73% of ET_a	Colorado	Feldhake et al., 1984
Tall fescue		48% of ET_o	Italy	Cereti et al., 2009
Bermudagrass	La Paloma	48 % of ET_o	Italy	Cereti et al., 2009
Zoysiagrass	Meyer	80% of ET_a	Kansas	Fu et al., 2004
Bermudagrass	Midlawn	60% of ET_a	Kansas	Fu et al., 2004
Tall Fescue	Falcon II	60-80% of ET_a	Kansas	Fu et al., 2004
Kentucky Bluegrass	Brilliant	100% of ET_a	Kansas	Fu et al., 2004
Buffalograss	UC Verde	~ 49% of ET_o	California	Henry et al., 2005
Zoysiagrass	De Anza	~ 49% of ET_o	California	Henry et al., 2005
Creeping Bentgrass	L-93	60 – 80% ET_a	New Jersey	DaCosta and Huang, 2006b
Colonial Bentgrass	Tiger 2	80-100% ET_a	New Jersey	DaCosta and Huang, 2006b
Velvet Bentgrass	Greenwich	60-80% ET_a	New Jersey	DaCosta and Huang, 2006b
Tall Fescue	Jaguar III	80% of ET_o	California	Richie et al., 2002
St. Augustinegrass		60% of ET_o	Texas	Pope and Fipps, 2000
St. Augustinegrass	Nortam	44% of ET_{pan}	Texas	Qian and Engelke, 1999
Bermudagrass	Tifway	35% of ET_{pan}	Texas	Qian and Engelke, 1999
Tall Fescue	Rebel	50-75% of ET_a	Colorado	Fry and Butler, 1989
Hard Fescue	Reliant	75% of ET_a	Colorado	Fry and Butler, 1989

Although substantial water conservation can be realized under moderate deficit (i.e., MDIL) irrigation practices, extreme drought or water scarcity may require irrigating at a severe deficit. The literature is less clear on the relationship between irrigation and turf cover under supra-MDIL practices. Existing allowable stress concepts are practical, and previous studies have found percent sod cover was linearly related to ET (Stewart and Mills, 1967). However, the relationship between ET_o and plant water requirements under changing community density may be more complex. For example, ET rates of orchardgrass were greatest from plots having 50% cover due to greater surface temperatures and more available surface area exposed to advective energy and wind currents (Marlatt, 1961). Quantification of turf cover or quality at various allowable stress levels is lacking. Minimum water requirements for maintaining reasonable bud survival for subsequent recovery have not been examined. Dry down studies have found most warm-season turfgrasses can survive up to 60 days without water on deep soils (Steinke et al., 2010). ‘Raleigh’ St. Augustinegrass irrigated three times weekly survived and recovered under irrigation as low as 20% of ET_o (Fontanier et al., 2012). St. Augustinegrass lawns in San Antonio, TX, maintained at deficits as low as 30% of ET_o declined in quality during the summer, but recovered to at least baseline levels during the fall (Pope and Fipps, 2000). Minimal water requirements can depend on irrigation frequency due to relative soil depletion rates (Fry and Butler, 1989). As available irrigation resources diminish, poor quality turf and low density plant materials will likely increase in abundance. The effects of drought-affected landscapes on local microclimates, hydrology, and population psychology demand further investigation.

As previously described, intra-specific variation in morphology and drought resistance exists among commercially available St. Augustinegrasses. Being perhaps the most common lawn grass in Texas, ‘Raleigh’ has not received the appropriate attention in scientific research. In general, the literature is void of St. Augustine irrigation management research for regions west of the Mississippi River. Greenhouse studies and data from Florida soils are available, but these results are not easily extrapolated to the more arid climates and shallow soils typical in most of Texas urban environments. Therefore, research conducted to assess irrigation management of ‘Raleigh’ St. Augustinegrass in Texas could provide meaningful data for the majority of Texas homeowners, municipalities and the green industry.

The Human Factor

Turfgrass science has demonstrated the hardiness and benefits of turfgrasses in urban environments (Beard et al., 1994). The amount of water needed to maintain healthy, attractive turf has been documented to a greater extent than other landscape plant materials (Beard et al., 1994). Even publicly defamed turfgrasses such as St. Augustinegrass have been shown to survive up to 60 days without water (Steinke et al., 2010). In many cases, the greatest issue facing water conservation proponents is the human factor, namely an uninformed or uninterested consumer (Beard et al., 1994). Many homeowners irrigate responsibly (at or below ET_c), but the top tier of water consumers can over-irrigate to the point that average water use changes significantly (Karen Guz, Conservation Director at San Anonio Water System, personal communication). To combat irresponsible irrigation, municipalities offer free irrigation system inspections or informational seminars. Unfortunately, many consumers are unmotivated to take advantage of such programs until they receive an exceptional bill. In many cases, consumers are simply unaware of the volume of water they are applying to the landscape (Jennifer Nations, Water Resource Coordinator at City of College Station , personal communication).

Successful irrigation conservation strategies should be easy to understand, not be a time sink, and be connected to a known turf response. Most people believe following best management practices is important but are not willing to adjust sprinkler run times on daily, weekly, or even monthly intervals (Bremer et al., 2012). Seasonal adjustments may be more practical and when paired with a simple rain sensing interrupter, allow considerable water conservation (Davis et al., 2009; Bremer et al., 2012). Automated ET-based SMART controllers present a novel approach to addressing the human factor in landscape irrigation. However, absolute water conservation of SMART controllers has been comparable to conservative historical ET-based irrigation (with a rain gauge) (Davis et al., 2009; Davis and Dukes, 2010). As SMART controller technologies become more accurate, potential water savings are greater.

Existing Water Restrictions

Aside from the general ideal of reducing waste, two specific goals exist for enhancing urban irrigation efficiency: water scarcity and peak demand. First, in some regions water has become a scarce resource and increasing supply is not easily accomplished. Shortages of supply require overall reductions in per capita water consumption but the timing and location of savings can be promoted in a number of situations. A second driver for water conservation efforts is reducing peak demand. Peak demand typically occurs during mid-summer due to outdoor discretionary practices such as car washes, landscape irrigation, and pool maintenance. Reducing peak demand minimizes infrastructure capacity needs and lowers pumping costs, but does not necessarily reduce overall consumption. Reducing peak demand can be equally important to wet regions as well as arid regions, particularly if population growth has been extensive. It is important to distinguish between these two goals when considering non-price water demand management tools such as landscape irrigation water restrictions. Considering landscape irrigation is a discretionary practice which accounts for substantial variability in summertime and annual total consumption, restrictions to irrigation would likely have significant impact on both peak demand and per capita water use.

The drought contingency plans for several Texas municipal water suppliers are listed in Table 1.3. Most municipalities have ordinances banning irrigation during the day, using broken or improperly adjusted sprinklers, and causing substantial runoff into the street. New installations often are required to install rain sensors capable of interrupting unnecessary irrigation events. In Austin, and presumably across the state, one- or two-day per week restrictions has effectively reduced peak demand (John Jacobs, City of Austin, personal communication). The efficacy of such policies in reducing average water use is not as clear. In Tampa, FL, homeowners increased water consumption during restriction periods (Ozan and Alsharif, 2013). This was in part due to higher plant water needs during declared restriction periods, and ultimately, penalties for violating restriction ordinances were not adequate to deter water use.

Urban Runoff

Urbanization has been linked to a number of hydrological, biological, and chemical changes to surface waters (Cadenasso et al., 2008; Carey et al., 2013). Impervious surfaces associated with urbanization increase peak discharge while decreasing the lag to peak discharge. Thus, overland flow entering urban streams has the potential to carry large volumes of high energy water. The necessary stormwater conveyance infrastructure to move water away from urban centers to centralized retention ponds represents a significant expense. Recent trends have promoted the decentralization of stormwater management through low impact development, pervious pavements, and a general increases in green space. The rate of runoff from pervious surfaces is dependent on several factors including infiltration rate, slope, depression storage, interception, and hydraulic roughness or tortuosity of the flow path (Dingman, 2008). Factors which affect infiltration rates include the depth of ponding, saturated hydraulic conductivity of the soil, antecedent moisture content, slope, surface roughness, chemical characteristics of the surface, and physical and chemical properties of the water (Dingman, 2008).

Table 1.3. Landscape irrigation restrictions for several municipal water suppliers in Texas. Restrictions typically pertain to automatic in-ground irrigation systems. Listed web site references were verified Feb 2013.

City	Stage	Irrigation Frequency	Comment	Trigger
San Antonio[†]	1	1 d wk^{-1}	8pm – 10am	Aquifer Level
	2	1 d wk^{-1}	Hours reduced	
	3	Every other week	Drip also reduced	
	4	Every other week	Drought surcharge	
Dallas[‡]	0	2 d wk^{-1}	Mandatory	Year round
Ft. Worth[§]	1	2 d wk^{-1}	Mandatory	Demand or reservoir level
	2	1 d wk^{-1}	Mandatory	
	3	prohibited	Mandatory	
College Station[¶]	1	2 d wk^{-1}	Voluntary	Demand
	2	2 d wk^{-1}	Mandatory	
	3	prohibited	Mandatory	
Austin[#]	1	2 d wk^{-1}	Voluntary	Demand or reservoir level
	2a	2 d wk^{-1}	Mandatory	
	2b	1 d wk^{-1}	Mandatory	
	3	prohibited	Mandatory	
Houston[††]	1	2 d wk^{-1}	Voluntary	Demand, reservoir level, or pressure
	2	2 d wk^{-1}	Mandatory	
	3	prohibited	Mandatory	
El Paso[‡‡]	0	3 d wk^{-1}	Mandatory	Year round
	1	3 d wk^{-1}	Voluntary 25% reduction	Demand or surface water allotment
	2	1 d wk^{-1}	Mandatory	
	3	prohibited	Mandatory	

[†] http://www.saws.org/Conservation/Ordinance/docs/Ch34_Ordinance_2009.pdf;

[‡] http://savedallaswater.com/pdf/WaterConservationOrdinance.pdf;

[§] http://fortworthtexas.gov/uploadedFiles/Water/Educational_Resources/Water_Conservation/Complete%20FW%20Drought%20Plan%20May%202008.pdf;

[¶] http://cstx.gov/Modules/ShowDocument.aspx?documentid=4851;

[#] http://www.lcra.org/library/media/public/docs/water/drought/Sample_DCP_Municipal_Use.docx;

[††] http://www.houstontx.gov/council/3/committees/20120912/47-7.pdf;

[‡‡] http://www.epwu.org/pdf/rules_regs.pdf.

Turf represents a significant portion of pervious urban land cover, thus the condition and management practices of urban lawns can have a substantial impact on the quality and quantity of urban runoff (Milesi et al., 2005). Turf management practices such as irrigation and fertilizer application increase plant density and overall biomass production. These in turn contribute to greater surface area for interception and hydraulic roughness for slowing overland flow. Conversely, frequent irrigation likely contributes to greater antecedent surface soil moisture and greater runoff volumes (Shuman, 2002). The majority of residential lawns are irrigated with municipal tap water. As a result, urban watersheds may often have a turf irrigation chemical signature characterized by elevated sodium and nutrients that has been considered detrimental to watershed quality (Aitkenhead-Peterson et al., 2011; Steele and Aitkenhead-Peterson, 2011). Rice and Horgan (2011) discussed a number of the negative consequences of excess nutrients in surface waters ranging from algal blooms to metabolic effects and endocrine disruption. A primary goal of lawn managers should be to eliminate surface runoff from their landscapes in order to minimize infrastructure costs and potential aquatic ecosystem injury. The hydrological dynamics of irrigation management and the resultant changing turf canopy are poorly described for warm-season turfgrasses. Mueller and Thompson (2009) investigated the use of residential lawns for disconnecting impervious areas and reducing stormwater conveyance needs. It was further proposed that turfgrass lawns can be managed as a low impact development in order to maximize on-site water retention through appropriate irrigation strategies.

Urban Infiltration Rates and Surface Runoff Routing

Infiltration rates of residential lawns can be highly variable and difficult to generalize across regions or even among similar soil types; direct measurement of infiltration rate is commonly performed using double-ring infiltrometers (Duan et al., 2012). Because infiltration rate varies with soil moisture, readings must be made until they reach a steady rate and can be used as a proxy for saturated hydraulic conductivity (Duan et al., 2012). Hillslope position was shown to be the primary factor affecting runoff from sandy loam soils in New York (Easton et al., 2005). Lower catena positions typically had greater clay content, lower infiltration rates, and higher soil moisture contents. Hamilton and Waddington (1999) reported that tiller density, soil bulk density, and soil texture did not affect infiltration rates of 15 Pennsylvania lawns, and that excavation and lawn establishment procedures were more predictive of infiltration rates. This is in agreement with previous research using simulated rainfall on lawns in Wisconsin (Kelling and Peterson, 1975). In both studies, infiltration rates were highly variable ranging from 0.1 to 8.9 cm hr^{-1}. In Florida, relatively high infiltration rates were reported between 37.7 to 63.4 cm hr^{-1} due to the sandy soils (Gregory et al., 2006). Despite the substantial difference between Florida and Pennsylvania infiltration rates, construction activity and localized compaction was the major factor affecting infiltration rates. Partsch et al. (1993) found that compaction during establishment could affect infiltration rates for up to 12 years after installation.

Several mechanistic models exist for predicting infiltration at a point (e.g., Green and Ampt Model; Dingman, 2008). Such models are often based on Darcy’s equation for flow through a porous medium and require quantification of soil hydraulic parameters such as porosity and saturated hydraulic conductivity (Dingman, 2008). When precipitation rate exceeds the infiltration rate and surface storage has been filled, ponding occurs. When these conditions occur on a slope, ponded water is subject to Hortonian overland flow and discharge velocity can be estimated using open channel flow models such as Manning's equation (Dingman, 2008). Empirically-derived Manning's *n* values have been reported to fall in the range of 0.05 to 0.40 for grass and pastures depending on community density (Engman, 1986). Flow through turf is assumed non-laminar due to the tortuous paths created by plant shoots; however, on close-mowed turfs such as golf fairways, runoff depth can extend above turf canopies and become laminar in nature (Phelps, 1970). Perhaps the most complete hydrological assessment of small plot turf runoff was performed by Linde et al. (1995). In their study, direct measurement of tiller density, verdure interception, thatch water retention, soil infiltration rate, and hydraulic resistance were compared between two species of cool-season turfgrasses. Significant differences between species related to logical differences in runoff volumes. In particular, the presence of a well-defined thatch layer provided additional surface storage and hydraulic resistance for increasing lag time, enhancing lateral diffusion of runoff, and ultimately reducing runoff volumes. They reported that creeping bentgrass (*Agrostis stonlonifera* L.) thatch was able to capture up to 4.2 mm (47% of total thatch depth) of precipitation. Southern lawn turfgrasses such as St. Augustinegrass are exceptional thatch producers and could be expected to have a much greater capacity to store precipitation when density and active growth is adequate to create a well-defined thatch layer.

The purpose for understanding and predicting runoff volumes is two-fold: 1) the ability to account for stormwater discharge that could lead to potential surface water pollution , and 2) accounting for on-site retention for adjusting irrigation schedules (i.e. adjust for effective rainfall). Event-interrupting rain gauges are inexpensive and water conserving, but are crude methods for adjusting irrigation for effective precipitation. With the development of SMART controllers, consumers and landscape professionals can input parameters such as slope and soil texture for proper irrigation run time cycling (Rainbird.com). Further development of accurate effective precipitation formula would be beneficial for advancing SMART controller technology.

Fate of Applied Fertilizers

Elevated nutrient concentrations (N and P) and associated algal blooms in surface waters have been linked to urbanization, primarily from overland flow due to interconnectedness of urban systems, proximity to surface waters, and loss of riparian zone health (Miller and Mattraw, Jr., 1982; Cadenasso et al., 2008; Kaushal et al., 2008). In the simplest terms, urbanization increases nutrient sources while decreasing nutrient sinks (Cadenasso et al., 2008). Although P is known to be most limiting in freshwater systems, recent discussion suggests both N and P should be controlled to reduce problems further downstream (Correll, 1998; Conley et al., 2009; Paerl, 2009). A visible component of urban settings, turf-based landscapes have been targeted as a significant source of nutrients in urban runoff. Specifically, the use of fertilizers has been targeted as a source of soluble N and P loading into surface waters (Cadenasso et al., 2008). However, the agronomic literature overwhelmingly suggests the magnitude of turf culpability is exaggerated (Petrovic, 1990; Soldat and Petrovic, 2008; Raciti et al., 2011a). When properly administered following soil test recommendations, there is good agreement in the agronomic community that fertilizer applications pose minimal risk to surface runoff or leaching. Furthermore, when soil deficiencies are present, withholding fertilizer may increase nutrient loss and sediment transport due to reductions in turf density (Gross et al., 1990; Bierman et al., 2010). Turf-centered runoff research has largely fallen into three categories: small plot research using worst case scenario rainfall simulation, small plot research using natural rain events to monitor typical conditions over a period of time, and field-scale studies which monitor changes in water quality of drainage areas (Soldat and Petrovic, 2008).

In several small plot runoff studies, nutrient load peaks occurred shortly after a fertilizer application (Shuman, 2002; Easton and Petrovic, 2004; Baker et al., 2007; Watts and Torbert, 2009). Under such conditions, nutrient source and rate have significant impacts on loading and leaching losses (Easton and Petrovic, 2004). Namely, soluble N sources result in greater nutrient losses compared to slowly available natural organic sources (Brown et al., 1977; Easton and Petrovic, 2005). However, natural organic fertilizers are typically high in total P and often increase short-term soluble P losses through runoff (Gaudreau et al., 2002; Easton and Petrovic, 2004; Baker et al., 2007; Watts and Torbert, 2009). Slow-release synthetic nitrogen fertilizers such as polymercoated sulfur-coated urea have reduced nutrient losses compared to soluble nitrogen sources (Guillard and Kopp, 2004). Although nominally a slow-release fertilizer, sulfur-coated urea has not been as consistent reducing nutrient losses (Burwell et al., 2011). Clearly, individual fertilizer applications can cause spikes in soluble N and P, but recent studies indicate the effects are largely transient (Raciti et al., 2011a). Evaluation of soil cores from the Baltimore LTER (Long-term Ecological Research) found homeowner management practices were not good predictors of exchangeable soil nitrate; rather, land use history and housing density were more indicative of soil nitrate and organic carbon concentrations (Raciti et al., 2011a; Raciti et al., 2011b). Further studies from the Baltimore LTER indicate residential lawns are effective sinks for N (Raciti et al., 2008); supporting prior research suggesting that increasing soil N levels is a function of site age (Qian et al., 2003). This is not surprising considering the numerous avenues for immobilizing inorganic N and P into organic species (Petrovic, 1990). Engelsjord et al. (2004) found thatch to be an important sink for applied N with the majority being stored in the organic form. Miltner et al. (1996) reported that 31% of applied urea was found in thatch 18 days after treatment (DAT). After two years, this amount had decreased to 20%. Approximately 35% of applied N was removed with clipping yield over the course of two years. Less than 1% of applied N was found in leachate, and only 25% of applied N was recovered in mineral soil solutions. Particularly when vegetation is sparse, edaphic properties and soil amendments can affect nutrient (P) losses. Addition of gypsum, alum, or similar cations have been shown to reduce soluble P losses in runoff (Watts and Torbert, 2009; Vietor et al., 2010). The presence of a dense turf may inhibit the efficacy of such reactions thus causing soluble P to be the primary form of P in runoff (Steinke et al., 2007). Inorganic N can quickly leave the turf system via atmospheric losses (denitrification or volatization). Atmospheric losses through denitrification appear to represent a significant portion of N exports under hot, wet conditions (Mancino et al., 1988; Horgan et al., 2002). Accordingly, frequent irrigation was found to increase denitrification in perennial ryegrass (Rolston et al., 1982). Starr and DeRoo (1981) estimated that 24 to 36% of N applied as ammonium sulfate was subject to gaseous losses. Horgan et al. (2002) reported that 3 to 27% of KNO_3–N was lost to denitrification depending on soil temperature. Spikes in gaseous losses occur immediately after fertilizer application, most notably if rainfall occurs shortly thereafter (Bremer, 2006). Gaseous losses have typically been greater in thatchy turfs due to greater urease activity (Nelson et al., 1980).

Field-scale research has similarly concluded that runoff volumes from turf sites are fairly low and nutrient export is less than commonly perceived. In North Carolina, several golf courses were monitored for changes in stream chemistry (Mallin and Wheeler, 2000). They reported increased NO_3^- associated with fertilizer applications but concentrations never exceeded 2.5 mg N L^{-1}. A non-replicated study of three North Carolina residential properties falling into varying maintenance categories (high, low, and undeveloped forest lot) demonstrated that low maintenance turf had more frequent runoff events than did the high maintenance turf which had more frequent runoff than did the undeveloped forested lot (Spence et al., 2012). However, when runoff occurred, volumes were similar for each property. Overall, overland flow represented less than 1% of measured rainfall and was not deemed a primary source of N or P loss from any of the sites. At a golf course in Austin, TX, 7.9% of applied N and 11% of applied P reached surface waters (King et al., 2001; King et al., 2007). Although NO_3-N concentrations were considered below any critical thresholds, soluble reactive P (SRP) was considered beyond eutrophication-causing concentrations (1.2 mg L^{-1} NO_3-N and 0.2 mg L^{-1} SRP).

Management Practices Affecting Turf Runoff Quality

In general, nutrient export is most strongly predicted by runoff volume (Kaushal et al., 2008; Bell and Koh, 2009; Rice and Horgan, 2011). Runoff volume (and thus nutrient export) from turf can be affected by a number of management factors. Turfgrass species and growth habit affects interception and hydraulic resistance of flow (Linde et al., 1998). Specifically, thatch-producing turfgrasses with horizontally-oriented leaves were able to reduce runoff volumes compared to bunch-type grasses. Similarly, turf density has been negatively correlated with runoff volume and nutrient export (Gross et al., 1991; Linde et al., 1995; Easton and Petrovic, 2004; Easton et al., 2005; Bierman et al., 2010). Clippings management has been shown to enhance N uptake and clipping yield, which would presumably increase density and thus reduce runoff volumes (Starr and DeRoo, 1980). Returning clippings did not affect P export from Kentucky bluegrass lawns (Bierman et al., 2010). Long-term modeling of a Kentucky bluegrass lawn predicted significant N and C sequestration over time (Qian et al., 2003). Petrovic (1990) suggests 25 to 60% of applied fertilizer N is recovered by removing clippings. Over time, adjustments to nitrogen application rates are required to prevent over-application

(Qian et al., 2003). Cultivation practices such as vertical mowing and solid tine aeration have not had consistent effects on runoff volumes or nutrient concentrations, but these findings may be more a factor of the variability and intensity of runoff events overcoming any potential detectable benefits of cultivation (Cole et al., 1997; Linde and Watschke, 1997; Kauffman and Watschke, 2007). Moss et al. (2007) reported that hollow-tine core aeration increased the response lag, but similar to other cultivation methods under high intensity rainfall, core aeration did not influence runoff volumes (Moss et al., 2007). To the contrary, Rice and Horgan (2011) found hollow-tine core aeration did reduce runoff volumes and nutrient exports compared to solid-tine aeration. In general, cultivation such as coring increases surface storage of precipitation and may have a greater effect on moderate to light rainfall events or controlled irrigation practices. Undisturbed buffer strips have been successfully used to reduce nutrient export in agriculture due to increasing infiltration rates, retarding flows and thus reducing the erosive power of flow, and filtering of sediment (Fiener and Auerswald, 2003). Turfgrasses can serve as plant materials for buffer strips and prior research suggests they are as effective as many native grasses for this purpose (Steinke et al., 2007). Cole et al. (1997) reported that buffer strips around turf fairways reduced pesticide and nutrient losses, but buffer mowing height had no effect on either pesticide or nutrient loss. Others have found that nutrient retention within buffer strips was attributed to the sudden change from short to taller grasses (Moss et al., 2006). Watts and Torbert (2009) reported buffer strips alone reduced soluble P in runoff from pastures treated with poultry litter. Research in the northern U.S. suggested the majority of runoff occurs during winter when the soil is frozen and buffer type (prairie mix or turf) did not affect runoff volumes (Steinke et al., 2007). Acceptance of buffer strips for residential lawns is probably not practical, but it is proposed that through proper management, comparable results can be achieved.

In many parts of Texas, irrigation can be the management practice having the largest individual impact on turf performance, turf system hydrology, and the urban ecosystem at large. Prior turf irrigation research has largely focused on best management practices to reduce water consumption (i.e., what is the minimum water requirement for acceptable turf performance). This type of research often ignores the full range of turf canopy responses to diminishing volumes of irrigation. Prior turf runoff research (small plot or otherwise) has similarly ignored irrigation strategy as a significant driver of the plant canopy and soil infiltration rates. Diamond (2003) reported that ET controllers and educational programs reduced residential irrigation application volumes and similarly decreased dry weather runoff by as much as 71% over the control group. The effects on storm runoff were not reported. In general, high density plant systems increase soil infiltration, reduce the energy of falling rain, and slow the movement of overland flow. These efforts ultimately reduce sediment transport and erosion. Gross et al. (1990) determined that the presence of any vegetation significantly decreased sediment losses compared to bare soil, but variability did not allow for separation among vegetated surface densities. Kauffman and Watschke (2007) found core aeration did not increase sediment loss despite creating substantial surface disruption. The fraction of a full sward needed to maintain the beneficial attributes of erosion control have not been documented.

Other Sources of N and P within Turf Systems

In summary, applications of soluble fertilizers appear to be transient contributors to runoff chemistry and sediment transport is minimal due to complete ground cover. Turf systems are considered to be net sinks (or at the least net neutral) for N and C. Thus, contributions to runoff dissolved organic carbon (DOC), N, and P are likely derived from plant material such as decomposing thatch or leaf leachate. Sharpley (1981) found that 14 to 94% of soluble P in runoff could be attributed to plant leachate from agricultural crops. Steinke et al. (2007) did not find a relationship between aboveground biomass nutrient concentrations and runoff nutrient concentrations, but suspected erosion and bulk deposition may have masked differences. Soldat et al. (2009) reported that soil test P was not a good predictor of dissolved reactive P in runoff and suspected leaching from vegetation was a significant unaccounted for variable. Steele and Aitkenhead-Peterson (2013) showed that irrigation water quality can be responsible for leaching DOC and N from vegetation. During an establishment period, overland flow is allowed to interact with the soil due to thin turf. Under such conditions, soil test P (Mehlich-3) and water extractable P have been well correlated with runoff concentrations (Hansen et al., 2007). Sharpley et al. (1981) attributed higher soluble P in grassed watersheds to reduced opportunities for soil adsorption. This suggests that soils under heavy vegetation are more likely P sinks rather than sources. In the context of irrigation management and water restrictions, changes to plant cell integrity would likely increase availability of nutrients for leaching from leaves. Roberson et al. (2007) reported that simulated drying (using applications of paraquat [1,1’-dimethyl-4-4’-biphyridinium ion]) of alfalfa

(*Medicago sativa* L.) and quackgrass (*Agropyron repens* L.) substantially increased soluble P in runoff. Sharpley (1981) reported that soluble P plant leachate increased with soil water stress for several agronomic crops.

CHAPTER II

HISTORICAL AVERAGE ET_O FOR IRRIGATION SCHEDULING OF ST. AUGUSTINEGRASS IN A CENTRAL TEXAS CLIMATE

Introduction

Municipal water demand is typically highest in summer due to landscape irrigation applied to combat rainfall deficits and peak evapotranspiration (ET) rates. During these peak irrigation months, outdoor water use may represent 40 to 60% of residential water consumption and increase per capita use two- to three-fold compared to winter season lows (Vickers, 1991; White et al., 2004). Residential water consumption may increase by 33% during the summer in cities east of the Mississippi (Kjelgren et al., 2000). In more arid regions, summer outdoor water use was estimated as 48% of annual consumption (Kjelgren et al., 2000). A report released by the Texas Water Development Board estimated that 31% of residential water consumption is dedicated to outdoor uses (Hermitte and Mace, 2012). Thus, decreases in outdoor water use such as landscape irrigation would produce substantial reductions in total water consumption. In response, defining the minimum water requirements for irrigation scheduling for lawns has been a primary objective of turfgrass research. Perhaps, the most common irrigation scheduling method is the reference ET - crop coefficient method (Eq. 1.2) (Allen et al., 1998).

St. Augustinegrass (*Stenotaphrum secundatum* (Walt.) Kuntze), the predominant lawn grass in Texas, is publicly perceived as having a high water requirement. This despite the fact that most warm-season turfgrasses, including St. Augustinegrass, have been shown to survive up to 60 days without water when provided an adequate top soil (Steinke et al., 2010). Reported K_c values for St. Augustinegrass have varied depending on location and methodology. Carrow (1995) used changes in soil moisture to estimate a K_c of 0.72 for 'Raleigh' St. Augustinegrass in Georgia. Using a similar method, Pannkuk et al. (2010) reported K_c's for 'Raleigh' to be 0.52 in San Antonio. Kneebone and Pepper (1982), using drainage lysimeters and a perched water table to measure ET, reported a K_c of 0.65 for St. Augustinegrass in Arizona. These values are not remarkably different from those published for other warm-season turfgrasses, therefore a single K_c has often been recommended for all warm-season species.

Although effective, the ET_o – K_c method typically requires daily or weekly adjustments to irrigation controllers making it impractical for many residents using in-ground irrigation systems. As a result, lawn irrigation practices have in some cases continued to be in excess of plant water requirements. Although residents often claim an interest in following best management practices (BMP's), often they are not willing to adjust their sprinkler run times on daily, weekly, or even monthly intervals (Bremer et al., 2012). Therefore, irrigation BMP's should be based on the dual objectives of meeting plant water needs while maintaining ease of implementation for the urban resident. In response, water conservation advocates often recommend the use of long-term historical average ET_o for irrigation scheduling. In some areas, this concept has been termed the *"One Inch per Week Rule"* in reference to the average water requirements for many turfgrasses during the peak of summer. The advantages of using historical averages include fewer actions needed by the urban resident, more predictable water use for water purveyors, and reduced reliance on weather station installation and maintenance. However, because ET_o can have substantial intra- and inter-annual variability, how a turf will respond in the short-term and how water conservation is affected in the long-term require further examination.

Objectives

The objectives of this study were to examine historical average ET_o-based irrigation scheduling for St. Augustinegrass: 1) identify the appropriate K_c for maintaining varying levels of turf quality, 2) quantify the inter-annual variability in water conservation, and 3) monitor any interactions with fertilizer management.

Hypotheses

1) A K_c of 0.6 will provide adequate moisture for turf maintenance each year.
2) A K_c less than 0.6 will provide adequate moisture for turf survival each year.
3) Fertility will hasten post-stress turf recovery.

Materials and Methods

Site Description and Experimental Design

A three year field study was conducted from 2011 to 2013 at the Texas A&M Turfgrass Field Lab on F and B Road in College Station, TX (30.617637, -96.365504). The site was an established ‘Raleigh’ St. Augustinegrass turf sodded in 2010 onto a Boonville sandy loam (Fine, smectitic, thermic Chromic Vertic Albaqualfs). The sod was sourced from a farm that had a similar soil texture as the A horizon of the study site. Plots were mowed weekly at 5 cm using a rotary mower and clippings were returned. Irrigation was applied using in-ground rotor sprinklers (T5, The Toro Co., Windom, MN) on a Monday, Wednesday, Friday schedule to simulate a common practice among urban residents. Sprinkler run times were adjusted for distribution uniformity using the lower half method ($DU_{LH,}$ Irrigation Association). Results of an irrigation audit indicated a precipitation rate of 33 mm hr^{-1} and a DU_{LH} of 0.68.

The experiment was arranged as a randomized complete block split-plot design with four replications. Main plots (6m x 6m) were assigned one of four irrigation levels as defined in terms of a K_c: 1.00, 0.60, 0.36, and 0.24 (referred to as *‘K100’*, *‘K60’*, *‘K36’*, and *‘K24’* for remainder of this chapter). Each level was selected to create the following qualitative treatments based on the average year: *K100* = Overwatering, *K60* = One Inch per Week, *K36* = Water Deficit, and *K24* = Severe Water Deficit. Each K_c was used to adjust historical average ET_o as calculated from monthly values (Table 2.1). Subplots (2m x 6m) were assigned one of three fertility levels: 0, 19, and 38 kg N ha^{-1} mo^{-1}. Thus 12 treatment combinations with 4 replicates resulted in n = 48.

Table 2.1. Historical average monthly ET$_o$ data used to calculate irrigation treatment depths.

Month	Days	Monthly	Daily[†]	Mon[‡]	Wed[§]	Fri[§]
		-----------------------------------	---------mm---------			-----------------------------------
Jan	31	55	1.8	5.3	3.5	3.5
Feb	28	68	2.4	7.3	4.8	4.8
Mar	31	106	3.4	10.2	6.8	6.8
Apr	30	130	4.3	13.0	8.7	8.7
May	31	156	5.0	15.1	10.1	10.1
Jun	30	172	5.7	17.2	11.5	11.5
Jul	31	178	5.7	17.2	11.5	11.5
Aug	31	171	5.5	16.6	11.0	11.0
Sep	30	140	4.7	14.0	9.3	9.3
Oct	31	108	3.5	10.4	6.9	6.9
Nov	30	70	2.3	7.0	4.7	4.7
Dec	31	55	1.8	5.3	3.5	3.5

[†] Calculated as Monthly ET$_o$ / Days.
[‡] Calculated as Daily ET$_o$ x 3 days
[§] Calculated as Daily ET$_o$ x 2 days

The experimental period was defined as July 1 to September 30 of each year. This period was selected to simulate water conservation efforts that target the peak demand of the year. Outside the experimental period, irrigation was applied at historical average ET$_c$ amounts similarly to all plots. Fertilizer applications during the experimental period were made using a urea-based product (Scotts Lawn Pro, 4.2% methylated urea, Scotts Miracle-Gro Co., Marysville, OH) having an analysis of 26-0-3 (N - P_2O_5 - K_2O). In addition, each spring, ammonium sulfate was applied uniformly to all plots at a rate of 48 kg N ha^{-1} in order to enhance post-dormancy recovery growth prior to the initiation of irrigation treatments.

Irrigation scheduling programs were evaluated using adequacy and excess estimates. To be adequate, a treatment was required to apply an annual amount greater than 80% of the theoretical plant water requirements. This value was determined each year by simulating a comparable calendar-based irrigation schedule while using measured ET_o data to estimate daily requirements as follows:

$$ET_c = K_c * ET_o - R_{eff} \qquad \text{(Eq. 2.1),}$$

where ET_c was the estimated daily plant water use, K_c was 0.6, ET_o was the daily FAO-56 Penman-Monteith reference ET, and R_{eff} was the effective rainfall. Effective rainfall was estimated as 75% of measured rainfall. Any water applied above the ET_c threshold was considered in excess.

Analyses of Plots

Several discrete measurements were conducted weekly at each plot after an irrigation event. Measurements included 1) turf quality, 2) percent turf cover and 3) volumetric soil water content. Each parameter was measured at three points along the central axis of the fertility sub-plot. Turf quality was evaluated using the National Turfgrass Evaluation Program (NTEP) numeric scale which ranges from 1 to 9, and a value of 6 was deemed to be a minimally acceptable turf quality (Morris and Shearman, 1998). Visual assessments were made by the same individual for each date within a given year, but due to changes in personnel, the individual rating changed from year to year. Turf quality scores were based on subjective assessments of color, density, and uniformity. Percent green cover of the turf canopy was estimated from green pixel batch analysis (SigmaScan, Systat Software, Inc., San Jose, CA) of digital images (CoolPix P7100, Nikon Corp., Tokyo, Japan) taken under a controlled light box (Richardson et al., 2001). Volumetric water content was measured to a depth of 75 mm using a calibrated handheld meter (Field Scout TDR300, Spectrum Technologies, Inc., Aurora, IL).

Statistical Analyses

Data were averaged within each sub-plot prior to further analysis. Data were tested for treatment effects using a linear mixed model repeated measures analysis within each year (SPSS 22, IBM, Inc., Armonk, NY). Block, irrigation, fertility, date, and their interactions were considered fixed factors. Means were separated using Fisher's protected LSD. A significance level of $p \leq 0.05$ was used for all tests. Regression was used to quantify relationships between percent green cover, turf quality, and effective crop coefficients.

Results

Turf Quality and Cover

Irrigation demonstrated a significant main effect on turf quality each year (Table 2.2). In general, *K100* and *K60* treatments were similarly superior to either deficit irrigation treatment, while *K36* was superior to *K24* in the two drier years (Table 2.3). In 2012 (wettest year), differences among treatments became less apparent. Significant irrigation by date interactions each year warranted further analysis by date. On each date,

Table 2.2. Fixed effects models for turf quality analyzed within year.

Source	**df**[†]	***p*-value**
	----------------------------2011----------------------------	
Block	3	.377
Irrigation (I)	3	.000
Fertility (F)	2	.209
I x F	6	.444
Date (D)	15	.000
D x I	45	.000
D x F	30	.998
D x I x F	90	1.000
	----------------------------2012----------------------------	
Block	3	.123
Irrigation (I)	3	.019
Fertility (F)	2	.000
I x F	6	.904
Date (D)	13	.000
D x I	39	.000
D x F	26	.000
D x I x F	78	.871
	----------------------------2013----------------------------	
Block	3	.141
Irrigation (I)	3	.001
Fertility (F)	2	.001
I x F	6	.595
Date (D)	14	.000
D x I	42	.000
D x F	28	.420
D x I x F	84	.975

[†] Degrees of freedom

Table 2.3. Main effects of irrigation on turf quality.

Irrigation[†]	2011	2012	2013
		---------------------------------Quality[‡]---------------------------------	
K100	6.6	5.8	6.3
K60	6.1	5.7	6.3
K36	4.0	5.1	5.3
K24	2.8	5.3	4.5
LSD (0.05)	0.8	0.4	0.8
p-value: Irrigation (I)	.000	.012	.001
p-value: I x Date	.000	.000	.000

[†]Irrigation levels were defined in terms of crop coefficient (K_c) adjustments to historical average ET_o: K_c = 1.00, 0.60, 0.36, and 0.24

[‡] Turf quality scores were visually assessed using NTEP standard methods: 1 = worst, 9 = best, 6 = acceptable (Morris and Shearman, 1998).

Treatment *K60* was statistically similar to *K100*, and resulted in a mean rating equal to or greater than the acceptability threshold on 10 of 16 dates and 9 of 13 dates in 2011 and 2013, respectively (Table 2.4). In 2012, large patch (*Rhizoctonia solani*) caused poor spring and early summer quality, particularly for *K60* and *K100* treatments. The combination of early season disease and a fairly wet summer delayed treatment differences until August. On one date (20-Jul), *K24* demonstrated superior quality to the *K60* treatment. During the two drier years, seasonal turf quality of deficit irrigation treatments generally followed a positive quadratic function of time. In June (prior to the experimental period), treatments appeared fairly similar and full recovery from the prior year was assumed. At the onset of irrigation treatments, soil water depletion was followed by turf density attrition which typically reached a minimum in late August. At the onset of seasonal rains, turf began recovery until treatment differences were again not apparent in late-October. In 2011, *K36* and *K24* treatments demonstrated rapid declines in quality within two and three weeks, respectively. Conversely, in 2012 and 2013, *K36* began to decline at approximately 6 weeks into the experimental period, and *K24* began to decline at 6 weeks and 4 weeks in 2012 and 2013, respectively. During the recovery period, *K36* reached similar quality as *K60* and *K100* each year, typically in mid-October. Although similar recovery patterns were seen for *K24* treatments in most years, plots did not fully recover until the spring of 2012 following the first experiment year.

Table 2.4. Irrigation by date interaction effects on turf quality.

	2011															
Irrigation[†]	**14-Jul**	**20-Jul**	**27-Jul**	**3-Aug**	**10-Aug**	**17-Aug**	**24-Aug**	**2-Sep**	**9-Sep**	**16-Sep**	**23-Sep**	**30-Sep**	**7-Oct**	**14-Oct**	**21-Oct**	**28-Oct**
	Quality[‡]															
K100	5.6	8.0	7.4	8.1	8.7	6.5	7.0	6.7	6.6	6.3	7.1	6.1	6.3	6.7	4.8	4.1
K60	5.5	7.5	7.0	7.0	7.7	6.0	5.8	5.9	5.9	6.1	6.0	6.1	6.2	6.4	4.9	4.2
K36	4.4	6.1	5.2	4.9	4.8	3.1	2.7	2.9	3.0	3.3	3.8	3.6	3.9	4.1	4.1	3.9
K24	3.2	3.6	3.3	3.3	3.1	2.0	1.8	1.6	2.0	1.7	2.6	2.6	3.3	3.7	3.4	2.9
LSD (0.05)	1.2	1.4	1.5	1.5	1.2	1.9	2.2	1.9	1.7	1.7	1.8	1.6	1.6	1.3	0.5	0.7
p-value	.005	.000	.001	.000	.000	.001	.001	.001	.001	.000	.001	.001	.003	.001	.000	.006

	2012													
	31-May	**13-Jun**	**29-Jun**	**6-Jul**	**13-Jul**	**20-Jul**	**27-Jul**	**3-Aug**	**10-Aug**	**17-Aug**	**24-Aug**	**11-Sep**	**21-Sep**	**28-Sep**
	Quality[‡]													
K100	5.0	5.1	5.6	5.8	5.7	5.5	6.1	6.3	6.2	6.1	6.2	5.6	5.8	6.0
K60	4.9	5.1	5.5	5.6	5.4	5.4	5.9	6.0	6.0	6.0	6.4	5.3	5.8	5.9
K36	4.4	4.9	5.1	5.1	5.3	5.3	5.7	5.1	5.1	4.9	5.3	4.4	5.2	5.6
K24	4.5	5.1	5.3	5.4	5.6	5.8	5.9	5.5	5.3	5.0	5.9	4.6	5.1	5.6
LSD (0.05)	0.3		0.3	0.4		0.3			0.6	0.8	0.7	0.7	0.6	
p-value	.010	ns	.018	.005	ns	.026	ns	ns	.004	.013	.031	.007	.048	ns

	2013														
	21-Jun	**27-Jun**	**3-Jul**	**12-Jul**	**19-Jul**	**26-Jul**	**1-Aug**	**9-Aug**	**16-Aug**	**30-Aug**	**6-Sep**	**13-Sep**	**27-Sep**	**16-Oct**	**29-Oct**
	Quality[‡]														
K100	5.1	5.3	5.3	5.5	5.9	6.0	6.8	7.3	7.1	7.1	7.6	7.4	7.0	6.5	4.8
K60	5.4	5.6	5.8	5.6	5.9	6.3	6.7	6.8	6.4	6.9	7.2	7.1	7.2	6.4	5.1
K36	5.4	5.5	5.4	5.2	5.5	5.9	6.0	5.8	4.4	4.8	4.8	4.2	5.4	5.9	5.4
K24	5.6	5.8	5.4	4.9	5.5	5.6	4.8	3.9	2.9	3.1	3.2	2.8	3.7	5.0	4.9
LSD (0.05)							1.0	1.8	1.6	1.3	1.2	0.9	0.9	1.0	
p-value	ns	ns	ns	ns	ns	ns	.005	.012	.001	.000	.000	.000	.000	.022	ns

[†] Irrigation levels were defined in terms of crop coefficient (K_c) adjustments to historical average ET_o: K_c = 1.00, 0.60, 0.36, and 0.24

[‡] Turf quality scores were visual assessments based on color, density, and uniformity of the turf using the following scale: 1 = worst, 9 = best, 6 = acceptable.

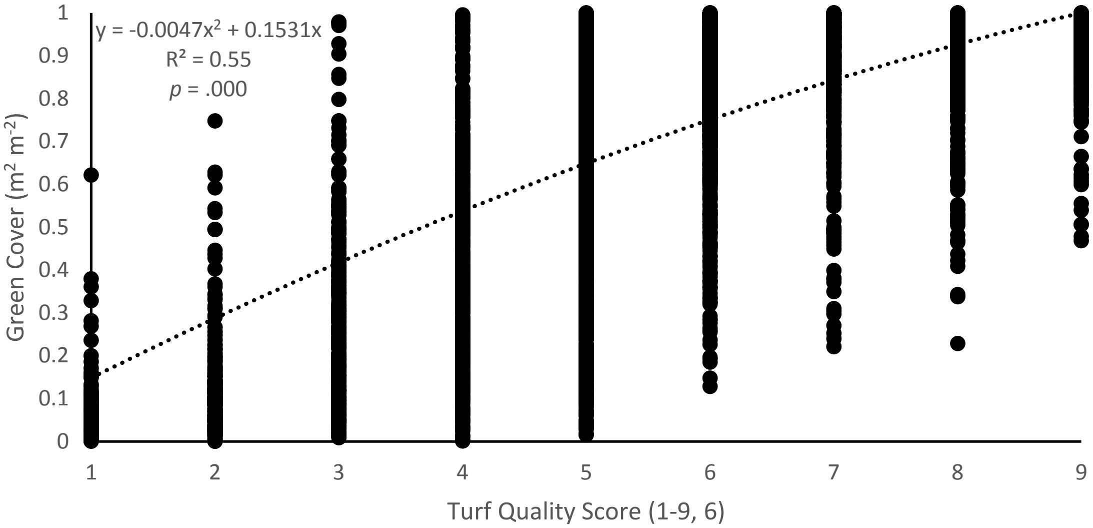

Fig. 2.1. Green cover plotted against turf quality scores for estimating acceptability thresholds of green cover image analysis. Data were pooled across all treatments, replications, and dates (N=4752).

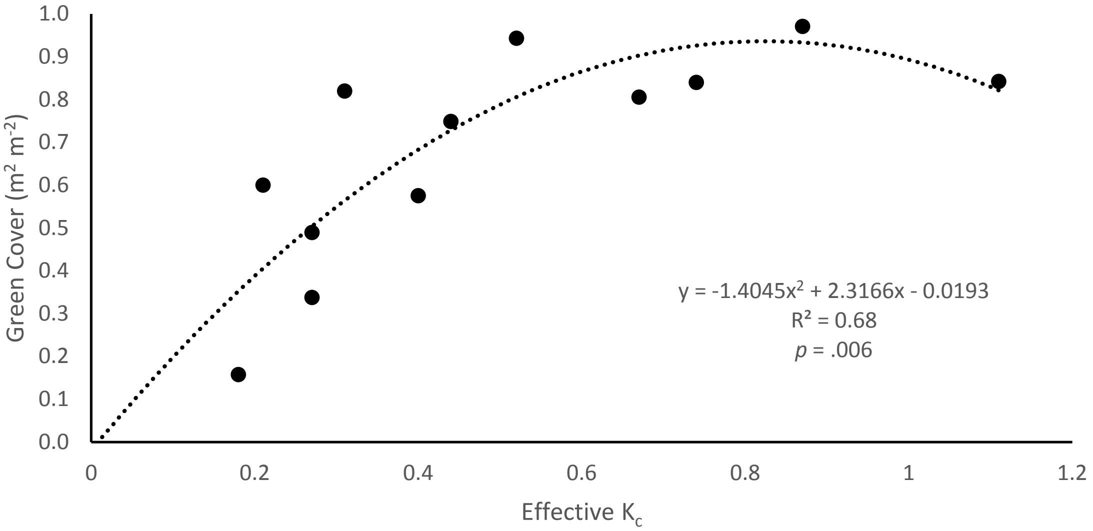

Fig. 2.2. Green cover plotted against effective K_c, as determined by comparing historical ET_c scheduling to actual ET_c scheduling across all years of the study (N=12).

Green Cover

Green cover was plotted against turf quality scores to estimate acceptability thresholds (Fig. 2.1). Across all years, a green cover of at least 75% was determined to be acceptable. In general, green cover data followed similar trends as seen in turf quality ratings (data not presented). After initial analysis, green cover data from the months of August and September were re-analyzed, and the mean for that period within each year was used for plotting against effective K_c data (Fig. 2.2). This was done to identify the relationship between K_c's and plant density minima. The data were a reasonable fit for a quadratic function ($R^2 = 0.68$). Graphical interpretation suggested maximal turf quality could be achieved using a K_c of 0.8. The K_c of 0.6 used in this study occurred near to an inflection point, suggesting this was near a critical threshold for turf health. Minimally acceptable turf quality (75% green cover) was achieved at a K_c of 0.47. Anecdotally, turf that maintained approximately 50% green cover on average over the course of late summer was able to recover rapidly during the fall. In order to achieve 50% cover, a K_c of 0.27 was adequate under the conditions of this experiment.

Soil Moisture

Soil moisture was monitored on the morning after an irrigation event each week (Fig. 2.3). Therefore, the data represented the maximum water content over a two to three day period. Differences between treatments corresponded to the varying irrigation volumes applied. However, *K100* and *K60* maintained similar moisture contents throughout the study; this despite *K100* receiving 40% more water. In 2011, substantial

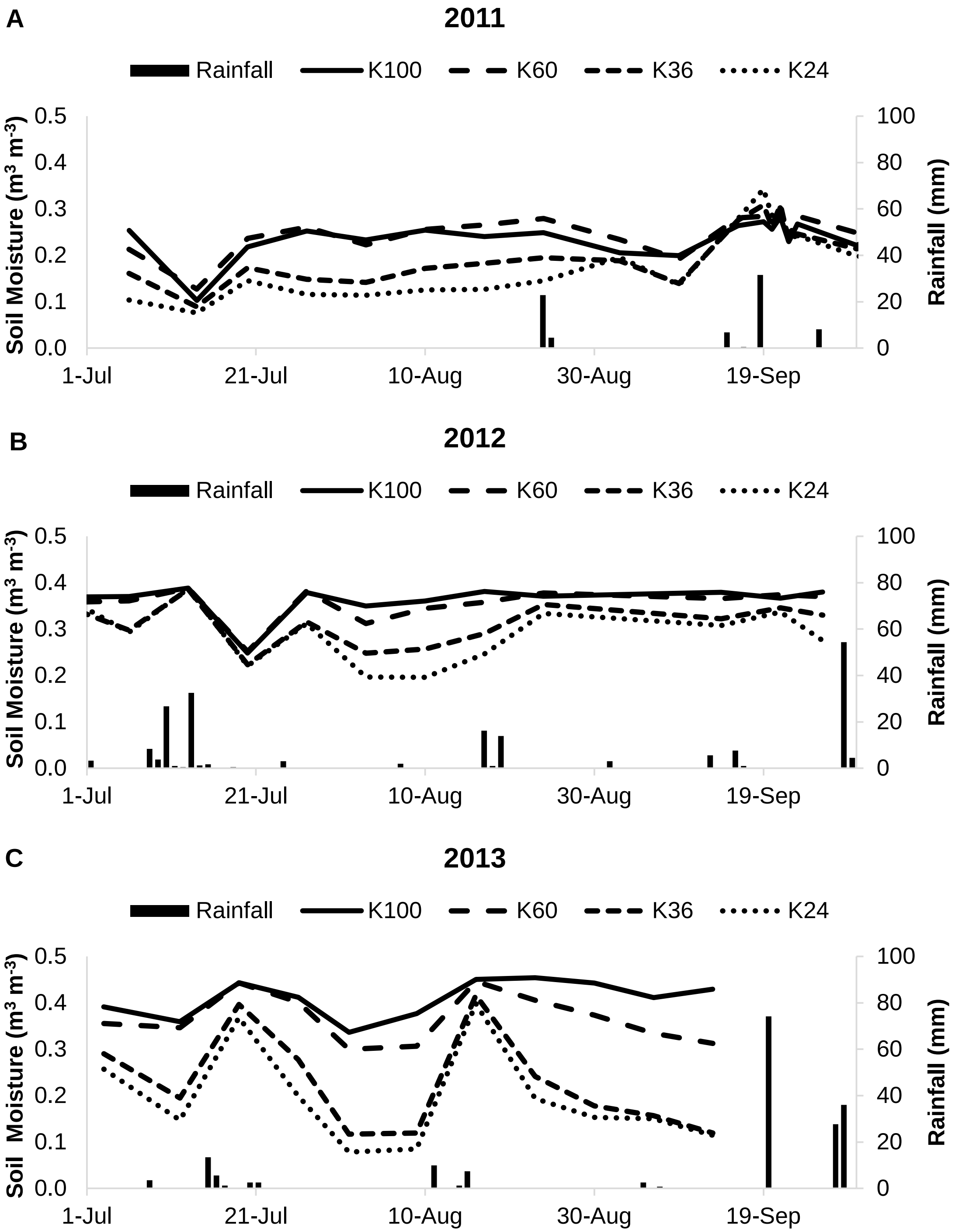

Fig. 2.3. Weekly changes in soil moisture (75 mm) as affected by irrigation treatment and rainfall. A) 2011, B) 2012, C)2013.

soil moisture depletion occurred fairly early in the season resulting in severe and prolonged drought stress. Conversely, in 2012, mean soil moisture did not fall below 0.2 $m^3 m^{-3}$ on any measurement date. In 2013, severe depletion occurred, but was relatively short-lived resulting in an acute form of drought stress.

Irrigation Excess and Adequacy – Inter-annual Variability

During the three years of the study, inter-annual variability for ET_o was substantial, ranging from 23% below average in 2011 to 18% above historical average in 2012 (Table 2.5). The *K100* treatment resulted in irrigation excess each year ranging from 1.3 fold in 2011 to 2.1 fold excess in 2012 (Table 2.6). Treatment *K60* resulted in irrigation excess in 2012 (wettest year), while other treatments were deemed below the excess threshold each year. Using the defined estimation methods, *K60* was adequate each year, while *K36* was adequate only in 2012. Treatment *K24* did not result in adequate irrigation in any of the three years. The adequacy ratings were in good agreement with measured parameters of turf performance. Specifically, turf attrition due to deficit irrigation was fairly evident in 2011, while in 2012, visual differences among treatments were muted.

Fertility Effects

Fertility did not affect annual mean turf quality in 2011, although there was some evidence that late season recovery was enhanced by N rate (Table 2.7). In 2012 and 2013, turf quality increased with increasing N rate. The fertility by date interaction was significant in 2012, and analysis by date indicated that fertilizer effect increased late in the season (data not presented). There were no significant irrigation by fertility interaction effects seen in the annual model.

Table 2.5. Expected water use for historical ET_o-based irrigation scheduling compared to actual adjusted ET_o for each year.

	--------2011--------		--------2012--------		--------2013--------	
Irr[†]	**Historical**	**Actual**	**Historical**	**Actual**	**Historical**	**Actual**
	-----------------	-----------------	-----------------	mm	-----------------	-----------------
K100	564	727	519	437	535	597
K60	345	429	321	253	331	349
K36	214	255	203	146	209	202
K24	148	170	144	94	148	131

[†] Irrigation levels were defined in terms of crop coefficient (K_c) adjustments to historical average ET_o: K_c = 1.00, 0.60, 0.36, and 0.24

Table 2.6. Expected water use for historical ET_o-based irrigation scheduling as a fraction of actual ET_c for each year.

Irr[†]	**2011**	**2012**	**2013**
	-----------------	Fraction ET_c	-----------------
K100	1.31	2.05	1.53
K60	0.80	1.27	0.95
K36	0.50	0.80	0.60
K24	0.35	0.57	0.42

[†] Irrigation levels were defined in terms of crop coefficient (K_c) adjustments to historical average ET_o: K_c = 1.00, 0.60, 0.36, and 0.24

Table 2.7. Main effects of fertility on turf quality.

Fertility	**2011**	**2012**	**2013**
kg N ha^{-1} mo^{-1}	-----------------	Quality[†]	-----------------
0	4.7	5.2	5.2
1.8	5.0	5.4	5.6
3.6	4.9	5.8	6.0
LSD (0.05)		0.1	0.3
p-value: Fertility (F)	ns	.000	.001
p-value: F x Date	ns	.000	ns

[†] Turf quality scores were visual assessments based on color, density, and uniformity of the turf using the following scale: 1 = worst, 9 = best, 6 = acceptable.

Discussion

Turfgrasses can be irrigated using K_c's below their expected water use rate, a practice termed deficit irrigation. Qian and Engelke (1999) used a linear irrigation gradient system to identify the minimal water requirements for acceptable turf quality. Their data showed 'Nortam' St. Augustinegrass could be sustained in the Dallas area at K_c's as low as 0.55 (calculated from ET_{pan} assuming $K_{pan} = 0.8$, Allen et al., 1998). In the present study, minimally acceptable turf could be maintained at effective K_c's of 0.45. A limitation of previous research has been neglect for irrigation water requirements below that needed to sustain acceptable turf. Under severe water shortages, a more appropriate management objective might be to apply irrigation during the summer only to sustain live plant buds such that a complete turf could recover quickly under more favorable moisture conditions often experienced in the fall. This proposed objective could be termed 'adaptive irrigation management', in light of a manager's willingness to adapt their expectations depending on the environmental conditions and time of year. Research conducted using actual residential lawns concluded that a K_c of 0.6 resulted in acceptable turf year round in San Antonio, TX (Fipps and Pope, 2000). Further, the same authors concluded that a K_c of 0.36 was adequate for seasonally poor turf that would recover each fall. Likewise, the present study suggested rapid recovery occurred when turf was maintained at 50% green cover during late summer. This corresponded to a K_c of approximately 0.3.

The use of historical average ET_o and a K_c of 0.6 provided a robust estimate for plant water requirements under the experimental conditions. Even under extreme drought in 2011, the turf maintained an acceptable appearance. Indeed, when rainfall was absent, historical ET_o mirrored actual ET_o reasonably well. However, under above average rainfall conditions such as July 2012, the standard K_c of 0.6 could be in excess of plant needs (Table 2.8). In such scenarios, rainfall recharged the rootzone, thus delaying the onset of soil moisture depletion. Indeed, this shortened the annual window and severity of drought stress endured by turfgrasses and ultimately reduced turf attrition while likely enhancing recovery rates (Steinke et al., 2013). Under rainy conditions, using a smaller K_c such as 0.45 or removing the DU adjustment is advised. Obviously, reliable forecasting of inter-annual variability in plant water requirements is difficult, and yet, a decision must be made at the onset of the season. It is proposed that a lawn manager is more likely to adjust their controller in favor of increasing water applied than the opposite scenario. Therefore, use of a smaller K_c such as 0.4 or 0.5 should be encouraged when using historical average ET_o-based scheduling. If conditions become excessively dry, the manager can add supplemental runs as needed so long as the program is not permanently changed.

It is necessary to point out that under more restrictive irrigation scheduling (1 day or 2 day per week), the performance of specific K_c's could vary. Certainly, a K_c's performance (adequacy or excess) can be affected by plant available water capacity of the soil and frequency of irrigation events. These are important concerns that are not well addressed by the present study, but future efforts in this regard are needed.

Table 2.8. Comparison of historical average and actual monthly rainfall during the study period.

	-------2011-------		-------2012-------		-------2013-------	
Month	**Historical**	**Actual**	**Historical**	**Actual**	**Historical**	**Actual**
	---mm---					
July	57	0	57	83	57	29
Aug	62	27	62	37	62	19
Sept	109	47	109	76	109	141

Conclusions

The use of historical average ET_o and a K_c of 0.6 for predicting St. Augustinegrass lawn irrigation requirements can provide adequate soil moisture for acceptable turf quality with high reliability. However, in wetter years, irrigation excess can be problematic unless rain sensors are used as interrupters or managers are willing to adjust for measured rainfall. It is reasonable to also assume that historical ET_o methods would perform more predictably in arid climates where rainfall would have less impact on ‘set it and forget it’ systems. When rainfall can be reliably expected, using a lower K_c is advisable for historical average ET_o scheduling.

CHAPTER III

EFFECTIVE RAINFALL ESTIMATES FROM MEASUREMENTS OF RUNOFF FROM SIMULATED LAWNS

Introduction

Over the last twenty years, research has contributed to the development of effective management systems for irrigating residential lawns. Perhaps, the most commonly recommended irrigation scheduling system is the reference ET - crop coefficient (ET_o - K_c) method (Allen et al., 1998). The method can be described by Eq. 1.2.

Irrigation should be applied so as to fully replace soil water depletion caused by estimated plant ET, so long as the water applied does not exceed the soil field capacity. St. Augustinegrass (*Stenotaphrum secundatum* (Walt.) Kuntze), the predominant lawn grass in Texas, has often been publicly perceived as having a high water requirement (Richard White, Professor of Turfgrass Physiology, Texas A&M University, personal communication). Reported K_c values for St. Augustinegrass have varied depending on location and methodology. Carrow (1995) used changes in soil moisture to estimate a K_c of 0.72 for 'Raleigh' in Georgia. Kneebone and Pepper (1982), using drainage lysimeters and a perched water table to measure ET, reported a K_c of 0.65 for St. Augustinegrass in Arizona. These values are not remarkably different from those published for other warm-season turfgrasses, therefore a single K_c of 0.6 has often been recommended for all warm-season species (Texas ET Network). Despite the apparent agreement on appropriate K_c's for southern lawn grasses, irrigation scheduling remains problematic for turf sites due to additional parameters needed to accurately define the water budget. An example of one such parameter is effective rainfall - the portion of measured rainfall that enters the soil and remains in the rootzone for plant uptake. For agricultural crops or water budget planning, monthly estimation methods are fairly commonplace. However, the need for weekly or event-based effective rainfall prediction is critical to accurate irrigation scheduling for lawns.

One of the more commonly used methods for estimating effective rainfall for turf is the coefficient method. That is, measured rainfall is multiplied by an empirically-derived coefficient (K_{er}) such as 0.5. This simplistic method obviously ignores the apparent interaction between rainfall depth and effective rainfall and assumes a linear relationship between the two variables. Others have suggested more complicated algorithms which weigh effective rainfall differently for varying storm sizes (Table 3.1).

Table 3.1. Texas ET Network effective rainfall model used to estimate runoff volume when measured runoff data were unavailable.

Measured Rainfall	Effective Rainfall
0 – 2.5 mm	0%[†]
2.5 to 25 mm	100%
25 to 50 mm	67%
>50 mm	0%

[†] The first 2.5 mm are ignored and considered lost to evaporation.

Because of the prevalence of high clay-containing, poorly drained soils in many urban centers, effective rainfall can largely be defined as measured rainfall minus surface runoff. Predictive modeling of runoff from a variety of land covers has been studied rigorously, and physically-based rainfall excess models such as Green-Ampt infiltration method or advanced empirical models such as the SCS Curve Number method can be fairly accurate if model assumptions are met and all parameters well-defined (Mein and Larson, 1973). Such models are often based on Darcy's equation for flow through a porous medium and require quantification of soil hydraulic parameters such as porosity and saturated hydraulic conductivity (Dingman, 2008). For lawn irrigation, these methods may be too data intensive, therefore simple empirical methods are likely to be more suitable.

Surface runoff occurs when precipitation or irrigation exceeds soil storage and infiltration. Infiltration rates of residential lawns can be highly variable and difficult to generalize across regions or even among similar soil types. Hillslope position was shown to be the primary factor affecting runoff from sandy loam soils in New York (Easton et al., 2005). Lower catena positions typically had greater clay content, lower infiltration rates, and higher soil moisture contents. Hamilton and Waddington (1999) reported that tiller density, soil bulk density, and soil texture did not affect infiltration rates of 15 Pennsylvania lawns, and that excavation and lawn establishment procedures were more predictive of infiltration rates. This is in agreement with previous research using simulated rainfall on lawns in Wisconsin (Kelling and Peterson, 1975). In both studies, infiltration rates were highly variable ranging from 0.1 to 8.9 cm hr^{-1}. In Florida, relatively high infiltration rates were reported between 37.7 to 63.4 cm hr^{-1} due to the sandy soils (Gregory et al., 2006). Despite the substantial difference between Florida and Pennsylvania infiltration rates, construction activity and localized compaction was the major factor affecting infiltration rates. Partsch et al. (1993) found that compaction during establishment could affect infiltration rates for up to 12 years after installation.

Perhaps the most complete hydrological assessment of small plot turf runoff was performed by Linde et al. (1995). In their study, direct measurement of tiller density, verdure interception, thatch water retention, soil infiltration rate, and hydraulic resistance were compared between two species of cool-season turfgrasses. Significant differences between species appeared to be related to logical differences in runoff volumes. In particular, the presence of a well-defined thatch layer provided additional surface storage and hydraulic resistance for increasing lag time, enhancing lateral diffusion of runoff, and ultimately reducing runoff volumes. Southern lawn turfgrasses such as St. Augustinegrass are exceptional thatch producers and could be expected to have a much greater capacity to store precipitation when density and active growth is adequate to create a well-defined thatch layer.

Runoff volume from turf can be affected by a number of management factors. Turfgrass species and growth habit affects interception and hydraulic resistance of flow (Linde et al., 1998). Specifically, thatch-producing turfgrasses with horizontally-oriented leaves were able to reduce runoff volumes compared to bunch-type grasses. Similarly, turf density has been negatively correlated with runoff volume and nutrient export (Gross et al., 1991; Linde et al., 1995; Easton and Petrovic, 2004; Easton et al., 2005; Bierman et al., 2010). Cultivation practices such as vertical mowing and solid tine aeration have not had consistent effects on runoff volumes, but these findings may be more a factor of the variability and intensity of runoff events overcoming any potential detectable benefits of cultivation (Cole et al., 1997; Kauffman and Watschke, 2007; Linde and Watschke, 1997). Moss et al. (2007) reported that hollow-tine core aeration increased the response lag, but similar to other cultivation methods under high intensity rainfall, core aeration did not influence runoff volumes (Moss et al., 2007). To the contrary, Rice and Horgan (2011) found hollow-tine core aeration did reduce runoff volumes compared to solid-tine aeration. In general, cultivation such as coring increases surface storage of precipitation and may have a greater effect on moderate to light rainfall events or controlled irrigation practices.

Although soil moisture has a known influence on surface runoff, it is rarely considered when calculating effective rainfall for an irrigation schedule. Rather, a single method is often applied to all instances, regardless of predicted soil moisture. Due to the increased promotion of deficit irrigation practices, drier soil conditions could serve to decrease runoff and therefore affect how effective rainfall is calculated. A two-year field study was conducted to investigate the effects of full and deficit irrigation on antecedent moisture conditions, turf performance, and effective precipitation.

Objectives

The objectives of this study were to quantify seasonal runoff volumes from St. Augustinegrass turf, estimate the effect of irrigation management on seasonal runoff volumes, and compare measured runoff to simple runoff models that could be used for irrigation scheduling.

Hypothesis

1) Runoff volumes will vary seasonally with antecedent soil moisture
2) Deficit irrigation will have not reduce runoff volumes if plant density loss occurs
3) Runoff models which account for initial abstraction will be more accurate than those that do not

Materials and Methods

Research was conducted at the Texas A&M Turfgrass Field Laboratory on F&B Rd in College Station, TX (N 30.618178, W -96.366250). The native soil was a Boonville series sandy loam (Fine, smectitic, thermic Chromic Vertic Albaqualfs). A surface runoff small plot research site was built to an average slope of 0.037 m m^{-1}, planted with St. Augustinegrass (*Stenotaphrum secundatum* (Walt.) Kuntze ‘Raleigh’), and equipped with flow discharge measurement capabilities. For a more detailed description of the site, see Wherley et al. (2014).

Turf was maintained similarly to a medium-intensity managed residential lawn. Mowing was performed weekly using a standard walk behind rotary mower with mulching blades set to a 6.3 cm height of cut and clippings were returned. Pesticide applications were made preventatively and curatively based on knowledge of site history

(Table 3.2). Each winter, gypsum was applied at a rate of 2.24 Mg ha^{-1} to reduce the impact of sodic irrigation water (Pannkuk et al., 2011) on site hydrology.

The experiment consisted of three irrigation levels and three fertilizer levels having three replicates arranged as an incomplete factorial, randomized complete block design (Table 3.3). Data were pooled over the three fertilizer treatments. Irrigation was applied on Tuesdays and Fridays to mimic a two-day per week calendar-based irrigation schedule as is common in several Texas cities. Run times were adjusted to apply amounts equal to the cumulative ET deficit (ET_{Def}) since the prior irrigation event. Cumulative ET deficit was calculated as

$$ET_{Def} = \sum K_s*[0.6* ET_o – R_{eff}] \qquad \text{(Eq. 3.1)},$$

where K_s was the stress coefficient, 0.6 was the warm-season turfgrass crop coefficient, ET_o was the daily FAO-56 PM ET_o (Allen et al., 1998), and R_{eff} was the daily effective rainfall. Treatments were defined in terms of K_s as 0.50, 0.75, and 1.00 (referred to as *K50*, *K75*, and *K100* for remainder of this chapter), which were selected so as to create severe, medium, and zero stress conditions, respectively. Effective rainfall was assumed to be measured rainfall for small rain events (< 25 mm). For larger events, when data were available, R_{eff} was calculated from the mean runoff volume as measured on site. If measured runoff data were unavailable, R_{eff} was calculated using a method promoted by the Texas ET Network (Table 3.1). Irrigation run times were adjusted for uniformity (DU_{LH}) as suggested by the Irrigation Association. Results of an irrigation audit indicated a precipitation rate of 39 mm hr^{-1} and a DU_{LH} of 0.84. The irrigation season was defined

Table 3.2. Pesticide applications made during maintenance of research plots.

Trade Name	TopChoice	Heritage G	Ronstar 2G	ProStar 70WG	MSM	Daconil Ultrex	Princep 4L	Barricade 4L
a.i.[†]	fipronil	azoxystrobin	oxadiazon	flutalonil	metsulfuron-methyl	chlorthalonil	simazine	prodiamine
Target	fire ants	large patch	summer annual weeds	large patch	winter weeds	large patch	winter annual weeds	winter annual weeds
Product Rate	100[‡]	100[‡]	170[‡]	6.7[‡]	7E-02[‡]	10[‡]	4.7[§]	2.0[§]
Dates Applied	3/26/2013 3/17/2015	4/8/2014 9/4/2014 9/16/2014 10/2/2014 10/23/2014 2/27/2015	3/11/2014 2/27/2015	10/23/2013 12/1/2014	3/17/2014	7/15/2014 7/29/2014	12/11/2014	9/6/2013 8/25/2014

[†] Active ingredient

[‡] $kg\ ha^{-1}$

[§] $L\ ha^{-1}$

Table 3.3. Incomplete factorial design used in the experiment. Data analyses used fertility and irrigation factors (and their interaction) when it improved model fit.

Treatment No.	Irrigation [†]	Fertility [‡]
1	0.50	2x
2	0.50	4x
3	0.75	0x
4	0.75	2x
5	0.75	4x
6	1.00	0x
7	1.00	2x
8	1.00	4x

[†] Irrigation levels were defined in terms of stress coefficient (K_s) adjustments to ET_c: K_s = 0.50, 0.75, and 1.00.

[‡] Fertility levels were 0x, 2x, or 4x applications yr^{-1} of 39 kg N ha^{-1} of a partially slow-release, high N fertilizer.

loosely as the period May 1 to Oct 31. Runoff volumes were continually monitored during winter dormancy periods.

Rainfall was measured using a tipping rain gauge (Isco 674, Teledyne Isco, Lincoln, NE) at a two minute temporal resolution. Runoff discharge was conveyed through a calibrated H-flume and measured with bubbler-type meters (model 4230, Teledyne Isco, Inc., Lincoln, NE) at a two minute resolution. Runoff ratio was calculated as measured runoff divided by measured rainfall. Initial abstraction was calculated as the amount of rainfall occurring prior to initial runoff as measured in the out-flowing flume. Over the two year period, runoff was measured from 34 rainfall events and one irrigation event (13 – Aug – 2013). The solitary irrigation event was forced to create an added data point during the summer.

Soil volumetric water content was measured at the 10 cm depth on 15 min temporal resolution using buried sensors (SDI-12, Acclima, Inc., Meridian, ID). Additional soil moisture measurements in the top 7.5 cm were made periodically using a handheld meter (Field Scout TDR300, Spectrum Technologies, Inc., Aurora, IL). Soil bulk density was measured using 10 cm diameter cores to a depth of 10 cm. Steady-state infiltration rate was determined using a double-ring infiltrometer and a constant head of 4 cm. Infiltration was monitored until rates remained constant for one hr. Turf performance was quantified on a biweekly interval as percent green cover by analyzing green pixels (SigmaScan, Systat Software, Inc., San Jose, CA) in images collected using a conventional digital camera (PowerShot SX170 IS, Canon, Inc. Tokyo, Japan) and controlled light box (Richardson et al., 2001). Green cover data were normalized by date to calculate relative green cover.

Treatment effects on runoff ratio, initial abstraction, and turf performance were analyzed using a linear mixed model repeated measures design (SPSS 22, IBM Corp., Armonk, NY). Block, irrigation, and date were considered fixed effects. Missing data were evaluated using a simplified mixed model, typically without the date by treatment interaction term. These data were merged with the original dataset and re-analyzed using the full model. Treatment means were separated using Fisher's protected least significant difference (LSD) at a significance level of $p \leq 0.05$. Seasonal effects were evaluated using a general linear model with season being defined as follows: spring (Apr – May), summer (Jun – Sep), fall (Oct – Nov), winter (Dec – Mar). Measured runoff from 51 events (>2.54 mm) during the irrigation season (Apr 1 to Oct 15) was further compared to four empirical models: Texas ET Network (TXETN) Method, SCS Curve Number (SCS-CN) Method, Coefficient Method, and Polynomial Method. The TXETN model is shown in Table 3.1 and follows a step function which increases the runoff ratio with increasing storm size category. Thresholds for each category and the runoff ratio for the third level were optimized to fit the data and compared to the base model. The SCS-CN method utilized an optimized CN number and appropriate adjustments for preceding 5-day rainfall + irrigation (USDA-SCS, 1972). If the 5-day antecedent rainfall plus irrigation was greater $\leq$ 35 mm, CNII was adjusted to CNI using equation 3.2. If the 5-day antecedent rainfall exceeded 53 mm, CNII was adjusted to CNIII using Eq. 3.3.

$$\text{CNI} = (4.2 * \text{CNII}) / (10 - 0.058 * \text{CNII}) \quad \text{(Eq. 3.2)}$$

$$\text{CNIII} = (23 * \text{CNII}) / (10 + 0.13 * \text{CNII}) \quad \text{(Eq. 3.3)}$$

The Coefficient method involved fitting the data to develop a K_{er} that could be multiplied against measured rainfall. The Polynomial method involved developing a best fit polynomial equation by plotting rainfall versus runoff using MS Excel. Model accuracy and parameter optimization was performed using Solver in MS Excel and Nash –Sutcliffe Efficiency (NSE) as the criterion.

Results

Turf Performance

Turf relative green cover varied with irrigation treatment during the growing season (Fig. 3.1). In general, deficit irrigation caused turf attrition in late July through early Sept, although the specific duration and intensity of attrition varied with year. By Oct of each year, turf had visibly recovered from summer drought stress. These data were corroborated with leaf area index measurements collected in late-August which demonstrate a measureable loss of density with diminishing irrigation water applied

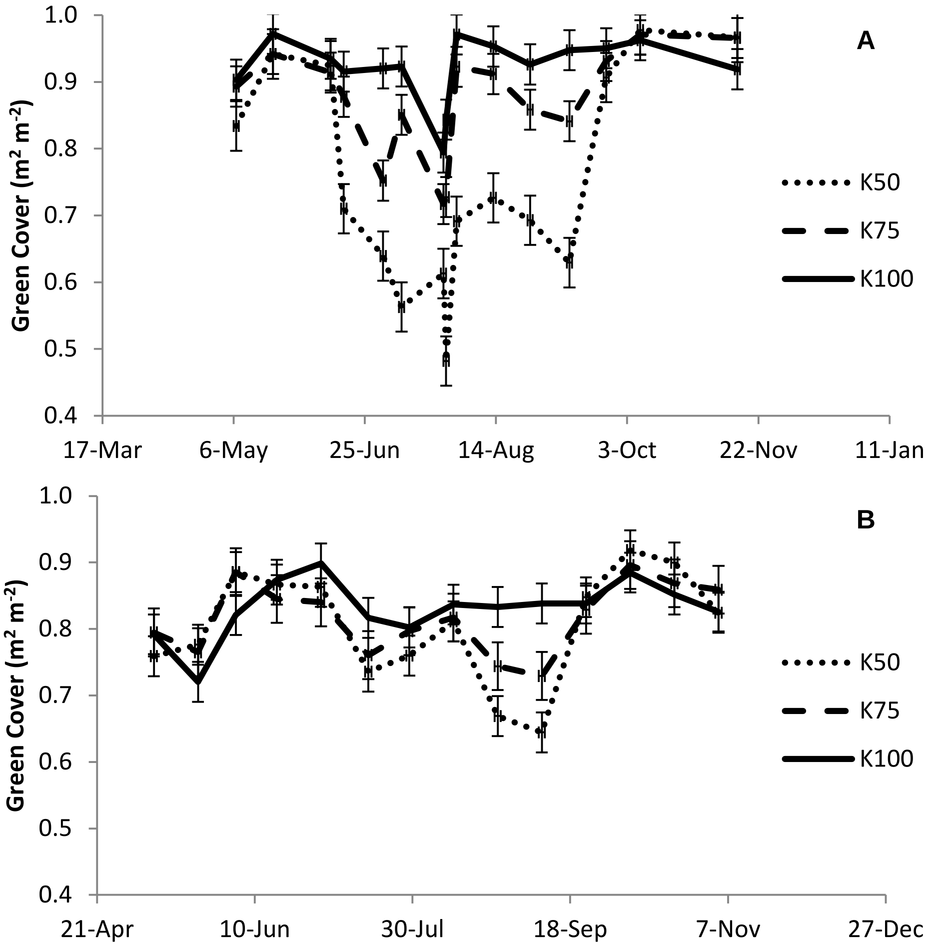

Fig. 3.1. Relative green cover as affected by irrigation treatment in A) 2013 and B) 2014. Error bars are standard errors of the mean. *K50*, *K75*, *K100* are irrigation levels defined as K_s = 0.50, 0.75, 1.00, respectively.

Table 3.4. Leaf area index as affected by irrigation main effect. Measurements were made by destructive sampling plugs at two locations within each plot. Data represent three replications of each irrigation level.

Irrigation†	-----2013-----		-2014-
	Jun	Aug	Aug
K50	2.4	0.8	2.4
K75	2.9	2.4	3.6
K100	2.5	4.0	3.4
p-value	*	**	ns

† Irrigation levels were defined in terms of stress coefficient (K_s) adjustments to ET_c: K_s = 0.50, 0.75, and 1.00.

(Table 3.4). In each case, some turf density remained for adequate recovery during the fall. Further, there existed a desiccated straw layer where turf attrition had occurred, as opposed to a truly bare soil.

Rainfall Seasonal Patterns

Over the two-year study period, storm events showed seasonal patterns typical for the Texas climate. Season did not affect rainfall depth (on average), but had a significant effect on rainfall duration, intensity, and peak intensity (Table 3.5). Rainfall during May was abundant and exceeded plant water requirements each year. The summer was characterized by periods of low rainfall followed by a series of high intensity storm events. Winter events were typically longer duration, lower intensity storms that often lasted for multiple days. The majority of annual rainfall occurred between June and Sept, but events were often of high intensity. The seasonal patterns in rainfall and runoff are reflected by representative event hydrographs and summary data shown in Fig. 3.2 and Table 3.6.

Table 3.5. Seasonal effects on rainfall event type (N=31).

	Duration	**Depth**	**Intensity**	**Peak**	**Intensity Fraction**†	**Soil Moisture**‡	**IA**§	**RR**¶
	min	mm	--------mm hr^{-1}--------			m^3 m^{-3}	mm	
spring	236	36	13	52	0.10	0.30	11	0.38
summer	197	41	22	67	0.17	0.21	14	0.16
fall	697	29	7	35	0.09	0.25	13	0.15
winter	965	37	4	26	0.01	0.35	12	0.40
p-value	*	ns	**	***	*	***	ns	**

† Fraction of storm duration in which rainfall intensity exceeded 25 mm hr^{-1}.
‡ Antecedent moisture content for each storm measured at a 10 cm depth.
§ Initial abstraction.
¶ Runoff ratio.

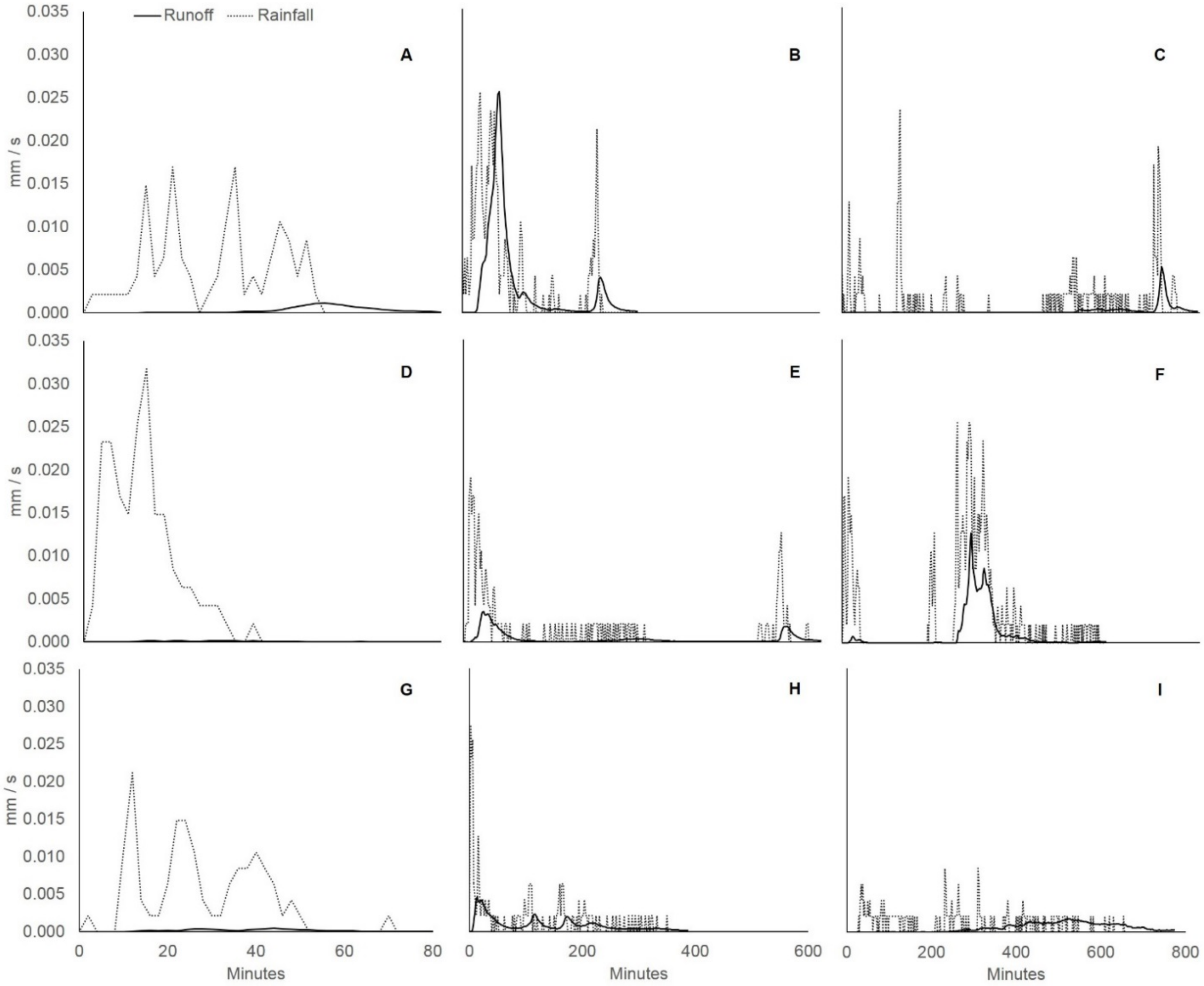

Fig. 3.2. Hydrographs and hyetographs from representative events during the two-year study period. A) 21-May-13, B) 9-May-13, C) 29-Sep-13, D) 3-Jul-14, E) 27-May-14, F) 12-Sep-14, G) 13-Oct-14, H) 31-Oct-14, I) 19-Dec-14.Table 3.6.

Table 3.6. Summary table of rainfall – runoff statistics from representative storm hydrographs.

		Rainfall				Runoff						
Event[†]	**Date**	**Depth**	**Duration**	**Intensity**	**Peak**	**Depth**	**Duration**	**Intensity**	**Peak**	**T_{Peak}**[¶]	**IA**[§]	**RR**[¶]
		mm	min	mm hr^{-1}	mm hr^{-1}	mm	min	mm hr^{-1}	mm hr^{-1}	min	mm	
A	5/21/2013	18	50	22	35	01	26	3	4	10	14	0.08
B	5/9/2013	73	234	19	76	52	252	12	92	38	10	0.72
C	9/29/2013	56	748	04	52	09	242	2	19	186	31	0.17
D	7/3/2014	25	36	41	81	01	26	1	1	-	13	0.01
E	5/27/2014	47	612	05	61	13	564	1	13	16	09	0.28
F	9/12/2014	115	572	12	85	35	402	5	46	268	12	0.30
G	10/13/2014	20	118	10	37	01	22	2	2	18	09	0.04
H	10/31/2013	37	348	06	62	21	350	4	16	08	06	0.56
I	12/19/2014	41	626	04	17	17	405	2	4	195	24	0.41

[†] The event letter corresponds to the hydrographs in Fig. 3.2.

[‡] Time to peak as calculated from initiation of runoff.

[§] Initial abstraction.

[¶] Runoff ratio.

Table 3.7. Fixed effects model for initial abstraction and runoff ratio using data from all storms or only data from storms having greater than 25 mm of rainfall.

	Initial Abstraction		Runoff Ratio	
Source	**All Events**	**Events > 25 mm**	**All Events**	**Events > 25 mm**
Block	.005	.000	.000	.000
Irrigation (I)	.061	.006	.081	.030
Date (D)	.000	.000	.000	.000
D x I	.446	.477	.514	.179

[†] Irrigation levels were defined in terms of stress coefficient (K_s) adjustments to ET_c: K_s = 0.50, 0.75, and 1.00.

Measured Runoff: Seasonal and Management Effects

Mean (± standard deviation) bulk density across the facility was 1.47 ± 0.08 g cm^{-3}. Infiltration rates were low and highly variable having a mean of 3.2 ± 3.6 mm h^{-1}. Runoff ratios (RR) averaged seasonally ranged from 0.15 to 0.40 and were higher during winter and spring due to elevated soil moisture conditions (Table 3.5). In the combined analysis, irrigation level demonstrated a nearly significant ($p \leq 0.10$) main effect on RR and initial abstraction (IA) (Table 3.7). When analyzing data from storms greater than 25 mm rainfall, irrigation demonstrated a significant main effect on both RR and IA. Further analysis revealed irrigation effects on RR were primarily during the summer and fall, suggesting soil moisture was the primary driver for differences in RR (Table 3.8). Beyond seasonal interactions, irrigation effects on RR were larger when rainfall events were greater than 25 mm and less than 60 mm. Effects on IA were similar to those observed for RR, although seasonal effects did not appear to be as important as individual event characteristics (Tables 3.4 & 3.7).

Predicting Effective Rainfall

Effective rainfall as defined in this paper was tested against several empirical models on an event basis. Data were averaged across all plots or all plots within a given irrigation level. In each case, parameters were optimized to maximize the Nash-Sutcliffe Efficiency (NSE). Prior to optimization, the base TXETN model resulted in an NSE of 0.82 (Table 3.9). Optimized parameters for the complete dataset indicate threshold 1 could be reduced from 25 to 15 mm, while threshold 2 and the coefficient could be

Table 3.8. Irrigation by date interaction effects on initial abstraction and runoff ratio.

Date	Rainfall	--------Initial Abstraction--------				--------Runoff Ratio--------				Antecedent Soil Moisture[†]		
		K50[‡]	*K75*	*K100*	*p*-value	*K50*	*K75*	*K100*	*p*-value	*K50*	*K75*	*K100*
	---mm---					---mm mm^{-1}---				---m^3 m^{-3}---		
09-May-13	73	12	13	12	ns	0.64	0.58	0.69	ns	0.24	0.29	0.29
10-May-13	16	8	8	7	ns	0.36	0.34	0.41	ns	0.34	0.34	0.38
16-May-13	15	8	9	7	ns	0.44	0.41	0.46	ns	0.36	0.33	0.38
21-May-13	18	15	15	15	ns	0.08	0.08	0.09	ns	0.26	0.28	0.26
02-Jun-13	32	25	23	25	ns	0.05	0.10	0.13	*	0.23	0.26	0.26
13-Aug-13	29	24	25	25	ns	0.03	0.03	0.18	**	0.09	0.13	0.20
20-Sep-13	48	17	12	10	*	0.10	0.16	0.32	***	0.07	0.11	0.19
29-Sep-13	56	39	40	29	**	0.13	0.11	0.18	**	0.15	0.19	0.20
13-Oct-13	105	-	-	-	-	0.28	0.23	0.30	ns	0.15	0.19	0.18
27-Oct-13	34	20	19	16	ns	0.25	0.23	0.25	ns	0.25	0.26	0.27
31-Oct-13	35	8	7	5	***	0.16	0.20	0.36	***	0.31	0.30	0.32
26-Nov-13	87	-	-	-	-	-	-	-	-	0.39	0.35	0.36
22-Dec-13	23	14	13	14	ns	0.20	0.19	0.25	ns	0.31	0.31	0.32
14-Jan-14	22	18	18	17	ns	0.15	0.16	0.19	ns	0.38	0.35	0.35
08-Mar-14	18	11	11	8	**	0.35	0.30	0.38	ns	0.37	0.35	0.35
09-May-14	28	19	16	10	***	0.19	0.23	0.38	***	0.17	0.21	0.31
13-May-14	72	14	13	10	***	0.45	0.40	0.46	ns	0.27	0.27	0.30
27-May-14	47	11	11	9	ns	0.32	0.24	0.30	ns	0.26	0.23	0.23
28-May-14	20	6	5	5	ns	0.54	0.47	0.50	ns	0.39	0.34	0.36
23-Jun-14	11	3	3	3	ns	0.01	0.02	0.02	ns	0.15	0.21	0.28
25-Jun-14	23	11	16	17	ns	0.04	0.03	0.04	ns	0.17	0.21	0.28
26-Jun-14	7	4	4	3	ns	0.01	0.06	0.05	ns	0.31	0.33	0.35
05-Jul-14	25	-	-	-	-	0.00	0.00	0.00	ns	0.26	0.30	0.33
07-Jul-14	10	1	7	7	ns	0.00	0.02	0.01	ns	0.24	0.28	0.31
18-Jul-14	115	10	8	7	ns	0.80	0.87	0.86	ns	0.12	0.17	0.17
15-Sep-14	115	17	18	14	ns	0.29	0.26	0.36	*	0.12	0.10	0.16
19-Sep-14	4	-	-	-	-	0.02	0.00	0.01	ns	0.29	0.29	0.32
02-Oct-14	18	10	9	8	ns	0.02	0.01	0.01	ns	0.18	0.19	0.17
11-Oct-14	11	-	-	-	-	0.00	0.00	0.00	ns	0.17	0.22	0.18
13-Oct-14	20	8	8	8	ns	0.04	0.04	0.04	ns	0.19	0.23	0.19
06-Nov-14	8	25	20	16	ns	0.15	0.07	0.14	ns	0.13	0.16	0.14
23-Nov-14	50	-	-	-	-	-	-	-	-	0.27	0.27	0.26
19-Dec-14	41	29	21	22	*	0.22	0.47	0.40	ns	0.25	0.26	0.24
31-Dec-14	8	4	5	5	ns	0.04	0.03	0.05	ns	0.34	0.34	0.36
01-Jan-15	17	9	11	10	ns	0.47	0.42	0.49	ns	0.40	0.37	0.37
03-Jan-15	29	4	5	3	ns	0.64	0.57	0.65	ns	0.41	0.37	0.37
12-Jan-15	40	10	9	8	*	0.51	0.47	0.52	ns	0.41	0.38	0.37
23-Jan-15	64	14	13	13	ns	0.42	0.45	0.40	ns	0.36	0.35	0.36
11-Mar-15	90	25	24	23	ns	0.59	0.52	0.50	ns	0.33	0.33	0.37
22-Mar-15	28	11	11	11	ns	0.37	0.27	0.29	ns	0.38	0.36	0.36

[†] Measured at a 10 cm depth.

[‡] *K50, K75, K100* are irrigation levels defined as K_s = 0.50, 0.75, 1.00, respectively.

Table 3.9. Summary of simple model outputs used to estimate runoff.

Method	No. of Events	Parameter	Base	Average	*K50*	*K75*	*K100*
TXETN	51	Threshold 1	25 mm	15 mm	16 mm	15 mm	15 mm
		Threshold 2	51 mm	67 mm	73 mm	66 mm	63 mm
		Coefficient	0.33	0.39	0.41	0.33	0.44
		NSE	0.78	0.84	0.82	0.81	0.87
SCS-CN	51	CN		83	82	82	85
		NSE		0.82	0.83	0.79	0.83
Coefficient	51	K_{er}		0.45	0.43	0.43	0.49
		NSE		0.63	0.62	0.59	0.68
	50	K_{er}		0.31	0.30	0.27	0.36
		NSE		0.63	0.57	0.60	0.68
Polynomial	51	Function[§§]		$0.00005873x^3 - 0.00372396x^2 + 0.26227383x$			
		NSE		0.86			

[†] *K50, K75, K100* represent irrigation levels applied as stress coefficients of 0.50, 0.75, and 1.00, relative to ET_c.

[‡] Texas ET Network

[§] Threshold 1, Threshold 2, and the Coefficient are described in Table 3.1.

[¶] Nash-Sutcliffe Efficiency

[#] SCS Curve Number

[††] Effective rainfall coefficient

[‡‡] Large leveraging event on 17 – Jul – 14 was removed for better prediction of more common events.

[§§] Polynomial function with variables f(x) = predicted runoff (mm) and x = measured daily rainfall (mm).

increased from 51 to 67 mm and 0.33 to 0.39, respectively. Unfortunately, the model fit was not remarkably enhanced through adjustments to the parameters. When applied within a specific irrigation management program, outputs were similar to the average although *K50* resulted in slightly higher threshold 2 value of 73 mm. The model appeared to perform best under *K100* treatments (NSE = 0.87). In general, the model over-predicted runoff during small and medium rain events, while under-predicting the largest event (Fig. 3.3).

The SCS-CN method performed similarly to the TXETN method having a NSE of 0.82 for the average across all plots (Table 3.9). The best fit curve number was 83 for the averaged dataset, but *K50* and *K75* performed best with a CN of 82, while *K100* was best fit to CN equal to 85. Again, the model over-predicted runoff during small and medium events, while under-predicting the largest event (Fig. 3.4).

The Coefficient method performed poorly regardless of irrigation level but best fit the *K100* data (NSE = 0.59 to 0.68). A K_{er} of 0.55 (RR = 0.45) was the best fit for the averaged dataset, but graphically, this value was found to be artificially elevated because of a strong leveraging point (Fig. 3.5). Removal of the largest event (17 July 2014), resulted in a similar model fit, but more agreeable runoff coefficient of 0.31 (Table 3.9).

The polynomial method was generally the best performing model among those tested (NSE: 0.86). It was not tested against individual irrigation treatment data because interpretation of model outputs would be meaningless. That is, small changes to the coefficients in a quadratic equation do not have any mechanistic definition.

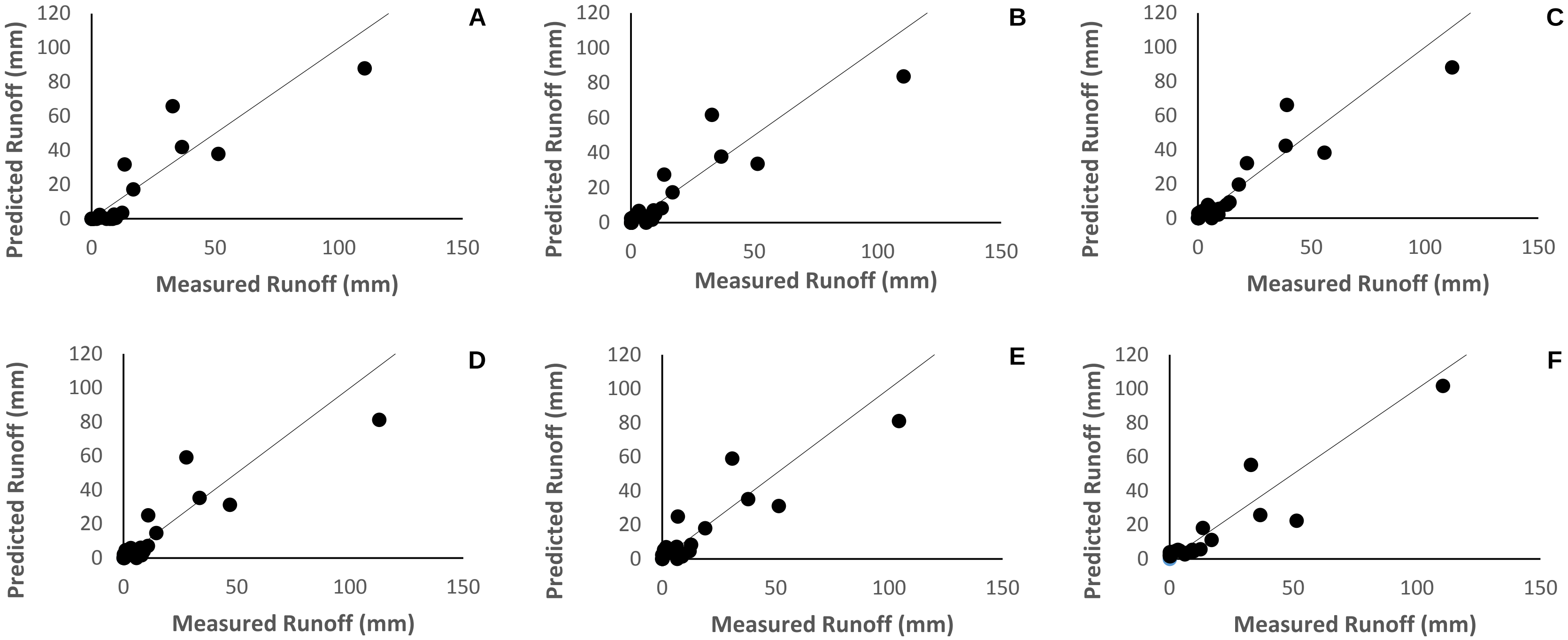

Fig. 3.3. Measured versus predicted runoff from 51 rainfall events (> 2.5 mm) using the Texas ET Network (TXETN) effective rainfall method and a polynomial model. A) TXETN base model, B) TXETN optimized for average across plots, C) TXETN optimized for average across *K100* plots, D) TXETN optimized for average across *K75* plots, E) TXETN optimized for average across *K50* plots, F) Polynomial function model. The solid line is the 1:1 reference line.

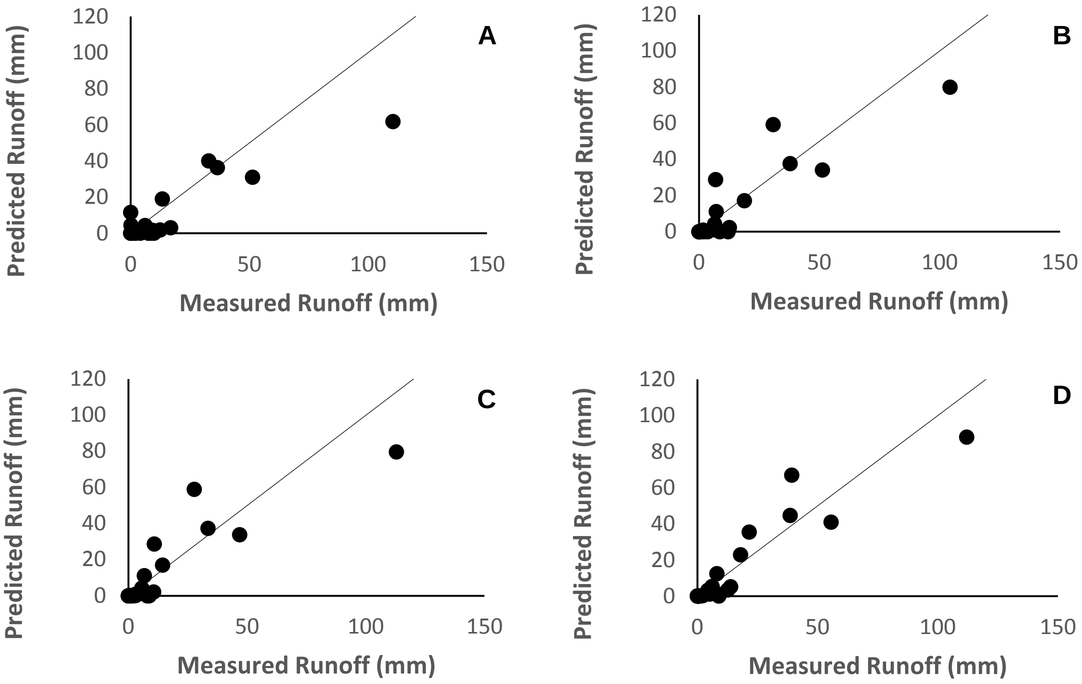

Fig. 3.4. Measured versus predicted runoff from 51 rainfall events (> 2.5 mm) using the SCS Curve Number method. A) Optimized for average across plots, B) Optimized for average across *K50* plots, C) Optimized for average across *K75* plots, D) Optimized for average across *K100* plots. The solid line is the 1:1 reference line.

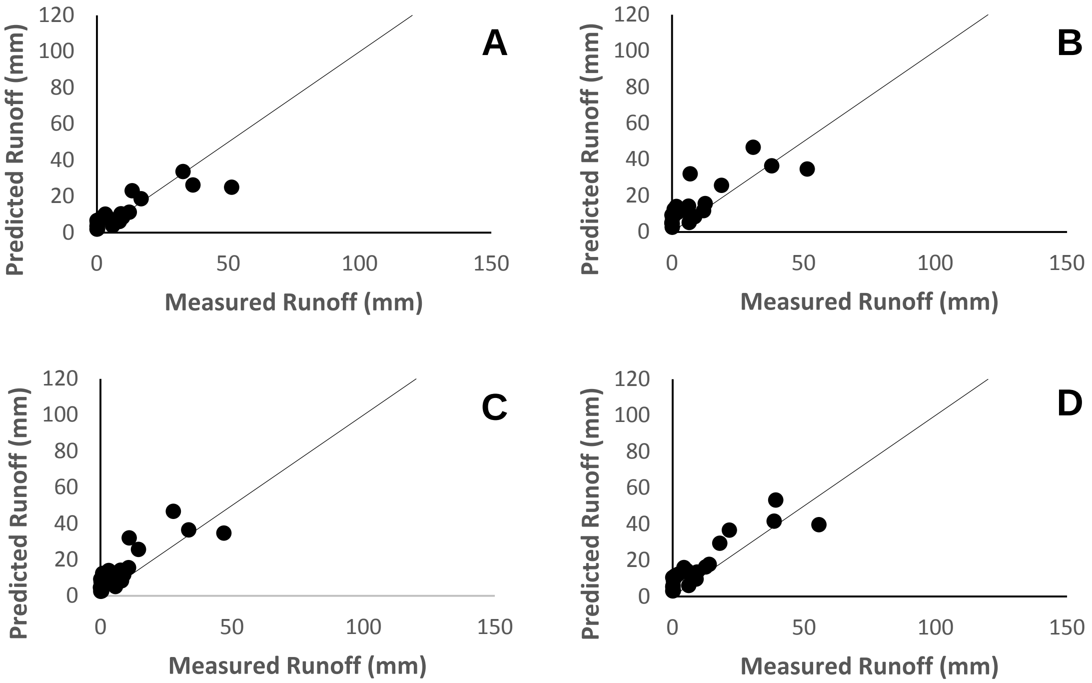

Fig. 3.5. Measured versus predicted runoff from 51 rainfall events (> 2.5 mm) using the Coefficient method. A) Optimized for average across plots, B) Optimized for average across *K50* plots, C) Optimized for average across *K75* plots, D) Optimized for average across *K100* plots. The solid line is the 1:1 reference line.

Discussion

The study site was a native sandy loam top soil and could be considered atypical of many residential soils that have been drastically disturbed and generally have higher clay content. However, due to the shallow clay B horizon, the soils have been classified in the hydrological group D and could be expected to behave hydrologically similar to a much heavier or compacted soil. The measured infiltration rates were uncharacteristically low for a sandy loam which can be attributed to the influence from a perched water table effect. Using small sprinkler runoff devices, Kelling and Peterson

(1975) measured lawn infiltration rates after 80 minutes of water application to be 0.1 to 8.8 cm hr^{-1}. Using double-ring infiltrometers, Hamilton and Waddington (1999) measured infiltration rates of 0.4 to 10 cm hr^{-1} on soils of diverse textures and bulk densities. Mueller and Thompson (2009), using large double-ring infiltrometers, measured infiltration rates of 0.1 to 9.7 cm hr^{-1} for loam soils of varying age in Wisconsin.

Initial abstraction can be considered the summation of depression storage, interception, and pre-ponding infiltration. The average IA measured throughout the year suggested that approximately 12.5 mm can be absorbed prior to measureable runoff occurring. This compares reasonably well to the predicted IA of 10.4 or 15.0 mm using the SCS-CN or TXETN methods, respectively. Surface depression storage was likely minimized through the design of the runoff plots and can be considered negligible (~ 1 mm). Although interception was not directly measured, prior research from Linde et al. (1995) suggested fairway height turf could intercept as much as 0.68 mm (3.4% of canopy height), but was dependent on grass type, primarily due to tiller density. Given the larger canopy height of a St. Augustinegrass lawn, it is reasonable to assume that interception would be much greater. Using a linear extrapolation from Linde et al. (1995), interception for the present study could reasonably be in excess of 2 mm. This is comparable to the winter minimum IA of 3 mm, which could serve as a reasonable estimate of interception plus depression storage. Others have suggested that IA of non-infiltrating lawns is 6.8 mm (Mueller and Thompson, 2009). Un-ponded infiltration can be assumed to occur through two process: infiltration through the thatch layer or infiltration into the soil. For many Texas soils, slow soil infiltration rates suggest water absorption by thatch might be more important in IA. Linde et al. (1995) reported that creeping bentgrass (*Agrostis stonlonifera* L.) thatch was able to capture up to 4.2 mm (47% of total thatch depth) of precipitation. Assuming a thatch thickness of 13 mm, one could expect the present study site to absorb 6 mm of water in thatch alone. The remainder of IA (2.5 mm) is likely to be direct infiltration into the soil.

Irrigation level demonstrated measureable differences in surface runoff, antecedent soil moisture, and ultimately, effective rainfall. When calculating effective rainfall for irrigation scheduling, the K_s should be considered, particularly when events exceed 25 mm of rainfall. Specifically, higher effective rainfall coefficients could be applied under deficit irrigation programs for further water savings. The increased water retention is akin to a positive feedback for conservation systems. Admittedly, the further reduction in water application (through use of higher K_{er}'s) could affect the viability of a given K_s to maintain acceptable turf quality. That is, it will hasten soil water depletion through the summer, thus adjustments to K_{er} should be made in conjunction with discussion of appropriate K_s values. Interestingly, the *K50* and *K75* RR's rarely differed throughout the irrigation season. A possible explanation for this similarity (despite measurably drier soil conditions under *K50*) is enhanced interception and hydraulic resistance associated with denser turf in *K75* plots. However, RR during fall rain events (when soil moisture was more similar) or during early summer (when turf density was more similar), did not clearly support this conclusion. Rather, a more likely explanation is that the poor infiltration properties of the soil reduced the importance of soil moisture conditions when both soils were comparatively dry. This is in agreement with Haith and Andre (2000), who adjusted soil moisture categories downward such that average conditions encompassed a larger range.

Weekly calculation of ET_c and effective rainfall are needed for accurate but timely dissemination of best irrigation management practices. The coefficient method is desirable for the obvious reason of simplicity, but in the present study the method was inadequate. The false assumption of a linear relationship between rainfall and runoff results in a model that is highly sensitive to large leveraging outliers. It would seem that effective rainfall requires a two-phase estimation process: estimation of IA followed by RR for rainfall occurring after ponding had occurred. The TXETN and SCS-CN methods both utilize such an approach, and consequently estimated effective rainfall reasonably well for conditions of the study. The TXETN method did not improve dramatically through parameter optimization, therefore the base values appear adequate for use in most conditions.

Appropriate curve numbers for turf have been suggested in a meta-analysis by Haith and Andre (2000). For soils classified as hydrologic group D, heavily thatched tall grass such as St. Augustinegrass received a CN of 70. Tall, dense grasses that lacked thatch received a CN of 78. These values are somewhat less than those optimized for the present study, but this could be related to differences in rainfall intensity which is often highest during the summer and fall in Texas. Furthermore, infiltration rates for the present study site were fairly low relative to other published values. In their study, Haith and Andre (2000) pre-selected a CN based on published values for meadows and range grasses. Rather than optimize the CN, they chose to optimize the antecedent moisture condition thresholds. The traditionally used value of 35 mm for use of CNI was reduced to 22 mm suggesting less moisture is required to reach average conditions and turf sites are less affected, relative to agricultural watersheds, by small differences in antecedent rainfall. In the present study, adjustments to antecedent moisture thresholds did not effectively improve NSE compared to optimizing the CN2 value. Further, the base threshold of 35 mm performed better than the recommended adjustment of 22 mm. King and Balogh (2008), used measured data from two golf courses to estimate turf CN's. There data were fit to a CN of 78 for a golf course in Minnesota having a hydrological soil D classification. The authors further concluded that 10% reductions from traditional CN's, as recommended by Haith and Andre (2000), may not be appropriate depending on local climate, soils, and slopes.

Not discussed in this chapter is the possible loss of excess rainfall through deep percolation. For regions having sandy soils, this is certainly a concern not addressed in this paper. In much of Texas and areas having similar soils, deep percolation is often negligible because of heavy soils and restrictive layers. However, compaction or poor soil preparation can often limit rooting depths thereby increasing the opportunity for water to escape below the effective rootzone. In the present study, effective rooting depth was defined as the depth containing 90% of total root length density and typically exceeded 30 cm (Brouwer and Heibloem, 1986). Further, soil water extraction could be seen as deep as 40 cm (data not presented). Anecdotally, effective rootzones in Texas lawns have been reported to be as low as 10 cm (Charles Swanson, Extension Program

Specialist with Texas A&M AgriLife Extension, personal communication). This discrepancy limits the conclusions that may be drawn from this paper, but further affirms the importance of deep rooting for sustainable irrigation of lawns.

The TXETN method assumes that the first 2.5 mm of rainfall is lost through evaporation of interception. The data for the present study seem to agree that approximately 2 to 3 mm of water can be retained on lawn grass leaves. The greater question is whether such a fate is truly ineffective when water evaporated from the leaf surface is done so in place of soil extracted moisture. Published standards for agricultural irrigation suggest interception should be considered ineffective, and further, effective rainfall calculation should not consider any potential increase in humidity that might reduce transpiration (Brouwer and Heibloem, 1986). Plant density, rooting depth, and crop height discrepancies between agriculture and turf might warrant separate treatment of effective precipitation. For example, the practice of ignoring small rain events (< 15 mm) for agricultural irrigation scheduling might be inappropriate for turf management due to the fairly short root systems that can benefit more from a shallow watering. Nevertheless, I do not consider subtraction of interception to be incorrect nor a requirement of calculating effective rainfall in turf.

Worth discussing are the limitations of scaling up small plot research to landscape scale processes. Perhaps the major difference between the two is the fraction of impervious cover. That is, a residential lot that has 30% impervious cover in the form of a roof would potentially be contributing 30% more rain water to the lawn. What then are the implications for effective rainfall (as determined from measured rainfall) and irrigation management? In some instances, perhaps effective rainfall could be greater than measured rainfall (e.g., small, flat yards without drain spouts), but in the large majority of cases the additional rainfall should be ignored. Irrigation is typically applied to meet the water needs of the driest point in the lawn. Further, the additional rainfall from a roof is not likely to move uniformly beyond the immediate footprint of the building. Consequently, the effective rainfall occurring on the driest part of the yard would remain unchanged by the presence of the impervious surface. The installation of drain spouts would further reduce the contribution of the roof runoff by focusing water through smaller areas or directly conveying the water onto impervious surfaces (Mueller and Thompson, 2009).

Conclusions

Effective rainfall defined as rainfall minus runoff varied with season and irrigation management. In general, St. Augustinegrass lawns can abstract 12.5 mm of water before rainfall becomes ineffective. Mid-summer, when soils were drier, IA was 14 mm. Effective rainfall during the irrigation season was on average 16% of measured rainfall, but varied with rainfall depth and irrigation management.

The commonly used K_{er} for estimating effective rainfall from measured rainfall was inadequate. A two-phase estimator such as the SCS-CN or similar algorithm such as the TXETN method was more accurate across a wider range of events. Further, parameter optimization could be implemented to better reflect deficit irrigation programs.

CHAPTER IV

NITRATE – N CONCENTRATIONS AND EXPORTS IN SURFACE RUNOFF FROM ST. AUGUSTINEGRASS TURF AS AFFECTED BY DEFICIT IRRIGATION AND FERTILITY

Introduction

Elevated nutrient concentrations (N and P) and associated algal blooms in surface waters have been linked to urbanization, often from overland flow due to the interconnectedness of urban systems and their proximity to surface waters, and loss of riparian zone health (Miller and Mattraw, Jr., 1982; Cadenasso et al., 2008; Kaushal et al., 2008). Although P is known to be most limiting in freshwater systems, recent discussion suggests both N and P should be controlled to reduce problems further downstream (Correll, 1998; Conley et al., 2009; Paerl, 2009). As visible components of the urban setting, turf-based landscapes have been targeted as potential sources of nutrients to surface waters (Hochmuth et al., 2012). Specifically, the use of fertilizers has been identified as a source of mineral N loading into surface waters (Cadenasso et al., 2008; Carey et al., 2012). However, the agronomic literature overwhelmingly suggests that the magnitude of turf culpability is exaggerated (Petrovic and Easton, 2005; Soldat and Petrovic, 2008; Raciti et al., 2011a).

Evaluation of soil cores from the Baltimore Long-term Ecological Research (LTER) center found that homeowner management practices were not good predictors of exchangeable soil nitrate; instead, land use history and housing density were more indicative of soil nitrate and organic carbon concentrations (Raciti et al., 2011a; Raciti et al., 2011b). Further studies from the Baltimore LTER indicated that residential lawns were effective sinks for N (Raciti et al., 2008); supporting prior research suggesting that increasing soil N concentrations is a function of site age (Qian et al., 2003). Engelsjord et al. (2004) found turfgrass thatch to be an important sink for applied N with the majority being stored in the organic form. Miltner et al. (1996) reported that 31% of applied urea was found in thatch 18 days after treatment. They further found that approximately 35% of the applied urea- N was removed with clipping yield over the course of two years and that less than 1% of applied urea-N was found in leachate.

In general, nutrient export as runoff from turf has been more strongly predicted by runoff volume rather than concentration (Kaushal et al., 2008; Bell and Koh, 2009; Rice and Horgan, 2011). Runoff volume (and thus nutrient export) from turf can be affected by a number of management factors. Turfgrass species and growth habit affects interception and hydraulic resistance of flow (Linde et al., 1998). In small plot research in Pennsylvania, sod-producing turfgrasses such as creeping bentgrass (*Agrostis palustris* Huds.) demonstrated lower runoff volumes than the bunch-type species perennial ryegrass (*Lolium perenne* L.) (Linde et al., 1998). Similarly, a number of studies from across the northern and eastern U.S. have shown that turf density is negatively correlated with runoff volume and nutrient export (Gross et al., 1991; Linde et al., 1995; Easton and Petrovic, 2004; Easton et al., 2005; Bierman et al., 2010). Because of this relationship between runoff volume and nutrient export, a primary goal of lawn managers should be to mitigate surface runoff volumes from their landscapes (Chapter 3). Turf management practices such as irrigation and fertilizer application increase plant density and overall biomass production. These in turn contribute to greater surface area for the interception of irrigation or rain water and hydraulic roughness for slowing overland flow. Conversely, frequent irrigation likely contributes to greater antecedent surface soil moisture and therefore greater runoff volumes (Shuman, 2002).

The competing influences of deficit irrigation practices, which result in drier soil conditions but reduce plant density, might not only affect runoff volumes, but desiccated plant tissue might change the chemistry of runoff as well. In arid and semi-arid regions of the country, irrigation can be the management practice having the largest individual impact on turf performance, turf system hydrology, and the urban ecosystem at large. The hydrological dynamics of irrigation management and the resultant changing turf canopy are poorly described for warm-season lawns thus, a two-year field study was conducted to investigate the effects of deficit irrigation and N fertilizer rate on NO_3-N exports in surface runoff from simulated lawns.

Materials and Methods

Site Description and Experimental Design

Research was conducted from May 2013 to Apr 2015 at the Texas A&M Turfgrass Field Laboratory on F&B Rd in College Station, TX (N 30.618178, W -96.366250). The native soil was a Boonville series sandy loam (Fine, smectitic, thermic

Chromic Vertic Albaqualfs). A surface runoff small plot research site was built to an average slope of 0.037 m m^{-1}, planted with St. Augustinegrass (*Stenotaphrum secundatum* (Walt.) Kuntze 'Raleigh'), and equipped with flow monitoring and sampling capabilities. For a more detailed description of the site, see Wherley et al. (2014).

Turf was maintained similarly to a medium-intensity managed residential lawn. Mowing was performed weekly using a standard push rotary mower with mulching blades set to a 6.3 cm height of cut and clippings returned. Pesticide applications were made preventatively and curatively based on knowledge of site history (Table 3.2). Each winter, gypsum was applied at a rate of 2.24 Mg ha^{-1} to reduce the impact of sodic irrigation water (Pannkuk et al., 2011) on soil nutrient losses (Steele and Aitkenhead-Peterson, 2012) and runoff to surface waters (Steele and Aitkenhead-Peterson, 2013).

The experiment consisted of eight treatments having three replicates arranged as a randomized complete block design (Table 3.3). Irrigation was applied on Tuesdays and Fridays to mimic a two-day per week calendar-based irrigation schedule as is common in several Texas cities. Irrigation run times were adjusted to apply amounts equal to the cumulative ET deficit (ET_{Def}) since the prior irrigation event. Cumulative ET deficit was calculated using Eq. 3.1.

Treatments were defined in terms of K_s as 0.50, 0.75, and 1.00 (referred to as *K50*, *K75, K100* for remainder of this chapter), which were selected to create severe, medium, and limited moisture stress conditions, respectively. Effective rainfall was assumed to be measured rainfall for small rain events (< 25 mm). For larger events, when data were available, R_{eff} was calculated from the mean runoff volume as measured on site. If measured runoff data were unavailable, R_{eff} was calculated using a method promoted by the Texas ET Network (Table 3.1). Irrigation run times were adjusted for uniformity (DU_{LH}) as suggested by the Irrigation Association (https://www.irrigation.org/).

Results of an irrigation audit indicated a precipitation rate of 39 mm hr^{-1} and a DU_{LH} of 0.84. The irrigation season was defined loosely as the period from May 1 to Oct 31 for each year of the study. Site hydrology and nutrient export was continually monitored during winter dormancy periods.

Fertilizer was applied at a single rate for each treatment, but varied in terms of the number of applications per year (0x, 2x, and 4x). Each application used Southern Turf Builder (32-0-10, N-P_2O_5-K_2O; Scotts Miracle-Gro, Marysville, OH) at a rate of 44 kg N ha^{-1} resulting in annual N rates of 0, 88, and 176 kg N ha^{-1} for 0x, 2x, and 4x treatments, respectively. The first application was made in May of each year, and subsequent applications were made on 6 or 12 week intervals depending on treatment (Table 4.1). Applications were made on the day before an irrigation event in addition to being watered in immediately with 2.5 mm of irrigation.

Table 4.1. Fertilizer application calendar for each level of the fertility factor.

-----------0x†-----------		-----------2x-----------		-----------4x-----------	
2013	**2014**	**2013**	**2014**	**2013**	**2014**
		May 6	May 15	May 6	May 15
		July 29	Aug 7	June 17	June 26
				July 29	Aug 7
				Sept 9	Sept 16

† Fertility levels were 0x, 2x, or 4x applications yr^{-1} of 39 kg N ha^{-1} of a partially slow-release, high N fertilizer.

Turf Performance Metrics

Turf quality was visually assessed using National Turfgrass Evaluation Program (NTEP) methods on a biweekly interval (Morris and Shearman, 1998). Ratings were given on a scale of 1 (worst) to 9 (best) with an 'acceptable turf' minimum of 6. Quality was evaluated based on subjective interpretations of turf color, uniformity, and density. Visual scores were independently given to 'upslope' and 'downslope' positions to overcome plot size and heterogeneity. The same individual evaluated turf quality for each rating date over the two year period.

Rainfall – Runoff Measurements

Rainfall was measured using a tipping rain gauge (Isco 674, Teledyne Isco, Lincoln, NE) at a two minute temporal resolution. Runoff discharge was conveyed through a calibrated H-flume and measured with bubbler-type meters (model 4230, Teledyne Isco, Inc., Lincoln, NE) at a two minute resolution. Samples were collected by auto-samplers (model 6712, Teledyne Isco, Inc.) using a flow-based pacing of 38 L. For each event, approximately five samples were selected for chemical analysis. Prior tests showed that concentrations of analytes did not differ significantly throughout the runoff event with the exception of the first and last sample. Therefore, samples were selected to represent the entire hydrograph, and the mean concentration was used as an input for later data analysis.

Over the two year period, samples were collected from 31 rainfall events and one irrigation excess event. The forced irrigation runoff event was implemented during a period of drought so that an additional data point could be gathered for the summer season. Briefly, the forced irrigation runoff event used the in-ground sprinkler system to apply water at approximately 40 mm hr^{-1} for 45 minutes. Runoff volume (and therefore exports) could not be measured for two of the 32 events due to freezing weather. The two missing dates occurred in November of each year and were not included in export analysis.

Chemical Analyses of Water

Electrical conductivity (EC) and pH were measured on unfiltered fresh aliquots of runoff, and a portion of the unfiltered sample reserved for later analysis of total suspended solids (TSS). The remainder of a sample was vacuum-filtered through ashed (400° C for 5 h) Whatman GF/F filters (0.7 µm nominal pore size). Total dissolved nitrogen (TDN) was measured using high temperature Pt-catalyzed combustion with a Shimadzu TOC-V_{CSH} and Shimadzu total measuring unit TNM-1 (Shimadzu Corp. Houston, TX, USA). Ammonium-N was quantified using the phenate hypochlorite method with sodium nitroprusside enhancement (USEPA method 350.1), and nitrate-N was analyzed using Cd–Cu reduction (USEPA method 353.3). Nitrate-N was analyzed within 24 hours of collection. Minimum detection levels were achieved as per the respective EPA methods. All colorimetric methods were performed with a Westco Scientific Smartchem Discrete Analyzer (Westco Scientific Instruments Inc. Brookfield, CT, USA). Instrument detection limits for each constituent analyzed were 0.05 mg L^{-1}

TDN, 0.005 mg L^{-1} NH_4-N, 0.002 mg L^{-1} NO_3-N. NIST traceable standards and blanks were run after every 10th sample to monitor instrument precision.

Total suspended solids (TSS) were measured gravimetrically by vacuum-filtering 100 mL of runoff event bulked samples through a 934-AH Whatman glass-fiber filters (USEPA method 160.2). Nutrient losses via leaching were not measured, nor were gaseous losses through volatilization or denitrification.

Chemical Analyses of Soil and Vegetation

A basic soil test for plant available nutrient concentrations was performed twice annually in the spring and fall (Table 4.2). Soil samples were collected from the top 10 cm of the soil profile using a 20 mm diameter soil probe on a 1.5 m grid pattern for each plot. Soils collected were composited for a single chemical analysis per plot. Plant tissue samples were collected as bagged clippings from a single pass of a mower over each plot. Clippings were oven-dried at 60° C for 48 hr prior to analysis for total N content (vario Max cube, Elementar Americas Inc., Mt. Laurel, NJ).

All plant and soil nutrient analyses were performed by the Texas A&M AgriLife Extension Service Soil, Water and Forage Testing Laboratory. Soil and plant nutrient concentrations were expressed on a dry weight basis. Soil pH and electrical conductivity were measured in 1:2 soil:deionized water extracts (Schofield and Taylor, 1955; Rhoades, 1982). Nitrate-nitrogen was extracted from soil using a 1 M KCl solution, reduced to nitrite and measured spectrophotometrically using a flow injection analyzer (FIALab Instruments, Inc., Bellevue, WA) (Kachurina et al., 2000). Phosphorus, K, Ca,

Table 4.2. Average background nutrient concentrations measured in soil samples from the 0 to 10 cm depth. Samples were collected April 2013 prior to treatments.

	pH[†]	**EC**[‡]	**NO_3-N**[§]	**P**[¶]	**K**	**Ca**	**Mg**	**S**	**Na**	**Organic C**	**Total N**
		dS m^{-1}	--mg kg^{-1}--							g g^{-1}	mg kg^{-1}
Mean	6.3	237	0.4	182	200	1130	110	40	265	0.018	2601
SD[#]	0.2	74	0.3	34	27	157	27	15	50	0.030	350

[†] Soil pH was measured in a 1:2 soil:deionized water extract (Schofield and Taylor, 1955).

[‡] Soil electrical conductivity (EC) was measured in a 1:2 soil:deionized water extract (Rhoades, 1982).

[§] Nitrate-nitrogen was extracted from soil using a 1 M KCl solution, reduced to nitrite and measured spectrophotometrically (Kachurina et al., 2000).

[¶] P, K, Ca, Mg, Na, and S were extracted using the Mehlich III extraction solution (Mehlich, 1984).

[#] Standard deviation

Mg, Na, and S were extracted using the Mehlich III extraction solution (Mehlich, 1984), followed by analysis using an inductively coupled plasma – optical emission instrument (Spectroblue, Spectro Analytical Instruments, Kleve, Germany). Soil total N was measured using similar methods as plant tissue.

Statistical Analyses

Treatment effects on turf quality, total runoff, and nutrient concentration in runoff were analyzed using a linear mixed model repeated measures analysis (SPSS 22, IBM Corp., Armonk, NY). Block, date, and treatment were considered fixed effects. When it improved the model fit, analyses used ‘irrigation’ or ‘fertility’ as factors rather than eight levels of ‘treatment’ combinations. In some cases, baseline runoff measurements were used as covariates in the analysis. Missing data were evaluated using a simplified mixed model, typically without the date by treatment interaction term. These data were merged with the original dataset and re-analyzed using the full model. Nutrient export was calculated as the product of the flow-weighted concentration and runoff volume per unit area. Export data were summed over the experimental period and analyzed using a general linear model or summed within season and subjected to linear mixed model repeated measures analysis. Runoff volume and nitrate-N concentration were analyzed as a single continuous experiment, while turf quality score data were analyzed within each year. Treatment means were separated using Fisher’s protected least significant difference (LSD) at a significance level of $p \leq 0.05$. Linear regression was used to identify relationships between nutrient concentration in runoff and plant tissue N content.

Results

Turf Quality

Turf quality was affected by the date by irrigation interaction in year 1 and date by irrigation and date by fertility interactions in year 2 (Table 4.3). From mid-July to early-September of year 1, turf quality declined with diminishing irrigation applied (Table 4.4). In year 2, the irrigation effects were less evident due to greater rainfall than in the previous year. Consequently, deficit irrigation did not begin to reduce turf quality until mid-August. Further, turf quality under severe deficit irrigation (*K50*) was statistically similar to *K75* on each date and remained greater than 6 (minimally acceptable) on all but three dates.

Table 4.3. Fixed effects model for visual turf quality scores. Assessments were made during the growing season (May to Nov). Data were analyzed across 11 and 12 assessment dates in 2013 and 2014, respectively.

	2013	2014
Source	----------***p*-value**----------	
Block	ns	.035
Fertility (F) [†]	ns	.000
Irrigation (I) [‡]	.000	ns
F x I	ns	ns
Date (D)	.000	.000
D x F	ns	.038
D x I	.000	.000
D x F x I	ns	.048
Slope[§]	.000	.039

[†] Fertility levels were 0x, 2x, or 4x applications yr^{-1} of 39 kg N ha^{-1} of a partially slow-release, high N fertilizer.

[‡] Irrigation levels were defined in terms of stress coefficient (K_s) adjustments to ET_c: K_s = 0.50, 0.75, and 1.00.

[§] Slope (Hillslope position) was used as a covariate.

Table 4.4. Date by fertility and date by irrigation interaction effects on turf quality scores.

Date	Fertility (F)[†]			Irrigation (I)[‡]			*p*-value		
	0x	**2x**	**4x**	***K50***	***K75***	***K100***	**F**	**I**	**F*I**
	------------------------Quality[§]------------------------								
21-May-13	6.9[¶]	7.0	7.2	7.2	7.0	7.0	ns	ns	ns
17-Jun-13	7.6	7.5	7.5	7.0	7.5	7.9	ns	ns	ns
2-Jul-13	6.8	6.1	6.6	6.3	6.4	6.7	ns	ns	ns
9-Jul-13	6.9	6.3	6.5	5.4c	6.3b	7.5a	ns	.000	ns
23-Jul-13	7.0	6.1	6.4	5.4c	6.3b	7.2a	ns	.000	ns
30-Jul-13	7.5	6.7	6.9	5.9c	7.0b	7.7a	ns	.000	ns
13-Aug-13	7.6	6.1	6.3	4.1c	6.7b	8.0a	ns	.000	ns
23-Aug-13	6.4	5.1	5.2	3.4c	5.6b	6.7a	ns	.000	ns
11-Sep-13	7.7	6.8	6.8	5.6c	7.0b	8.0a	ns	.000	ns
28-Sep-13	7.1	6.4	6.6	5.4b	6.7a	7.4a	ns	.000	ns
8-Oct-13	7.3	7.0	7.2	6.6	7.3	7.3	ns	ns	ns
11-Jun-14	5.7b	6.3b	7.6a	7.1	6.7	6.3	.004	ns	.015
17-Jun-14	5.8b	6.2b	7.1a	6.7	6.4	6.2	.001	ns	.000
1-Jul-14	5.7b	6.2b	8.2a	7.6	6.7	6.4	.000	ns	.000
17-Jul-14	5.6c	6.3b	7.0a	6.7	6.2	6.4	.000	ns	ns
29-Jul-14	5.7	5.8	6.6	5.8	5.8	6.4	ns	ns	ns
14-Aug-14	5.7b	6.0b	6.9a	6.1	6.2	6.6	.011	ns	ns
26-Aug-14	6.1a	6.7a	6.9a	5.8b	6.3b	7.4a	.050	.003	ns
10-Sep-14	6.3	6.3	6.9	5.4b	6.6ab	7.3a	ns	.005	ns
23-Sep-14	6.7b	6.7b	7.7a	6.5b	7.1ab	7.4a	.002	.008	ns
7-Oct-14	5.5b	6.3b	7.5a	6.9	6.3	6.6	.003	ns	ns
21-Oct-14	7.2b	7.6a	7.9a	7.3b	7.4b	8.0a	.001	.001	ns
7-Nov-14	6.2	6.8	7.2	6.7	6.5	7.2	ns	ns	ns

[†] Fertility levels were 0x, 2x, or 4x applications yr^{-1} of 39 kg N ha^{-1} of a partially slow-release, high N fertilizer.

[‡] Irrigation levels were defined in terms of stress coefficient (K_s) adjustments to ET_c: K_s = 0.50, 0.75, and 1.00.

[§] Turf quality scores were visually assessed using NTEP standard methods: 1 = worst, 9 = best, 6 = acceptable (Morris and Shearman, 1998).

[¶] Means having similar letters within a row and factor are not significantly different (LSD .05).

In year 1, fertility effects on turf quality were not evident, but the following year, fertility demonstrated a significant effect on turf quality on 8 of 12 assessment dates (Table 4.4). The 4x level enhanced turf quality relative to the 0x level on each of the significant dates. Interestingly, the 2x level resulted in superior turf quality relative to the control on only two of the 12 rating dates. Despite not having received N fertilizer for two years, turf quality of the 0x level had an acceptable rating ($\geq$ 6) often, although turf quality declined from year 1 to year 2.

During June of year 2, a significant fertility by irrigation interaction effect was observed for turf quality. The interaction was evaluated graphically and determined not to influence main effect inferences (Fig. 4.1). Rather, the effect was the result of winter damage associated with large patch disease (*Rhizoctonia solani*).

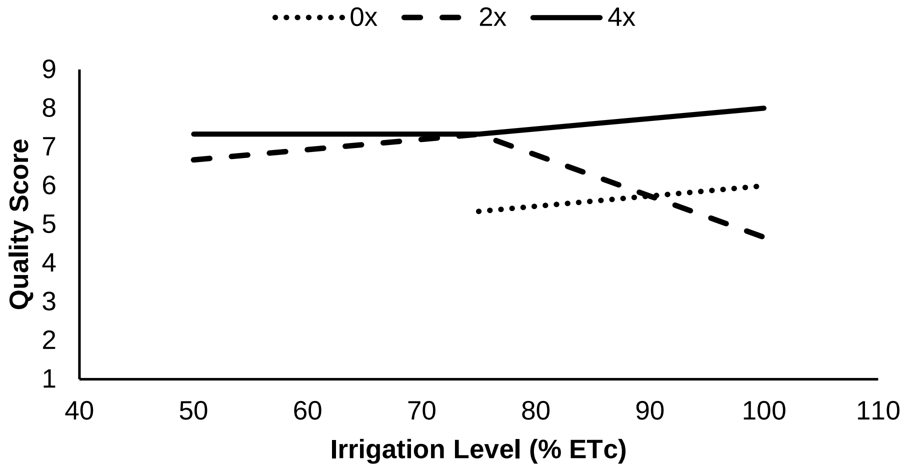

Fig. 4.1. Date by irrigation by fertility interaction effect on turf quality scores in year 2. Scores were visually assessed using a the following scale: 1 = worst, 9 = best, 6 = acceptable. The effect was the result of winter damage associated with large patch disease (*Rhizoctonia solani*). Data presented were from a rating on 11 June 2014.

Table 4.5. Fixed effects model for [NO_3-N] analysis. Data were collected from 32 rainfall / runoff events over a two year period.

Source	*p*-value
Block	.459
Fertility (F)[†]	.000
Irrigation (I)[‡]	.044
F*I	.018
Date (D)	.000
D*F	.000
D*I	.901
D*F*I	.273
Baseline TDN[§]	.001

[†] Fertility levels were 0x, 2x, or 4x applications yr^{-1} of 39 kg N ha^{-1} of a partially slow-release, high N fertilizer.

[‡] Irrigation levels were defined in terms of stress coefficient (K_s) adjustments to ET_c: K_s = 0.50, 0.75, and 1.00.

[§] Measured total dissolved nitrogen (TDN) from an event in April 2013 was used as a covariate.

Table 4.6. Fertility and irrigation main effects and interaction effects on [NO_3-N]. Data were collected from 32 rainfall / runoff events over a two year period.

Fertility[†]	Irrigation[‡]	NO_3-N
		mg L^{-1}
0x		1.3c[§]
2x		2.5b
4x		3.2a
	K50	3.2a
	K75	2.4b
	K100	2.0b
0x	*K50*	
	K75	1.1c
	K100	1.4c
2x	*K50*	2.6b
	K75	2.5b
	K100	2.3b
4x	*K50*	3.7a
	K75	3.5a
	K100	2.2b

[†] Fertility levels were 0x, 2x, or 4x applications yr^{-1} of 39 kg N ha^{-1} of a partially slow-release, high N fertilizer.

[‡] Irrigation levels were defined in terms of stress coefficient (K_s) adjustments to ET_c: K_s = 0.50, 0.75, and 1.00.

[§] Means having similar letters within a row are not significantly different (LSD .05).

Nitrate-N Concentrations

Nitrate-N concentration was measured in surface runoff from 31 rainfall events and 1 irrigation event over a two year period. Nitrate-N concentration was affected by fertility, irrigation, and date main effects and fertility by date and fertility by irrigation interactions (Table 4.5). In general, [NO_3-N] increased with increasing fertility, but this trend varied with rain event (Table 4.6). Irrigation main effects indicated [NO_3-N] increased with decreasing supplemental water. However, the significant fertility by irrigation interaction revealed that the irrigation effect was evident in fertilized plots. Specifically, deficit irrigation (*K50* and *K75*) resulted in higher [NO_3-N] than the *K100* treatment, but only at the 4x fertility level. When analyzed across all treatments, [NO_3-N] demonstrated seasonal patterns in year 1, but remained fairly constant throughout year 2 (Fig. 4.2). For example, during the growing season (approximately April through Oct), mean [NO_3-N] was typically below 3 mg L^{-1} in year 1 and did not exceed 2 mg L^{-1} after May of year 2.

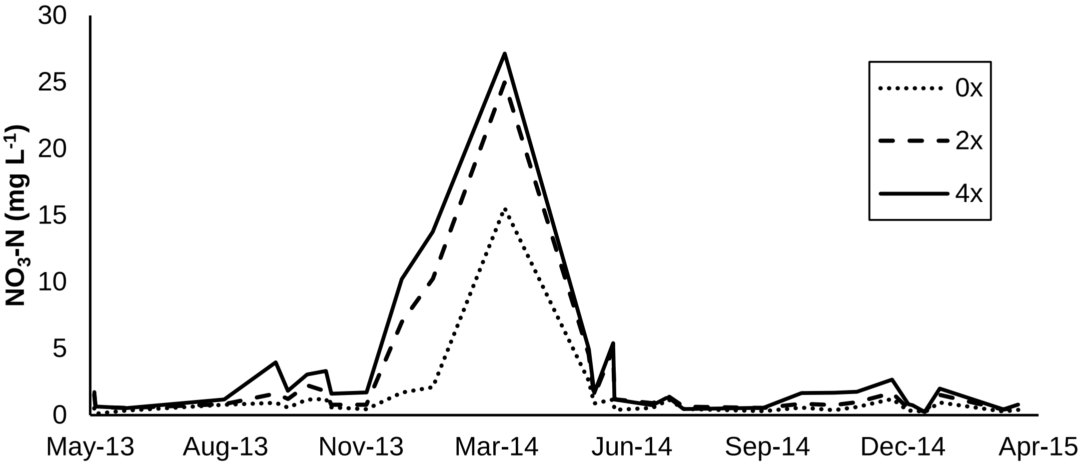

Fig. 4.2. Nitrate-N concentration as affected by fertility. Data were collected from 32 runoff events over a two year period. Fertility levels were 0x, 2x, or 4x applications yr^{-1} of 39 kg N ha^{-1} of a partially slow-release, high N fertilizer.

During winter of year 1, [NO_3-N] progressively increased from Nov to Mar, peaking at a mean value of 23.4 mg L^{-1} just prior to spring green-up. Due to the significant fertility by date interaction, data were further analyzed by date. Of the 32 measured events, the 4x level resulted in a greater [NO_3-N] in 21 and 14 events compared to 0x and 2x levels, respectively (Table 4.7). The 2x treatment resulted in greater [NO_3-N] than 0x treatments in 7 of 32 events. Of the 11 events that did not demonstrate a significant fertility effect, 8 occurred between May and September. On five dates in 2014, [NO_3-N] was affected by a fertility by irrigation interaction. Means comparison testing indicated the interaction did not alter the inferences drawn from the fertility main effect, but showed irrigation effects were evident only under the 4x fertility level.

Plant tissue total N content was plotted against the experiment-wide mean [NO_3-N] (Fig. 4.3). Data showed that plant tissue N (averaged across 7 samplings over two years) accounted for 77% of the variance in [NO_3-N].

Table 4.7. Date by fertility interaction effects on [NO$_3$-N].

	-------------- [NO$_3$-N] --------------			-------*p*-value-------	
Date	**0x[†]**	**2x**	**4x**	**F[‡]**	**F x I[§]**
		-------mg L^{-1}-------			
9-May-13	0.51b[¶]	1.57a	1.73a	*	ns
10-May-13	0.12b	0.62a	0.66a	*	ns
2-Jun-13	0.35	0.54	0.54	ns	ns
13-Aug-13	0.80	0.83	1.18	ns	ns
20-Sep-13	0.94b	1.62b	3.98a	***	ns
29-Sep-13	0.56b	1.21b	1.84a	**	ns
13-Oct-13	1.18c	2.25b	3.05a	**	ns
27-Oct-13	1.22b	1.79b	3.31a	***	ns
31-Oct-13	0.60b	0.79b	1.61a	***	ns
26-Nov-13	0.45b	0.80b	1.72a	***	ns
22-Dec-13	1.69b	7.00ab	10.21a	**	ns
14-Jan-14	2.10b	10.25a	13.76a	**	ns
8-Mar-14	15.56	24.98	27.15	ns	ns
9-May-14	2.58	4.55	4.95	ns	ns
13-May-14	0.87b	1.45a	1.67a	*	ns
27-May-14	1.18b	4.94a	5.41a	***	ns
28-May-14	0.39b	1.20a	1.19a	***	ns
25-Jun-14	0.55	0.91	0.74	ns	ns
5-Jul-14	1.05	1.23	1.29	ns	*
7-Jul-14	1.16	1.41	1.33	ns	*
18-Jul-14	0.46	0.65	0.47	ns	ns
15-Sep-14	0.31	0.55	0.55	ns	ns
13-Oct-14	0.57b	0.87b	1.68a	*	ns
6-Nov-14	0.39b	0.76b	1.69a	*	ns
23-Nov-14	0.62b	0.97b	1.75a	*	ns
19-Dec-14	1.23	1.67	2.68	ns	ns
31-Dec-14	0.30b	0.47b	0.83a	***	*
3-Jan-15	0.37b	0.57b	0.76a	**	*
12-Jan-15	0.22	0.26	0.25	ns	ns
23-Jan-15	0.95b	1.53b	2.01a	**	ns
11-Mar-15	0.28c	0.43b	0.45a	**	*
22-Mar-15	0.41b	0.60b	0.80a	*	ns

[†] Fertility levels were 0x, 2x, or 4x applications yr^{-1} of 39 kg N ha^{-1} of a partially slow-release, high N fertilizer.

[‡] Fertility

[§] Fertility*Irrigation interaction

[¶] Means having similar letters within a row are not significantly different (LSD .05).

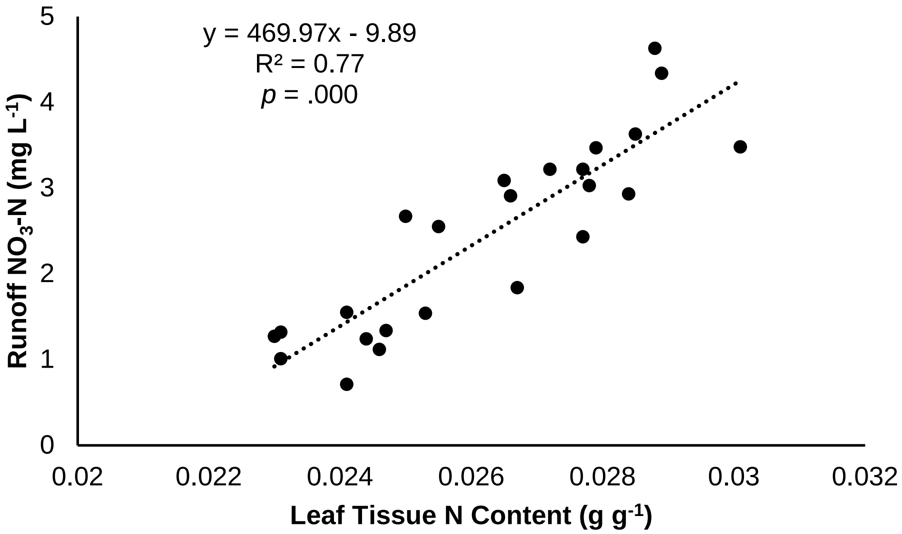

Fig. 4.3. Significant linear relationship between leaf tissue N content and surface runoff [NO_3-N]. Data were averaged across seven tissue sampling dates and 32 rainfall / runoff events.

Table 4.8. ANOVA table for cumulative NO_3-N exports. Data were summed across 30 runoff events over a two-year period.

Source	SS	df	MS	F	Sig.
Block	69.49	2	34.75	7.42	.007
Fertility (F) †	62.54	2	31.27	6.68	.010
Irrigation (I) ‡	4.54	2	2.27	.48	.627
F x I	38.62	3	12.87	2.75	.085
Error	60.89	13	4.68		
Total	1447.52	24			

† Fertility levels were 0x, 2x, or 4x applications yr^{-1} of 39 kg N ha^{-1} of a partially slow-release, high N fertilizer.

‡ Irrigation levels were defined in terms of stress coefficient (K_s) adjustments to ET_c: K_s = 0.50, 0.75, and 1.00.

Nitrate-N Exports

Cumulative NO_3-N exports demonstrated significant fertility main effects (Table 4.8). Mean treatment export ranged from 2.92 to 9.82 kg ha^{-1} over the course of two years (Table 4.9).

Table 4.9. Season by treatment effects on cumulative NO_3-N exports. Data were summed across dates within each season over a two-year period.

	Fertility (F) [†]	**--------0x--------**		**------------2x------------**			**------------4x------------**				**------------*p*-value------------**		
	Irrigation (I) [‡]	***K75***	***K100***	***K50***	***K75***	***K100***	***K50***	***K75***	***K100***	**Mean**	**F**	**I**	**F*I**
Year	Season[§]	--kg ha^{-1}--											
2013	Spring	0.18	0.30	0.57	0.38	1.37	0.86	0.82	0.74	0.65	***	ns	ns
	Summer	0.06	0.34	0.18	0.17	0.45	0.25	0.32	0.67	0.31	***	***	ns
	Fall	0.23	0.73	0.65	0.70	1.57	0.91	1.21	1.18	0.90	***	**	ns
	Winter	0.70	1.78	2.18	1.96	2.38	2.97	3.14	1.33	2.05	ns	ns	ns
2014	Spring	0.66	0.71	1.60	0.86	2.07	2.42	1.43	1.35	1.39	***	*	*
	Summer	0.49	0.58	0.87	0.83	0.60	0.91	0.66	0.56	0.69	ns	ns	ns
	Fall	0.01	0.01	0.01	0.00	0.01	0.03	0.01	0.03	0.01	*	ns	ns
	Winter	0.60	0.93	0.89	0.84	0.98	1.47	1.82	0.91	1.05	*	ns	ns
Total		2.92	5.37	6.95	5.75	9.42	9.81	9.41	6.76	7.05	ns	ns	ns

[†] Fertility levels were 0x, 2x, or 4x applications yr^{-1} of 39 kg N ha^{-1} of a partially slow-release, high N fertilizer.

[‡] Irrigation levels were defined in terms of stress coefficient (K_s) adjustments to ET_c: K_s = 0.50, 0.75, and 1.00.

[§] Seasons were arbitrarily defined as follows: Spring = Apr – May, Summer = Jun – Sep, Fall = Oct – Nov, Winter = Dec – Mar.

Table 4.10. Fixed effects model for cumulative NO_3-N exports analyzed with seasonal effects.

Source	**Sig.**
Block	.000
Fertility (F) [†]	.000
Irrigation (I) [‡]	.028
F x I	.102
Season (S) [§]	.000
S x F	.016
S x I	.007
S x F x I	.303

[†] Fertility levels were 0x, 2x, or 4x applications yr^{-1} of 39 kg N ha^{-1} of a partially slow-release, high N fertilizer.

[‡] Irrigation levels were defined in terms of stress coefficient (K_s) adjustments to ET_c: K_s = 0.50, 0.75, and 1.00.

[§] Seasons were arbitrarily defined as follows: Spring = Apr – May, Summer = Jun – Sep, Fall = Oct – Nov, Winter = Dec – Mar.

Analysis using seasonal summations demonstrated significant irrigation by date and fertility by date interaction effects (Table 4.10). Further analysis within season revealed strong fertility main effects during spring through fall of year 1 and spring of year 2 (Table 4.9). In general, these effects were due to higher exports under 4x levels, presumably due to elevated [NO_3-N]. During spring of year 2, a significant fertility by irrigation interaction indicated that fertility main effects were exacerbated by deficit irrigation practices. Irrigation main effects were only documented in summer and fall of year 1 and spring of year 2. In year 1, each deficit irrigation level reduced exports compared to *K100*. In spring of year 2, the *K50* treatment demonstrated higher exports, but this only occurred at the 4x fertility level. Interestingly, irrigation did not affect summer exports in year 2, presumably due to the reduced irrigation water requirements under a cooler, wetter summer (Fig. 4.4 & 4.5).

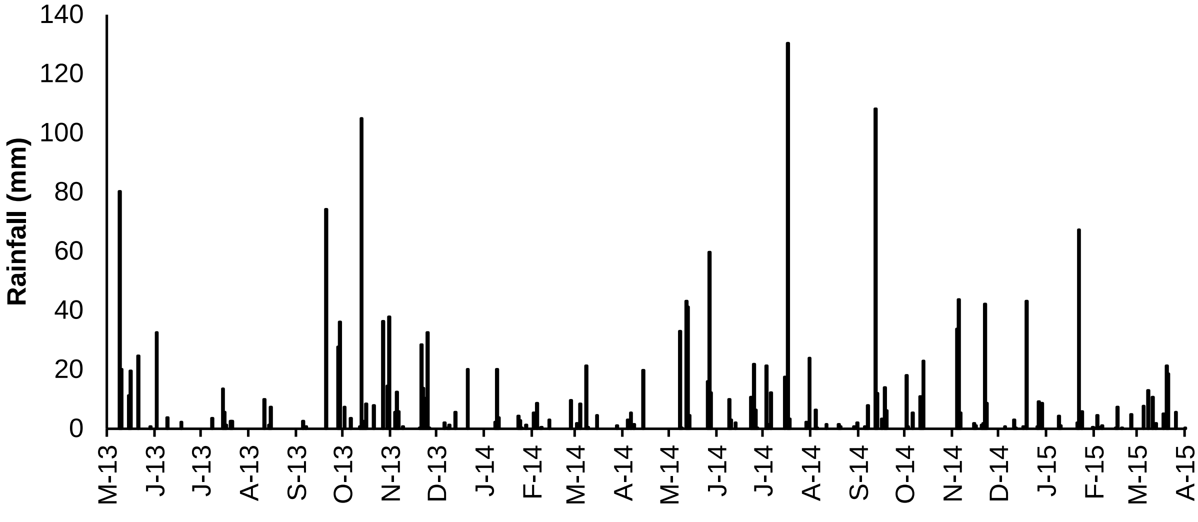

Fig. 4.4. Rainfall during the study period as measured at nearby weather station (Texas ET Network).

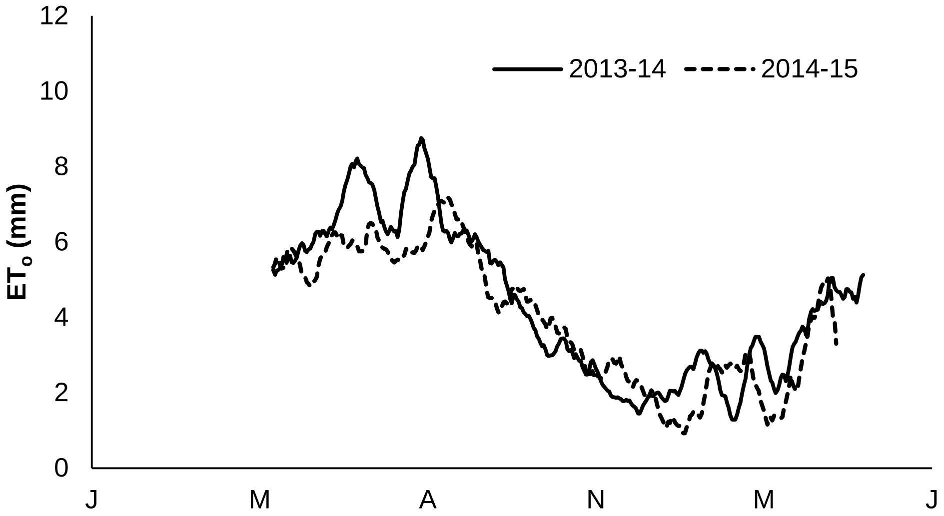

Fig. 4.5. Reference ET (FAO-56 Penman Monteith) for the study period as measured at nearby weather station (Texas ET Network).

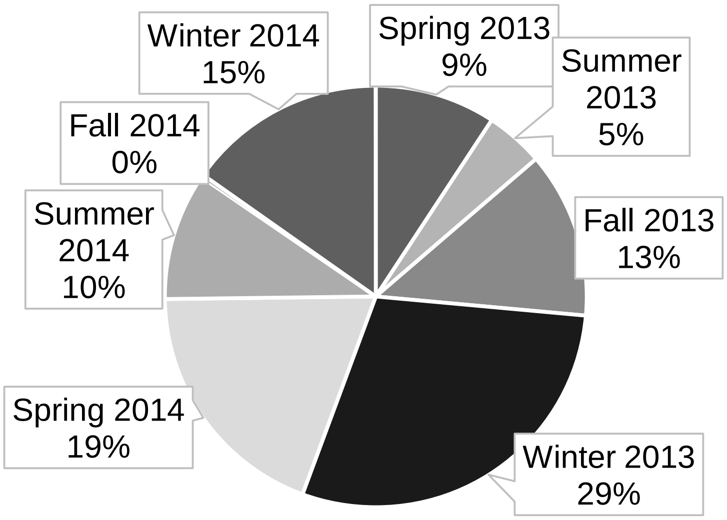

Fig. 4.6. Seasonal effect on NO_3-N exports in surface runoff from 30 events over a two year period. Data were pooled across irrigation and fertility treatments. Freezing rain prevented accurate runoff measurement for a single significant event in November of each year. Seasons were arbitrarily defined as follows: Spring = Apr – May, Summer = Jun – Sep, Fall = Oct – Nov, Winter = Dec – Mar.

A disproportionate amount of annual N export occurred in only a few major storm events. In general, the majority of annual export occurred in the winter and early spring when soil moisture was high and active turf growth minimized (Fig. 4.6).

Discussion

It is useful to point out that the irrigation levels were selected to achieve targeted amounts of turf plant attrition while maintaining adequate density for recovery during wetter periods of the same year. That is, the emphasis of the study was not to create complete drought-induced dormancy or some similar worst-case scenario. Subsequently, irrigation levels largely achieved the desired turf canopies by maintaining good turf quality through much of July before plant attrition began in August.

Prior to being developed for turf small plot research, the site had been used for continuous hay production and often received manure applications. Due to pre-existing fertility of the native soil, fertility treatments did not demonstrate substantial turf enhancement until year 2.

The observed fertility effects on runoff [NO_3-N] suggest the 4x program was excessive for the study site. Indeed, the higher annual mean [NO_3-N] caused by both the 2x and 4x levels (compared to the 0x) might suggest both fertilizer rates were excessive. However, 2x increased [NO_3-N] irregularly throughout the study, and annual means may have been biased by a few events during the winter of year 1. Published values for NO_3-N from runoff vary with fertility and study, but have generally ranged from 0.15 to 1.5

mg L^{-1} (Shuman, 2002; Moss et al., 2006; Moss et al., 2007; Rice and Horgan, 2011; Spence et al., 2012). Many of these studies were performed on cool-season grasses or simulated golf course fairway turfs. The markedly higher concentrations seen in this study apparently implicate the high soil fertility although such an interpretation is confounded by grass species and mowing height of cut. For example, surface runoff from a fairway turf could potentially overtop the height of the canopy. Under such scenarios, sheet flow interacts less with N sources such as plant tissue and soil, and would presumably result in lower nutrient concentrations in runoff. Considering the land-use history of the site, the soil fertility could be comparable to an established lawn under continuous high N fertility for many years. Qian et al. (2003) suggested N application rate recommendations should be reduced as a lawn ages. Others have similarly concluded that continuous use of high N fertilizers could increase mineral N leaching losses over time (Hesketh et al., 1995; Frank et al., 2006). Certainly, the conditions of the present experiment are in agreement that high N fertilizer applied to already N-rich soils may increase the risk of nutrient losses through runoff.

During the growing season, [NO_3-N] was typically lower than other periods of the year, regardless of treatment, suggesting plant uptake of applied N was rapid, and fertilizers were largely unavailable for direct surface runoff losses. The notion that turf rapidly assimilates mineral N has been documented by a number of previous papers (Hesketh et al., 1995; Wherley et al., 2009). Peak [NO_3-N] occurred in the late winter, long after N applications had been made. Because fertilizer applications ended in mid-September, the winter NO_3-N release was not likely due to direct fertilizer loss.

Interestingly, the large spike in winter of year 1 was not repeated in year 2, suggesting there was a year effect. Indeed, the winter of year 1 was measurably colder and resulted in full dormancy of the turf, while in year 2, temperatures remained adequate to ward off dormancy. Recent research in Florida had similarly found NO_3-N exports in leachate from warm-season turf peaked during some winters presumably due to cold and disease damage (Trenholm et al., 2012; Telenko et al., 2015). That is, damaged turf constituted a decreased sink for mineral N in the soil. The results of the present study further suggest that periodic warming during the winter can increase mineralization of dormant thatch thus increasing available sources of mineral N at a time when plant assimilation capacity is minimal. Considering that thatch and clippings have been reported to be an important sink for N in turf systems, it is plausible that mineralization of these plant components could reintroduce mineral N for transport (Miltner et al., 1996; Engelsjord et al., 2004). Alternatively, irrigation water quality, specifically sodicity, has been shown to affect leachability of DON from senesced plant tissue (Steele and Aitkenhead-Peterson, 2013). It is plausible that the highly sodic water used for irrigation during summer of year 1 could have increased soil DON for mineralization during periods of the winter. Greater rainfall during summer of year 2 reduced irrigation water requirements and thus reduced sodium inputs. Additionally, the strong link between plant tissue N and [NO_3-N] suggests living or senescent tissues could be contributing the bulk of N in runoff.

Previous research has documented that irrigation best management practices can reduce nutrient losses through leaching (Barton and Colmer, 2006). The results of this project are mixed in that seasonal effects of irrigation management are evident, and maintaining drier soil conditions through deficit irrigation appears to have measureable reduction on runoff volume and nutrient export. However, annual or long-term benefits may not be substantial, depending on climate and other management practices. That is, the Texas annual rainfall pattern results in high runoff volumes during fall through spring when irrigation is not being actively applied. Therefore, substantial runoff reductions are required during a small window in order to sustain meaningful long-term runoff reduction. Further, if rainfall is above average during the summer, the seasonal effects of irrigation management can be mitigated.

This study differed from prior research in that it compared traditional best management practices to deficit irrigation practices (as opposed to excessive irrigation). One of the objectives of the current study was to determine if fertility recommendations should be adjusted for deficit irrigation programs. Certainly, there appeared to be an increased risk associated with surface runoff [NO_3-N] when fertilizing under-watered turf. However, the results do not indicate an increased risk of direct loss of fertilizer. Rather, a short-term decrease in N (mineral or organic) exports through runoff, leaching, or gaseous pathways appeared to concentrate available N in the system. That is, higher N use efficiency could have detrimental long-term effects on N pollution if fertilizer rates are not adjusted downward.

Conclusions

Fertilizer applications at commonly recommended rates can cause nutrient pollution in the form of runoff exports if soils are relatively N rich. Deficit irrigation is a viable tool for sustainable management of St. Augustinegrass in the central Texas climate. Although deficit irrigation reduced runoff volumes, the benefits were offset by elevated [NO_3-N] resulting in a net neutral effect on total exports compared to well-watered turfs. This was primarily evident under high N fertility where short-term N retention ultimately served to increase N availability at a later date. In regions undergoing strict water conservation efforts, best practices for N fertilizer applications should be based on plant tissue testing to reduce the risk of surface water impairment.

CHAPTER V

NITROGEN SPECIES CONCENTRATION AND EXPORTS IN RUNOFF FROM SIMULATED ST. AUGUSTINEGRASS LAWNS IN TEXAS

Introduction

Low infiltration rates are commonplace for urban soils due to site construction practices and soil texture (Kelling and Peterson, 1975; Partsch et al., 1993; Hamilton and Waddington, 1999). Under such environments, runoff is likely to be the primary avenue for nutrient transport into surface waters. Enrichment of surface waters can result in algal blooms and low dissolved oxygen concentrations, which negatively impact the ecosystem as well as anthropogenic uses for the water. In urban ecosystems, surface runoff often demonstrates elevated N concentrations compared to local reference watersheds (Groffman et al., 2004). Turf represents a significant component of the urban landscape and has been targeted as a potential source of N into surface waters (Hochmuth et al., 2012). Much of the emphasis on N management in lawns has focused on controlling inorganic N or more specifically, NO_3-N. This is, perhaps, due to published drinking water standards for NO_3-N but not for other N species. Alternatively, N exports from natural ecosystems are typically dominated by dissolved organic nitrogen (DON) which has led many to assume that DON is largely refractory or limited in its contribution to algal growth (Bronk et al., 2007). Despite this history, the scientific community has recently begun identifying DON as a possible leak in both agricultural and urban ecosystems (van Kessel et al., 2009; Lu et al., 2015). Furthermore, labile components of DON have been increasingly linked to algal blooms (Bronk et al., 2007). As such, transport of DON is likely to contribute to the enrichment of surface waters. Thus, there is a need for examination of total dissolved N (TDN) exports from turfgrasses and inquiry into how the relationships among N species change seasonally or with land management.

The biogeochemical properties of a lawn likely contribute to the chemistry of surface runoff and ultimately the risk of nutrient pollution to the environment (Lu et al., 2015). Evaluation of soil cores from the Baltimore Long-term Ecological Research (LTER) found homeowner management practices were poor predictors of exchangeable soil nitrate; rather, land use history and housing density were more indicative of soil nitrate and organic carbon concentrations (Raciti et al., 2011a; Raciti et al., 2011b). Long-term field studies on Kentucky bluegrass (*Poa pratensis* L.) in Ohio demonstrated significant differences in soil organic matter and microbial biomass due to differences in long-term fertilizer management (Cheng et al., 2008). Specifically, soil organic matter and microbial biomass increased under organic fertilizer use compared to inorganic fertilizer use which was greater than the non-fertilized control. While comparing two vastly different urban watersheds, Toor et al. (2013) reported irrigation runoff during the dry season in California resulted in TDN concentrations of 10.9 mg L^{-1}, whereas wet season storm flow in Florida resulted in concentrations < 3 mg L^{-1}. In the same report, approximately, 50% of N was nitrate-N in California, while < 25% of N was in the nitrate form in Florida. Apparently, climate, local geography, and management can have important effects on TDN as well as the relative preference for a particular species.

Many lawns receive regular irrigation and N fertilizer. Engelsjord et al. (2004) found thatch to be an important sink for applied N with the majority being stored in the organic form. Miltner et al. (1996) reported that 31% of applied urea was found in thatch 18 days after treatment. They further found that approximately 35% of the applied urea-N was removed with clipping yield over the course of two years and that less than 1% of applied urea-N was found in leachate. In the Baltimore LTER, residential lawns served as effective sinks for N (Raciti et al., 2008). Their data support prior reports that turfgrass systems can accumulate and store N over time, thus soil N content can be described as a function of site age (Qian et al., 2003). Although N inputs typically do not enhance exports through hydrological processes, there are several reports which suggest denitrification may be an important output of the N cycle. Using a ^{15}N-labelled fertilizer, Horgan et al. (2002) suggested that 19% of applied N was lost through denitrification in Kentucky bluegrass lawns. Raciti et al. (2011c) used laboratory measurements of denitrification from soil cores and long-term field data to estimate annual denitrification exports as 14.1 kg N ha^{-1} or 15% of applied fertilizer. In general, each study suggested added fertilizer as well as high soil moisture resulted in large ephemeral spikes in denitrification. In some cases, over 80% of the N exports occurred during 5% of the growing season (Raciti et al., 2011c).

Soil water availability has a dramatic effect on plant health, carbon assimilation, soil microbial activity, and the carbon and N cycles in general (Peacock and Dudeck, 1984; Stark and Firestone, 1995; Lundquist et al., 1999). Turfgrasses often require supplemental irrigation to overcome soil water deficits during the summer. Concurrently, policies which restrict irrigation application have become increasingly commonplace, and substantial effort has been made to conserve water in the landscape. In the extreme case, residents can replace traditional landscapes with xeriscapes, which require little or no supplemental water. However, the traditional turf-based landscape can often be maintained under water conserving programs such as deficit irrigation (Chapter 2). Deficit irrigation refers to irrigating at rates less than the water use rate of the plant. Over the course of the summer, deficit irrigation results in depletion of soil water reserves, and turf attrition can occur. The implications for nutrient cycling and, relevant to this study, nutrient exports through runoff have not been explored.

Objectives

To investigate N exports and N species relative concentration in surface runoff from St. Augustinegrass turf as affected by season and management.

Hypotheses

1) Deficit irrigation practices will increase total N losses due to reduced assimilatory capacity of the turf.
2) Relationships between NO_3-N, NH_4-N, and DON will vary seasonally and by turf management.

Materials and Methods

Site Description and Experimental Design

Research was conducted from May 2013 to Apr 2015 at the Texas A&M Turfgrass Field Laboratory on F&B Rd in College Station, TX (N 30.618178, W -96.366250). The native soil was a Boonville series sandy loam (Fine, smectitic, thermic Chromic Vertic Albaqualfs). A surface runoff small plot research site was built to an average slope of 0.037 m m^{-1}, planted with St. Augustinegrass (*Stenotaphrum secundatum* (Walt.) Kuntze 'Raleigh'), and equipped with flow monitoring and sampling capabilities. For a more detailed description of the site, see Wherley et al. (2014).

Turf was maintained similarly to a medium-intensity managed residential lawn. Mowing was performed weekly using a standard push rotary mower with mulching blades set to a 6.3 cm height of cut and clippings returned. Disease and weed management were performed based on historical knowledge of the area (Table 3.2). Each winter, gypsum was applied at a rate of 2.24 Mg ha^{-1} to reduce the impact of sodic irrigation water (Pannkuk et al., 2011) on site hydrology and nutrient losses (Steele and Aitkenhead-Peterson, 2012) and runoff to surface waters (Steele and Aitkenhead-Peterson, 2013).

The experiment consisted of eight treatments having three replicates arranged as a randomized complete block (Table 3.3). Irrigation was applied on Tuesdays and Fridays to mimic a two-day per week calendar-based irrigation schedule as is common in several Texas cities. Run times were adjusted to apply amounts equal to the cumulative ET deficit (ET_{Def}) since the prior irrigation event. Cumulative ET deficit was calculated using Eq. 3.1.

Treatments were defined in terms of K_s as 0.50, 0.75, and 1.00 (referred to as *K50*, *K75*, *K100* for remainder of this chapter), which were selected so as to create severe, medium, and zero stress conditions, respectively. Effective rainfall was assumed to be measured rainfall for small rain events (< 25 mm). For larger events, when data were available, R_{eff} was calculated from the mean runoff volume as measured on site. If measured runoff data were unavailable, R_{eff} was calculated using a method promoted by the Texas ET Network (Table 3.1). Irrigation run times were adjusted for uniformity (DU_{LH}) as suggested by the Irrigation Association. Results of an irrigation audit indicated a precipitation rate of 39 mm hr^{-1} and a DU_{LH} of 0.84. The irrigation season was defined loosely as the period May 1 to Oct 31. Site hydrology and nutrient export was continually monitored during winter dormancy periods.

Fertilizer was applied at a single rate for each treatment, but varied in terms of applications per year (0x, 2x, and 4x). Each application used Southern Turf Builder (32-0-10, N-P_2O_5-K_2O; Scotts Miracle-Gro, Marysville, OH) at a rate of 44 kg N ha^{-1}. The first application date was made in May of each year, and subsequent applications were made on 6 or 12 week intervals depending on treatment level (Table 4.1). Applications were made on the day before an irrigation event in addition to being watered in immediately with 2.5 mm of irrigation.

Rainfall – Runoff Measurement

Rainfall was measured using a tipping rain gauge (Isco 674, Teledyne Isco, Lincoln, NE) two minute temporal resolution. Soil volumetric water content was measured at the 10 cm depth on 15 min temporal resolution using buried sensors (SDI-12, Acclima, Inc., Meridian, ID). Runoff discharge was conveyed through a calibrated H-flume and measured with bubbler-type meters (model 4230, Teledyne Isco, Inc., Lincoln, NE) at a two minute resolution. Samples were collected by auto-samplers (model 6712, Teledyne Isco, Inc.) using a flow-based pacing of 38 L. For each event, approximately five samples were selected for chemical analysis. Prior tests showed that concentrations of analytes did not differ significantly throughout the runoff event with the exception of the first and last sample. Therefore, samples were chosen to represent the entire hydrograph, and the mean concentration was used as an input for later data analysis.

Over the two year period, samples were collected from 31 rainfall events and one irrigation excess event (13-Aug-2013). The irrigation event was implemented during a period of drought so that an additional data point could be gathered for the summer season. Briefly, the irrigation event used the in-ground sprinkler system to apply water at approximately 40 mm hr^{-1} for 45 minutes. Runoff volume (and therefore exports) could not be measured for two of the 32 events due to freezing weather. The two missing dates occurred in November of each year and were not included in export analysis.

Chemical Analysis of Water

Electrical conductivity and pH were measured on unfiltered fresh aliquots, and a portion of the unfiltered sample reserved for later analysis of total suspended solids (TSS). The remainder of a sample was vacuum-filtered through ashed (400° C for 5 h) Whatman GF/F filters (0.7 μm nominal pore size). Total dissolved nitrogen (TDN) was measured using high temperature Pt-catalyzed combustion with a Shimadzu TOC-V_{CSH} and Shimadzu total measuring unit TNM-1 (Shimadzu Corp. Houston, TX, USA). Ammonium-N was quantified using the phenate hypochlorite method with sodium nitroprusside enhancement (USEPA method 350.1), and nitrate-N was analyzed using Cd–Cu reduction (USEPA method 353.3). Nitrate-N was analyzed within 24 hours of collection. Minimum detection levels were achieved as per the respective EPA methods. All colorimetric methods were performed with a Westco Scientific Smartchem Discrete Analyzer (Westco Scientific Instruments Inc. Brookfield, CT, USA). Instrument detection limits for each constituent analyzed were 0.05 mg L^{-1} TDN, 0.005 mg L^{-1} NH_4-N, 0.002 mg L^{-1} NO_3-N. NIST traceable standards and blanks were run after every 10th sample to monitor instrument precision. Soil pH and electrical conductivity were measured in 1:2 soil:deionized water extracts (Schofield and Taylor, 1955; Rhoades, 1982). Nitrate-nitrogen was extracted from soil using a 1 M KCl solution, reduced to nitrite and measured spectrophotometrically using a flow injection analyzer (FIALab Instruments, Inc., Bellevue, WA) (Kachurina et al., 2000). Phosphorus, K, Ca, Mg, Na, and S were extracted using the Mehlich III extraction solution (Mehlich, 1984), followed by analysis using an inductively coupled plasma – optical emission instrument

(Spectroblue, Spectro Analytical Instruments, Kleve, Germany). Total N was measured using high temperature combustion methods (vario Max cube, Elementar Americas Inc., Mt. Laurel, NJ). Nutrient losses via leaching were not measured, nor were gaseous losses through volatilization or denitrification.

Statistical Analyses

Treatment effects on N species concentration in runoff, nitrate-N : ammonium-N (NIT:AMM) ratio, and dissolved organic N : total dissolved N (DON:TDN) ratio were analyzed as a single continuous experiment over two years using a linear mixed model repeated measures design (SPSS 22, IBM Corp., Armonk, NY). Data were natural log-transformed if assumptions of normality were not met. For the analyses ‘irrigation’ and ‘fertility’ were treated as factors rather than eight levels of ‘treatment’. Block, date, and interactions between irrigation, fertility, and date were also considered fixed factors. In some cases, baseline runoff measurements were used as covariates in the analysis. Missing data were valuated using a simplified linear mixed model, typically without the date by treatment interaction term. These data were merged with the original dataset and re-analyzed using the full model. If the date by treatment interaction was significant, further analysis was performed within each date. In order to understand more generally how nutrient concentrations varied with season, data were averaged across dates within time periods which reflected roughly the biological calendar. In this manner, seasons were defined as follows: Spring = Apr & May, Summer = Jun – Sep, Fall = Oct & Nov, Winter = Dec – Mar. Nutrient export was calculated as the product of flow-weighted concentration and runoff volume per unit area. Export data were summed over the two year period before being subjected to a general linear model (SPSS 22, IBM Corp., Armonk, NY). For each significant multi-factor test, means were separated using Fisher's protected least significant difference (LSD) at a significance level of $p \leq 0.05$. Pearson bivariate correlation was used to compare relationships among nutrient concentrations and hydrological parameters such as rainfall depth, antecedent soil moisture content, and runoff ratio (RR).

Results

Nutrient Concentrations

Nitrate-N concentration remained relatively low (< 5 mg L^{-1}) throughout the study except for the winter of year 1 when the mean concentration increased dramatically reaching values over 20 mg L^{-1} (Fig. 5.1). Ammonium-N concentration also remained relatively low (< 2 mg L^{-1}) except for a sharp increase in winter of year 1. Interestingly, [NH_4-N] peaked during the event immediately prior to the [NO_3-N] peak event. Dissolved organic N concentration was typically higher than other N species.

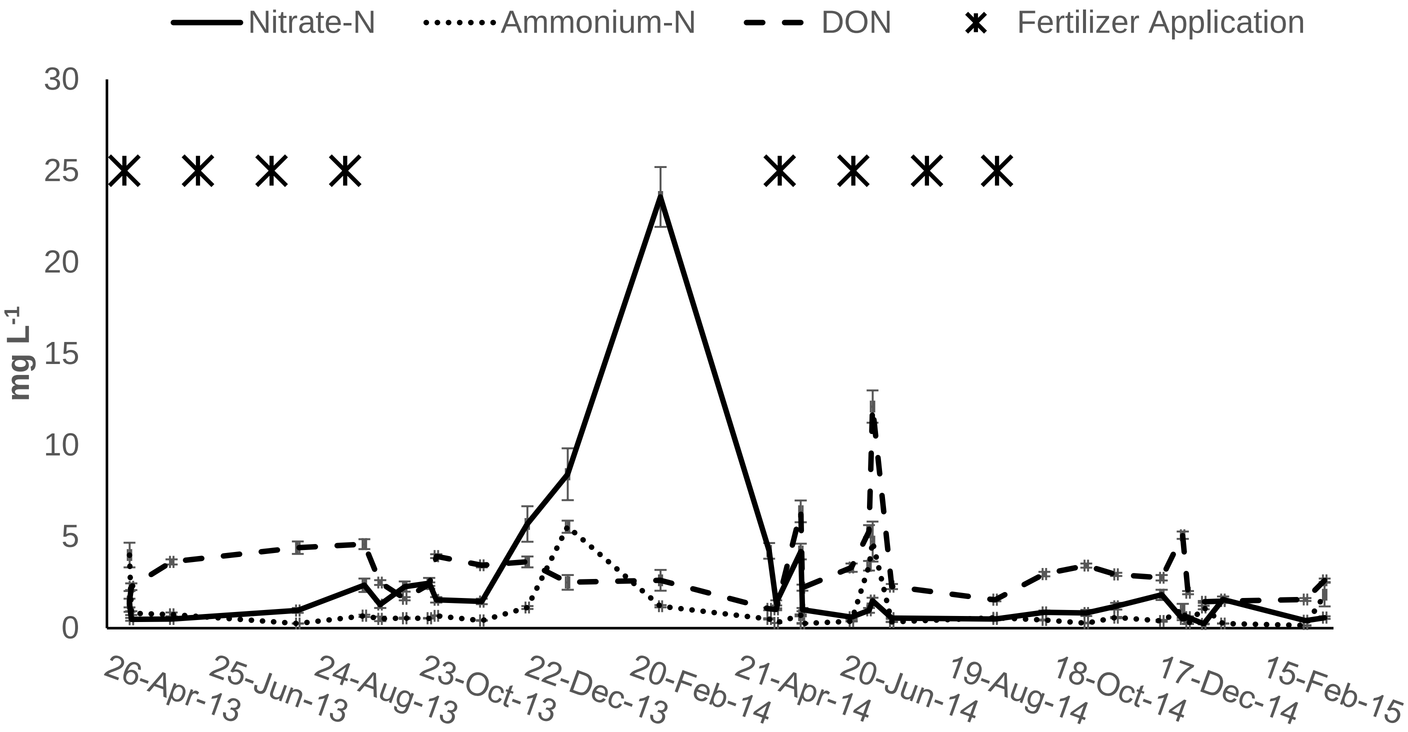

Fig. 5.1. Seasonal pattern for nutrient concentrations by N species. Data were pooled across all treatments and reps (N=24). Error bars are standard error of the mean.

Statistical analysis of each N species concentration demonstrated several significant interactions for each species; therefore, data were further analyzed within each event date (Table 5.1). Nitrogen concentration demonstrated significant fertility main effects on 28, 13, and 14 of 32 dates for NO_3-N, NH_4-N, and DON, respectively (Table 5.2). In order to simplify inferences, data were averaged within pre-determined seasons each year (N = 8).

Table 5.1. Fixed effects model for linear mixed model analysis of runoff nutrient concentration.

Source	NO_3-N	NH_4-N	DON
Block	.019	.336	.473
Fertility (F) †	.000	.085	.006
Irrigation (I) ‡	.118	.027	.080
F x I	.011	.364	.794
Date (D)	.000	.000	.000
D x F	.000	.000	.000
D x I	.000	.000	.004
D x F x I	.000	.000	.074
Covariate : baseline TDN	.002	.141	.661

† Fertility levels were 0x, 2x, or 4x applications yr^{-1} of 39 kg N ha^{-1} of a partially slow-release, high N fertilizer.

‡ Irrigation levels were defined in terms of stress coefficient (K_s) adjustments to ET_c: K_s = 0.50, 0.75, and 1.00.

Table 5.2. Significance levels from linear mixed model analysis of nutrient concentration data separated by date.

Date	---------NO_3-N---------			---------NH_4-N---------			---------DON---------		
	F[†]	I[‡]	I x F	F	I	I x F	F	I	I x F
9-May-13	.000	NS	.019	.000	.033	NS	.000	NS	NS
10-May-13	.000	NS	NS	.012	.010	.000	.046	NS	NS
2-Jun-13	.038	NS	NS	NS	NS	NS	NS	NS	NS
13-Aug-13	NS	.030	NS	.034	NS	NS	NS	.031	NS
20-Sep-13	.000	NS	NS	.030	NS	NS	.006	NS	NS
29-Sep-13	.000	NS	NS	NS	NS	NS	NS	.047	NS
13-Oct-13	.000	NS	NS	NS	NS	NS	NS	.003	NS
27-Oct-13	.000	.019	.000	NS	.000	.009	.031	NS	NS
31-Oct-13	.000	NS	.021	.027	NS	NS	.037	.031	NS
26-Nov-13	.000	NS	NS	NS	NS	NS	.030	NS	NS
22-Dec-13	.000	NS	.002	NS	.030	NS	NS	NS	NS
14-Jan-14	.000	NS	.038	NS	NS	NS	NS	NS	NS
8-Mar-14	.030	NS	NS	NS	NS	NS	NS	NS	NS
9-May-14	NS	.008	NS	NS	NS	NS	.011	.013	.008
13-May-14	.009	.023	NS	NS	NS	NS	NS	NS	NS
27-May-14	.000	NS	NS	.000	NS	NS	.000	NS	NS
28-May-14	.000	NS	NS	NS	NS	NS	.000	NS	NS
25-Jun-14	.005	NS	NS	NS	NS	NS	.000	.000	.030
5-Jul-14	.000	.010	.000	.000	.000	.000	.000	.000	.000
7-Jul-14	.000	.000	.000	.000	.000	.000	.000	.000	.000
18-Jul-14	.016	NS	NS	.017	NS	NS	NS	NS	NS
15-Sep-14	NS	.001	NS	NS	.014	NS	NS	NS	NS
13-Oct-14	.000	.000	.000	.000	.000	.000	.000	.000	.000
6-Nov-14	.000	NS	NS	.000	NS	.028	.002	NS	NS
23-Nov-14	.001	NS	NS	NS	NS	NS	NS	NS	NS
19-Dec-14	.002	NS	.007	.016	NS	NS	NS	NS	.040
31-Dec-14	.000	.039	.030	NS	.002	.000	NS	.023	.000
3-Jan-15	.001	NS	.011	NS	NS	NS	NS	NS	NS
12-Jan-15	NS	NS	.029	.003	NS	NS	NS	NS	NS
23-Jan-15	.000	NS	NS	NS	NS	NS	NS	NS	NS
11-Mar-15	.001	NS	.018	NS	.030	NS	NS	NS	NS
22-Mar-15	.037	NS	NS	NS	NS	NS	NS	NS	NS

[†] Fertility. Levels were 0x, 2x, or 4x applications yr^{-1} of 39 kg N ha^{-1} of a partially slow-release, high N fertilizer.

[‡] Irrigation. Levels were defined in terms of stress coefficient (K_s) adjustments to ET_c: K_s = 0.50, 0.75, and 1.00.

Analysis of seasonally aggregated data resulted in a significant season by fertility interaction effect for each parameter (Table 5.3). Analysis within season resulted in unique responses for each N species (Table 5.4). Nitrate-N concentration from 0x plots ranged from 0.3 to 1.2 mg L^{-1} each season except for winter of year 1 when it reached 6.5

mg L^{-1}. Nitrate-N concentration was greater for 4x than for 2x which was greater than for 0x each season except for the spring in which 2x and 4x were similar. High fertility (4x) increased [NO_3-N] by two- to three-fold each season from spring 2013 through spring 2014. After which in the summer, fall, and winter of year 2, fertility effects remained statistically significant, but the overall mean [NO_3-N] and magnitude of treatment mean differences were muted compared to previous seasons.

Ammonium-N concentrations from 0x plots were highest in winter of year 1 and summer of year 2. In each of these two seasons, the fertility effect was not significant. The highest seasonal mean [NH_4-N] was during the spring of 2013 when fertilized plot means were 3.0 and 2.8 mg L^{-1} (2x and 4x, respectively), which was three-fold higher than the non-fertilized control. Interestingly, in summer of year 2, 0x resulted in greater [NH_4-N] than either fertilized treatment.

Dissolved organic N concentration from 0x plots ranged from 1.3 to 3.5 mg L^{-1} and remained fairly stable throughout the year although there was a general decline from spring to fall. In general, 2x and 4x fertility levels increased runoff [DON] similarly over the 0x level (4x = 2x > 0x), although in summer of year 2, 4x demonstrated higher [DON] than the 2x which was greater than the 0x (4x > 2x >0x). Fertility affected [DON] most dramatically during the spring each year when both 2x and 4x levels increased [DON] nearly two-fold. Although fertility effects were evident in each season except winter, the magnitude of treatment differences were often quite small (~ 0.1 or 0.2 mg L^{-1}).

Table 5.3. Fixed effects model from linear mixed model analysis of nutrient concentration using season as a factor. Data were averaged across individual dates within season prior to analysis.

Source	NO$_3$-N	NH$_4$-N	DIN	DON	TDN	DON:TDN	NIT:AMM
Block	.025	ns	ns	ns	.005	ns	.009
Fertility (F) [†]	.000	.008	.000	.004	.000	.000	.000
Irrigation (I) [‡]	ns	.014	.022	ns	.001	ns	ns
F x I	.010	ns	ns	ns	ns	ns	.002
Season (S)	.000	.000	.000	.000	.000	.000	.000
S x F	.000	.000	.000	.000	.000	.000	.007
S x I	ns	.003	ns	ns	.000	ns	ns
S x F x I	.007	.000	.019	ns	.000	ns	ns
Covariate: TDN[§]	.001	ns	.001	ns	.000	.009	.003

[†] Fertility levels were 0x, 2x, or 4x applications yr^{-1} of 39 kg N ha^{-1} of a partially slow-release, high N fertilizer.

[‡] Irrigation levels were defined in terms of stress coefficient (K_s) adjustments to ET_c: K_s = 0.50, 0.75, and 1.00.

[§] TDN concentration in runoff from a storm event on 2-Apr-13 was used as a baseline covariate.

Table 5.4. Season by treatment effects on nutrient concentrations and ratios.

	Fertility (F) [†]			Irrigation (I) [‡]					
	0x	**2x**	**4x**	***K50***	***K75***	***K100***	**F**	**I**	**F x I**
Spring	**2013**								
NO_3-N	0.3b[§]	1.0a	1.2a	1.1	0.7	1.0	.000	ns	.016
NH_4-N	0.9b	3.0a	2.8a	3.8a	2.0b	1.9b	.000	.013	.009
DIN	1.2b	4.1a	4.0a	4.9	2.7	2.9	.000	.002	.000
DON	3.7b	6.5a	6.1a	6.1	5.7	5.2	.000	ns	ns
TDN	4.9c	10.6a	10.1b	11.0a	8.4b	8.2c	.000	.006	ns
DON:TDN	0.75	0.67	0.66	0.63	0.71	0.70	ns	ns	.021
NIT:AMM	0.7	0.7	0.8	0.6	0.6	0.9	ns	ns	.026
	2014								
NO_3-N	1.2b	3.0a	3.4a	3.9a	2.2b	2.4b	.000	.035	ns
NH_4-N	0.3b	0.5a	0.5a	0.5	0.4	0.4	.005	ns	ns
DIN	1.6b	3.4a	3.9a	4.4a	2.6b	2.8b	.000	.037	ns
DON	1.3b	3.3a	2.9a	3.1	2.5	2.5	.000	ns	ns
TDN	2.9b	6.7a	6.8a	7.5a	5.2b	5.3b	.000	.027	ns
DON:TDN	0.48	0.46	0.42	0.40	0.47	0.47	ns	ns	ns
NIT:AMM	3.5b	6.2a	6.8a	7.2a	5.2b	5.3b	.000	.039	.043
Summer	**2013**								
NO_3-N	0.6c	1.0b	2.0a	1.7	1.0	1.3	.000	ns	ns
NH_4-N	0.5	0.4	0.6	0.6	0.4	0.6	ns	ns	ns
DIN	1.2b	1.4b	2.6a	2.3a	1.4b	1.9ab	.000	.037	ns
DON	3.6a	3.0b	3.8a	3.6a	2.9b	3.9a	.002	.001	ns
TDN	4.7b	4.5b	6.4a	5.8a	4.3b	5.8a	.000	.000	ns
DON:TDN	0.74a	0.68b	0.61c	0.64	0.69	0.67	.002	ns	ns
NIT:AMM	1.5b	2.8a	4.2a	3.7	2.7	2.8	.001	ns	ns
	2014								
NO_3-N	0.6c	0.7b	1.1a	1.0a	0.7b	0.8b	.000	.001	.000
NH_4-N	2.6a	1.4c	1.8b	1.7a	2.5a	1.4b	.000	.000	.000
DIN	3.2a	2.2c	2.9b	2.8b	3.2a	2.2c	.000	.000	.006
DON	3.2c	4.9b	6.1a	5.7	4.5	4.8	.000	ns	.042
TDN	6.4c	7.0b	9.0a	8.4a	7.7b	7.0b	.000	.004	.000
DON:TDN	0.63	0.67	0.67	0.64b	0.64b	0.69a	.039	.006	ns
NIT:AMM	1.3a	1.0c	1.1b	1.2a	1.0b	1.3a	.000	.000	.000
Fall	**2013**								
NO_3-N	1.0c	1.7b	2.8a	2.2	1.7	2.0	.000	ns	ns
NH_4-N	0.5b	0.5a	0.6a	0.6	0.5	0.5	.005	.005	ns
DIN	1.5c	2.2b	3.4a	2.9	2.2	2.5	.000	ns	ns
DON	2.5b	3.0a	2.9a	3.2a	2.7b	2.7b	.046	.006	ns
TDN	4.0c	5.2b	6.3a	6.1a	5.0b	5.2b	.000	.011	ns
DON:TDN	0.62a	0.58a	0.46b	0.53	0.57	0.53	.000	ns	ns
NIT:AMM	2.3c	3.2b	4.9a	3.6	3.3	3.9	.000	ns	ns
	2014								
NO_3-N	0.4c	0.7b	1.6a	1.4	0.8	0.8	.000	ns	.040
NH_4-N	0.4b	0.4b	0.5a	0.5	0.4	0.4	.013	ns	.002
DIN	0.8c	1.1b	2.0a	1.9	1.2	1.2	.000	ns	.027
DON	3.0b	2.8b	3.5a	3.3a	3.1ab	3.0b	.000	.014	.016
TDN	3.8b	3.9b	5.5a	5.2a	4.3b	4.2b	.000	.009	.026
DON:TDN	0.78a	0.73b	0.64c	0.67	0.73	0.72	.000	ns	ns
NIT:AMM	1.1c	1.8b	3.6a	3.2	1.9	2.1	.000	ns	ns
Winter	**2013**								
NO_3-N	6.5c	12.5b	16.6a	14.6	12.8	10.9	.000	ns	.024
NH_4-N	2.6	2.6	2.6	3.0	2.5	2.4	ns	ns	.048
DIN	9.1c	15.1b	19.2a	17.6	15.3	13.4	.000	ns	.010
DON	3.5	3.0	2.3	3.6	2.7	2.7	ns	ns	ns
TDN	12.7c	18.2b	21.6a	21.2	18.1	16.0	.000	ns	.003
DON:TDN	0.36a	0.25b	0.14c	0.23	0.25	0.22	.001	ns	ns
NIT:AMM	6.1c	9.2b	11.7a	10.6	9.1	8.8	.000	ns	ns
	2014								
NO_3-N	0.5c	0.7b	1.1a	1.0	0.8	0.7	.000	ns	.011
NH_4-N	0.9	0.7	0.6	0.8	0.6	0.8	ns	ns	ns
DIN	1.4b	1.4b	1.8a	1.8	1.3	1.5	.005	ns	.009
DON	2.4	2.4	2.4	2.5	2.4	2.4	ns	ns	ns
TDN	3.8b	3.7b	4.2a	4.3	3.7	3.9	.035	ns	ns
DON:TDN	0.68a	0.64ab	0.58b	0.60	0.64	0.63	.015	ns	.034
NIT:AMM	1.7b	2.4b	4.1a	3.5	2.5	2.9	.001	ns	ns

[†] Fertility levels were 0x, 2x, or 4x applications yr^{-1} of 39 kg N ha^{-1} of a partially slow-release, high N fertilizer.

[‡] Irrigation levels were defined in terms of stress coefficient (K_s) adjustments to ET_c: K_s = 0.50, 0.75, and 1.00.

[§] Means having similar letters within a row and factor are not significantly different (LSD .05).

The DON:TDN ratio was not affected by fertility during spring of either year. In summer of year 1, DON:TDN ratio decreased with increasing fertility. During the period beginning in fall 2013 through spring 2014, the DON:TDN ratio decreased rapidly to a low of 0.14 for the 4x level. During the remainder of the study, seasonal means ranged from 0.62 to 0.78, 0.67 to 0.73, and 0.58 to 0.67 for 0x, 2x, and 4x levels, respectively.

Nitrate-N to ammonium-N ratios followed similar patterns as [NO_3-N]. The NIT:AMM ratios of 0x plots ranged from 1.1 to 2.3 during summer and fall. During the spring and winter, the NIT:AMM ratios from 0x plots were more variable ranging from 0.7 to 3.5 in spring and 1.7 to 6.1 in winter. Fertility effects were evident in each season except for May of year 1. In general, fertility effects on NIT:AMM ratios followed the pattern 4x > 2x > 0x.

Irrigation effects for most parameters at various times suggested that N species concentration in runoff was greatest at the *K50* level. At other times, N concentration increased with decreasing supplemental water applied such that *K50* > *K75* > *K100*. Because the fertility by irrigation interaction was significant for several parameters during multiple seasons, data were re-analyzed at each level of fertility. Examination of the interaction revealed that in many cases, the significant irrigation main effect was only evident in the 2x or 4x fertility levels (Fig. 5.2).

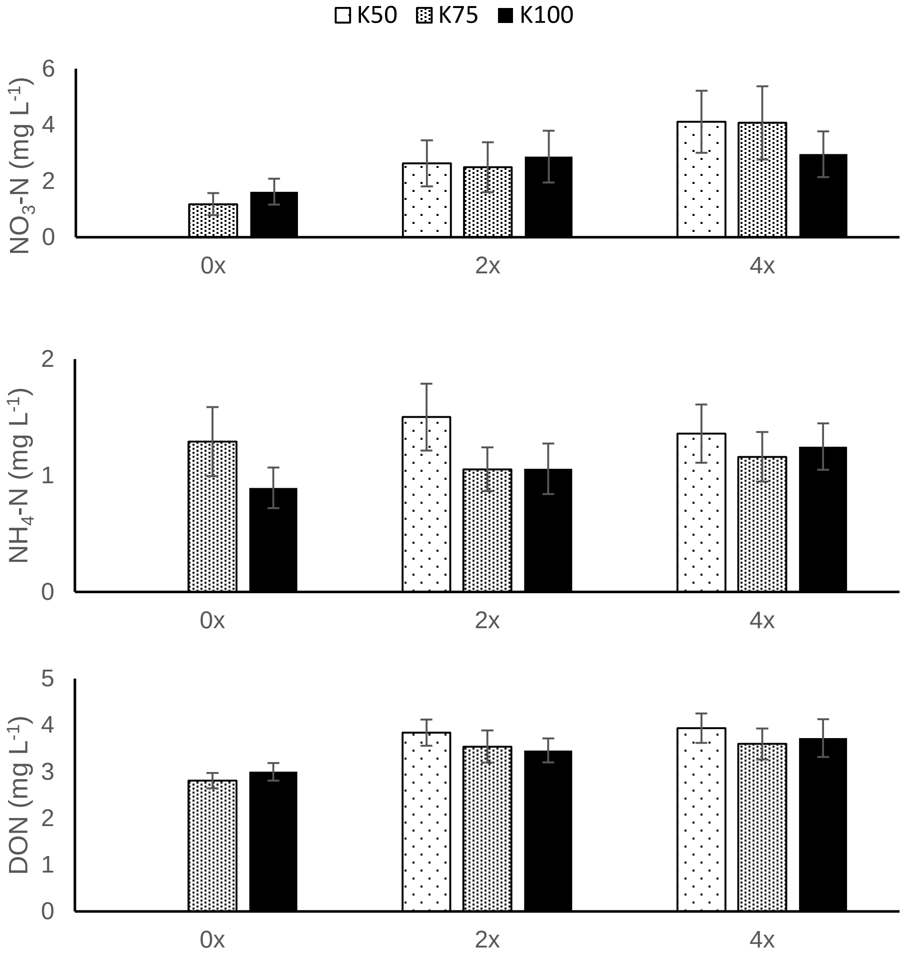

Fig. 5.2. Fertility and irrigation interaction effects on nutrient concentration. Data were averaged within each season prior analysis.

Each nutrient concentration was negatively correlated with runoff ratio during the summer (Table 5.5). For spring events, RR was correlated with [DIN] but not [DON], and interestingly, NO_3-N and NH_4-N demonstrated opposite signs. For the winter, [NO_3-N] was unaffected by RR, but other species demonstrated a negative correlation. Soil antecedent moisture content (VWC) at the 10 cm depth was correlated with each N

Table 5.5. Correlation among nutrient concentration and hydrological properties. Data were pooled across all treatments and dates within each season.

Season†		**NO_3-N**	**NH_4-N**	**DON**	**TDN**	**NIT:AMM**	**DON:TDN**
		----------mg L^{-1}----------					
Summer	RR‡	-.200**¶	-.242**	-.320**	-.353**	-.046	.144*
	VWC§	-.074	.383**	.365**	.394**	-.316**	-.042
	Rainfall (mm)	-.190**	-.314**	-.516**	-.511**	-.029	-.081
Fall	RR	.214*	.272**	-.178	.095	.121	-.336**
	VWC	.246**	.345**	.108	.286**	.088	-.298**
	Rainfall (mm)	.277**	.184*	-.409**	-.010	.217**	-.505**
Winter	RR	-.126	-.277**	-.339**	-.247**	-.016	.192**
	VWC	.105	.104	-.155*	.091	-.003	-.106
	Rainfall (mm)	-.320**	-.315**	-.441**	-.458**	-.092	.257**
Spring	RR	-.396**	.493**	.074	.074	-.444**	.172*
	VWC	-.363**	-.139	-.017	-.228**	-.317**	.404**
	Rainfall (mm)	.015	.372**	.065	.201*	-.079	-.268**

[†] Season was defined as follows: Summer = Jun – Sep, Fall = Oct – Nov, Winter = Dec – Mar, Spring = Apr – May.

[‡] Runoff Ratio

[§] Antecedent soil moisture content defined as volumetric water content at 10 cm depth

[¶] Significant correlations are denoted with asterisks.

species but specific relationships varied with season. In spring, VWC was positively correlated with [NH_4-N] and [DON] but not [NO_3-N]. In the fall, VWC was positively correlated with [DIN] but not [DON]. In the spring, [NO_3-N] showed a negative correlation with VWC while other species were not correlated. During the summer and winter, rainfall was negatively correlated with each N species concentration, but in fall [NO_3-N] and [NH_4-N] were positively correlated with rainfall depth, while in the spring, [NH_4-N] was positively correlated with rainfall depth.

Data were also compared using ANOVA by categorizing each event by rainfall depth and analyzed with storm category as the only factor. Although each species appeared to demonstrate a similar dilution pattern with increasing rainfall depth, only [DON] resulted in a significant test (Fig. 5.3).

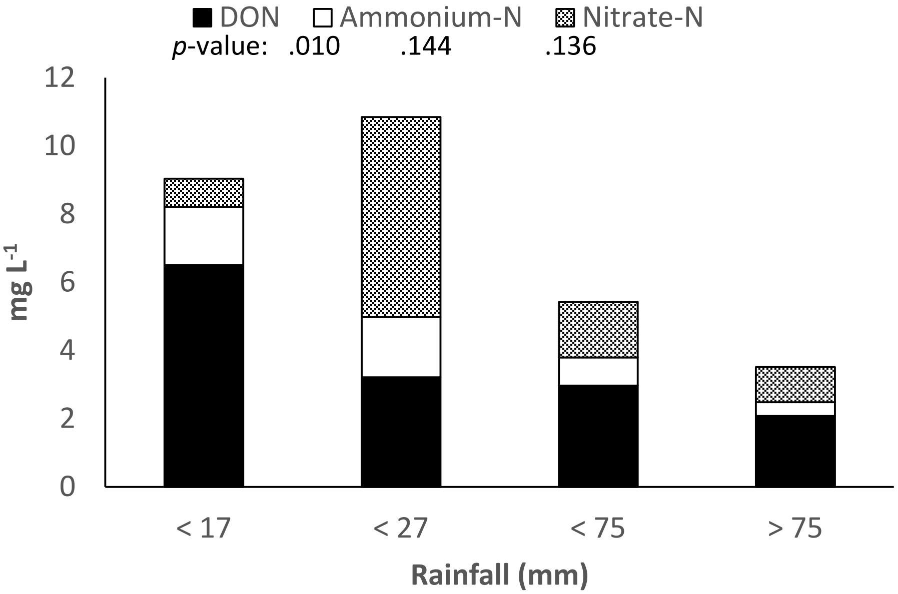

Fig 5.3. Effect of rainfall depth on runoff nutrient concentration. Storm category thresholds were determined by fitting rainfall data to DON concentration after initial patterns were noticed graphically.

Seasonal and Annual Exports

Seasonal exports followed similar patterns as nutrient concentrations (Fig. 5.4). The largest export of NO_3-N occurred March 2014 due to high concentrations. Exports were also high during May, primarily due to high runoff volumes. Analysis of the cumulative exports data demonstrated significant fertility main effects for each N species and significant irrigation main effects for NH_4-N and TDN (Table 5.6). The fertility by irrigation interaction was nearly significant ($p = .056$) for NO_3-N. For each significant fertility effect, the 2x and 4x similarly increased nutrient exports over the course of the experiment (Table 5.7). The only significant irrigation effect suggested *K75* reduced NH_4-N exports compared to other irrigation levels.

Inputs from fertilizer, rainfall, and irrigation were tabulated for comparison to cumulative exports (Table 5.8). It was estimated that 10 kg N ha^{-1} were supplied to the site through rainfall and another 1 or 2 kg N ha^{-1} was supplied through irrigation depending on treatment. Each of these inputs was overwhelmed by fertility applications which ranged from 176 kg N ha^{-1} to 352 kg N ha^{-1} for the 2x and 4x levels, respectively. For the 0x level, the N balance suggests a net loss of nutrients through runoff. Conversely, 2x and 4x levels lost 3 to 7% of total N inputs or 2 to 5% of applied N as fertilizer via runoff.

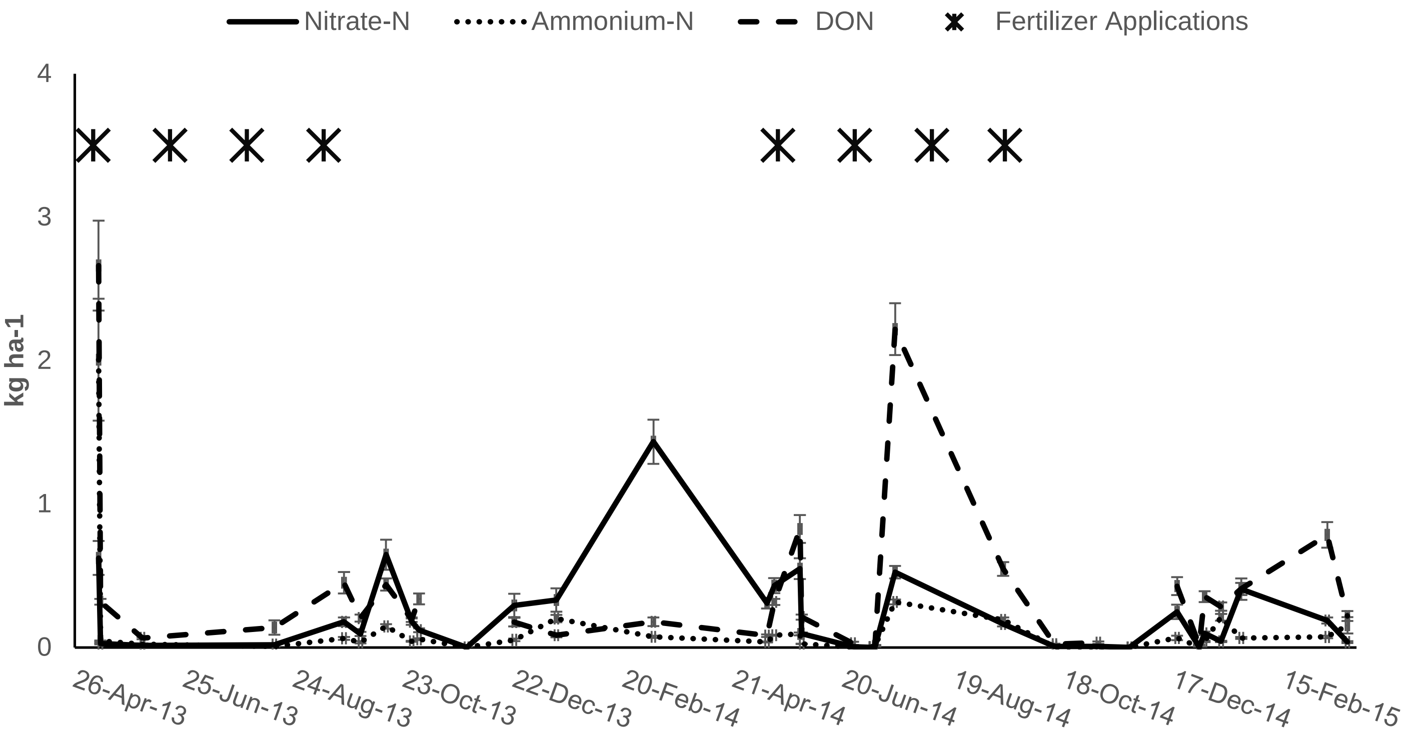

Fig. 5.4. Seasonal pattern for runoff nutrient exports by N species.

Table 5.6. Significance levels from ANOVA of summed nutrient exports for each N species.

Source	NO_3-N	NH_4-N	TDN	DON	DIN
Block	.004	.000	.000	.032	.001
Fertility (F) †	.004	.024	.001	.044	.062
Irrigation (I) ‡	.360	.044	.049	.052	.215
F x I	.056	.735	.140	.420	.970

† Fertility levels were 0x, 2x, or 4x applications yr^{-1} of 39 kg N ha^{-1} of a partially slow-release, high N fertilizer.

‡ Irrigation levels were defined in terms of stress coefficient (K_s) adjustments to ET_c: K_s = 0.50, 0.75, and 1.00.

Table 5.7. Fertility and irrigation main effects on N species exports. Data represent a summation of 32 events over a two year period.

Factor	Level	NO_3-N	NH_4-N	DON	TDN	DIN
		---kg ha^{-1}---				
Fertility†	0x	4.1b‡	2.5b	10.2	16.8b	6.5b
	2x	7.2a	4.7a	12.8	24.7a	11.9a
	4x	9.0a	4.7a	12.5	26.1a	13.7a
Irrigation‡	*K50*	8.6	5.5a	12.4	26.5	14.1
	K75	5.9	3.2b	11.1	20.2	9.1
	K100	7.2	4.1ab	12.8	24.1	11.3

† Fertility levels were 0x, 2x, or 4x applications yr^{-1} of 39 kg N ha^{-1} of a partially slow-release, high N fertilizer.

‡ Irrigation levels were defined in terms of stress coefficient (K_s) adjustments to ET_c: K_s = 0.50, 0.75, and 1.00.

§ Means having similar letters within a row and factor are not significantly different (LSD .05).

Table 5.8. Total N inputs via rainfall, irrigation, and fertilizer.

Fertility[†]	**Irrigation**[‡]	**Inputs**				**Exports**			
		Fertilizer	**Irrigation**	**Rainfall**	**Total**	**% of Inputs**	**SE**[§]	**% of Fertilizer**	**SE**
		kg ha^{-1}							
0x	*K75*	0	2	10	14	106%	12.5%		
	K100	0	2	10	15	130%	23.7%		
2x	*K50*	176	1	10	364	7%	1.1%		
	K75	176	2	10	366	6%	0.4%	4%	0.3%
	K100	176	2	10	367	8%	1.4%	5%	1.2%
4x	*K50*	352	1	10	716	4%	0.4%		
	K75	352	2	10	718	4%	0.8%	3%	1.2%
	K100	352	2	10	719	3%	0.5%	2%	0.1%

[†] Fertility levels were 0x, 2x, or 4x applications yr^{-1} of 39 kg N ha^{-1} of a partially slow-release, high N fertilizer.

[‡] Irrigation levels were defined in terms of stress coefficient (K_s) adjustments to ET_c: K_s = 0.50, 0.75, and 1.00.

[§] Standard error of the mean

Discussion

The immediacy and consistency of the fertility effect on [NO_3-N] suggests fertilizer was rapidly assimilated and oxidized within the system. Torello and Wehner (1983) reported urease activity within turfgrass thatch and clippings to be 18 to 30 times that of soil (dry weight basis). Furthermore, the high mineralization rates common to turf likely promoted rapid transformation of organic N sources such as clippings (Shi et al., 2006).

Groffman et al. (2004) compared N budgets from agricultural, urban, and forested watersheds in Maryland. They reported that [NO_3-N] in streams ranged from approximately 4 to 5 mg L^{-1}, 1 to 4 mg L^{-1}, and less than 1 mg L^{-1} for agricultural, suburban, and forested watersheds, respectively. Those same watersheds resulted in total N exports of 16.4, 6.5, and 0.5 kg ha^{-1} yr^{-1} with NO_3-N representing 85% and 24% of total N from the suburban and forested watersheds, respectively. In the present study, runoff from turf resulted in [NO_3-N] and NO_3-N exports comparable to those of the suburban watershed, but NO_3-N represented a much smaller portion (24 to 34%) of the total N in runoff. This discrepancy could be a problem of scale since the suburban watershed contained both green spaces and impervious surfaces which likely diluted DON sources while increasing DIN sources. For example, Hale et al. (2015) compared nutrient loads from various watersheds in a metropolitan area in Arizona. They reported a negative correlation between the rainfall by imperviousness interaction on [TDN] and

[NH_4-N], but no relationship with [NO_3-N]. Alternatively, treated wastewater or sewage could be contributing to the suburban watershed described by Groffman et al. (2004) and thus skewing stream chemistry in favor of DIN (Aitkenhead-Peterson et al., 2009). The Arizona study also reported that [DIN] was greater during the summer than the winter, which was attributed to seasonal differences in rainfall patterns and rainfall chemistry (Hale et al., 2005). In the present study, rainfall chemistry did not demonstrate any clear seasonal patterns, but seasonal effects on [DIN] resulted in highest concentrations in late winter and spring, presumably due to reduced sink capacity of dormant or disease-stressed plants.

Hale et al. (2015) also reported a positive correlation between [TDN], [NH_4-N] and [NO_3-N] and antecedent dry days. In the present study, higher [DIN] was generally seen during year 1 (drier) than year 2, but the underlying mechanism for such a result is not evident. It has been widely reported that urban lawns are active denitrification zones which remove N from the urban hydrological system (Raciti et al, 2011). Denitrification rates were not measured in the present study, but it could be surmised that rates would be much higher in year 2 due to regular saturation of the upper soil. Perhaps DIN loss through gaseous export reduced substrate available for runoff loss.

The rapid increase in [NO_3-N] during winter of year 1, both in magnitude and relation to other N species, was fairly surprising, but there seem to be several plausible explanations for this sudden spike. Recent research on NO_3-N leaching in Florida showed a similar spike which was attributed to winter injury (Telenko et al., 2015). However, in their study, fertilizer was applied later in the year and measured exports were possibly due to direct loss of the most recently applied N. Landscape-scale research by King et al. (2001) measured inorganic N concentrations upstream and downstream of a golf course in Austin, TX. Mean concentration was fairly low throughout the year, but the highest increases were typically seen during the dormancy period. Wherley et al. (2009) reported that NO_3^- applied to bermudagrass during dormancy resulted in 80 to 90% remaining in the soil after 16 d. This contrasts with summer applied NO_3^-, which resulted in less than 10% remaining after 3 d. An experiment using grass cover crops reported increased soluble P in runoff from plant canopies with increasing freeze-thaw cycles (Bechmann et al., 2005). In year 1 of the present study, winter temperature variability (including freezing temperatures) and aerobic soil conditions likely encouraged substrate availability, mineralization, and nitrification of dormant turf thatch, while limiting denitrification. Further, the spike in runoff [NH_4-N] shortly before the [NO_3-N] spike could be viewed as evidence of the mineralization processes. Alternatively, the increased [DIN] during winter could be related to turnover in the microbial biomass. Yao et al. (2011) reported that the highest microbial biomass under turf in North Carolina occurred during December. This coincided with reduced turfgrass competition for N. The frequent freezes which occurred during winter of year 1 could have reduced the assimilatory capacity of the microbial population or simply reduced population size.

Irrigation effects were difficult to decipher throughout the analysis. The incomplete factorial design frequently caused the *K50* level to result in erroneously large mean concentrations of each N species. In some instances, however, the irrigation effect was real, and deficit irrigation in general and *K50* specifically resulted in higher mean N concentrations, although this occurred primarily under medium and high fertility (2x and 4x). In chapter 4, I suggested that enhanced N use efficiency resulted in higher N content of the *K50* surface which enhanced N availability for transport. Further, there is evidence that nitrification and denitrification rates each occurred more regularly under the higher soil moisture conditions of *K100* than *K50* or *K75* levels. Stark and Firestone (1995) reported on mechanisms of nitrification rate reductions associated with soil moisture depletion. Under moderately dry conditions, nitrification was reduced by substrate limitation; while under drier conditions, adverse effects on cellular physiology reduce overall microbial activity. Similarly, there is reason to suspect *K100* plots were able to export a substantial amount of additional inorganic N through gaseous losses. Alternatively, *K100* plots during summer and fall often resulted in greater runoff volumes which could have diluted concentrations relative to drier plots.

Yao et al. (2011) reported seasonal fluctuations in soil microbial activity and water extractable organic and inorganic N (WEON & WEIN) under turfgrass systems in North Carolina. They measured the highest WEON and WEIN concentrations during May and the lowest concentrations in September. Further, N potential mineralization rates were highest for soil cores collected in May and lowest for those collected in September. The present study was generally in agreement with these findings in regards to runoff [DON] and [NH_4-N] which were typically lowest during the fall and highest during May.

Aitkenhead-Peterson et al. (2009) measured stream chemistry from a range of land covers in a subtropical savannah in Texas. They reported mean [DON] between 0.62 and 1.90 mg L^{-1}. They further reported that DON:TDN in rural watersheds ranged from 0.63 to 0.81 and in urban watersheds ranged from 0.57 to 0.74, while in streams containing a wastewater treatment plant ranged from 0.13 to 0.24. Pellerin et al. (2006) reported a DON:TDN of 0.35 for urban streams compared to 0.55 for forested and 0.27 from agricultural watersheds. Mean [DON] was 0.18, 0.47, 0.72 mg L^{-1} for forest, urban, and agricultrual watersheds, respectively. In the present study, [DON] was substantially higher although DON:TDN ratios were fairly similar to those reported for natural and urban streams (not containing waste water treatment plants). Total dissolved N exports were much higher from the present turf system than those reported by Groffman et al. (2004), but this appears largely due to differences in reported [TDN] primarily in the form of DON. The implications for these losses also warrant further examination since bulk DON can be fairly variable in its content (Bronk et al., 2007). Recent reports from urban watersheds in Tampa Bay, FL indicate DON plus particulate organic N (PON) represented 63% of total N (Lusk and Toor, 2014). They reported mean [DON] ranging from 0.36 to 0.80 mg L^{-1}. Although PON was affected temporally due to a ‘first flush’ effect, [DON] was fairly stable within their period of study (June to September). They further noted that [DON] was not well correlated to storm properties such as rainfall depth or intensity. In the present study, [DON] similarly did not demonstrate any clear temporal patterns during the summer, but [DON] generally declined during the fall and winter. In contrast to Lusk and Toor, [DON] was well correlated with runoff ratio and rainfall depth. These differences are likely due to differences in scale and season.

Inorganic N exports were within the range previously reported for cool-season turfgrasses in New York (Easton and Petrovic, 2004). Runoff N exports, in terms of retention, were similar to or slightly higher than published reports from bermudagrass [*Cynodon dactylon* L. (Pers.)] fairways in Oklahoma (< 2% of applied N) and creeping bentgrass (*Agrostis palustris* Huds.) fairways in Pennsylvania (~2 % of applied N) (Moss et al., 2005; Linde and Watschke, 1997; Moss et al., 2007). These similarities emphasize the important interactions between runoff chemistry and hydrology. That is, higher rainfall climates can often result in lower nutrient concentration in runoff, but because annual runoff is greater, the mass load over time seems to be fairly constant across regions and grass species.

Conclusions

Mineral N fertilizer applications can have seasonal and annual effects on N exports across each of the major N species. Irrigation management in conjunction with fertilizer applications also enhanced N exports, primarily in the form of NO_3-N. Despite relatively high DIN in runoff from the study site, DON remained the major component of TDN exports during most events. The export of DON through surface runoff has largely been considered unimportant or a sign of a healthy ecosystem. The relative quality of

DON could vary, however, with land cover and management suggesting closer examination of DON components is warranted.

CHAPTER VI

CONCLUSIONS

Despite the negative public perception, St. Augustinegrass tolerated relatively severe water conservation schedules. Under the average year, moderate turfgrass attrition can occur, but seasonal rainfall patterns are often enough to promote full recovery within 4 to 6 weeks during the fall. Furthermore, the drier soil conditions of moderate or severe deficit irrigation incur a positive feedback wherein greater water retention can promote further water conservation. Although the reduction in runoff associated with deficit irrigation reduced N exports, careful fertility management is required to ensure N saturation does not occur under the enhanced N use efficiency expected under conservation irrigation schedules. Inter-annual variability in NO_3-N losses appears to be most important during the winter when colder temperatures incur complete dormancy of the turf canopy. It may be advisable to physically remove dormant turf during the late winter in order to reduce a potential source of N pollution. Dissolved organic N as an export from turf has largely been ignored by previous research. These data suggest DON could be the primary species of N leaving turf sites, and further study on the relative lability and quality of N in runoff is warranted.

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APPENDIX A

GLOSSARY OF TERMS

Turfgrass – typically a plant in the grass family (Gramineae) which can persist under regular mowing (Duble, 2001).

Turf - a covering of mowed vegetation, usually a turfgrass, growing intimately with an upper soil stratum of intermingled roots and stems (Turgeon, 1996).

Turf Quality – an abstract measure of the utility and appearance of a turf which can consider the following traits: plant density, leaf texture, uniformity, color, growth habit, smoothness, and playability (Turgeon, 1996).

Verdure – the amount of aerial shoots remaining after mowing (Turgeon, 1996).

Tiller Density – the number of aerial shoots per unit area (Turgeon, 1996).

Thatch – a layer of undecomposed or partially decomposed organic residues situated above the soil surface and constituting the upper stratum of the medium that supports turfgrass growth (Turgeon, 1996).

Winter Dormancy – the loss of chlorophyll and reduction in growth rate which occurs in warm-season turfgrasses during colder temperatures of winter

Effective Rainfall –rainfall which enters the rootzone and becomes available for uptake by the desirable plant.

Runoff Ratio – the fraction of rainfall which occurs as surface runoff.

Initial Abstraction – the portion of a rainfall event which occurs prior to surface runoff.

Interception – rainfall which adheres to the canopy of plants and often evaporates prior to reaching the soil (Dingman, 2008).

Antecedent Moisture Condition – the soil moisture content of the upper soil immediately prior to a rainfall – runoff event.

Surface Roughness – an empirically derived value which defines to what degree the land will retard runoff down a slope.

APPENDIX B

ANCILLARY MEASUREMENTS

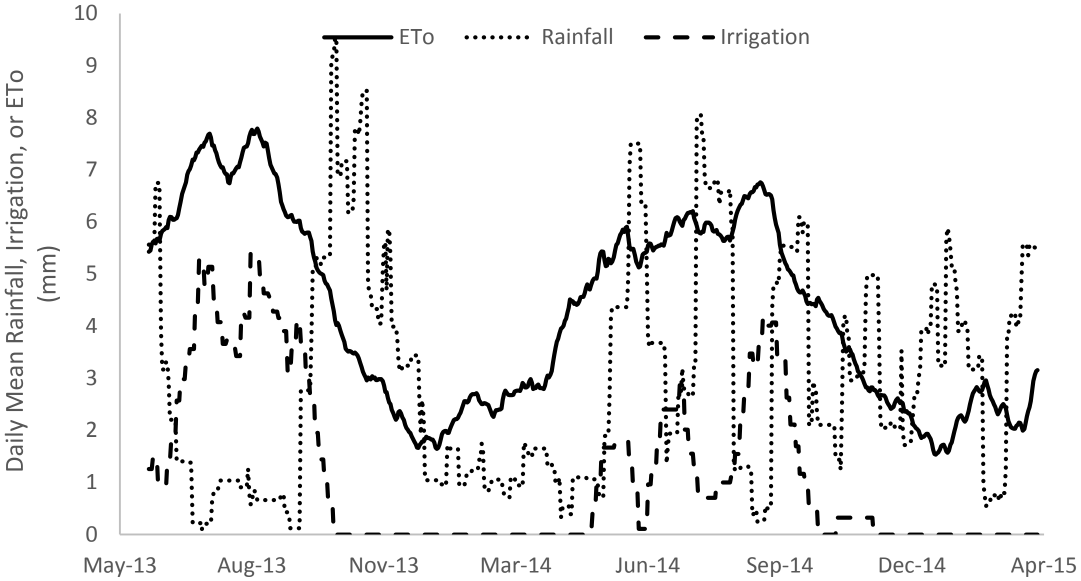

Fig. B.1 Rainfall, irrigation, and ET_o over the study period.

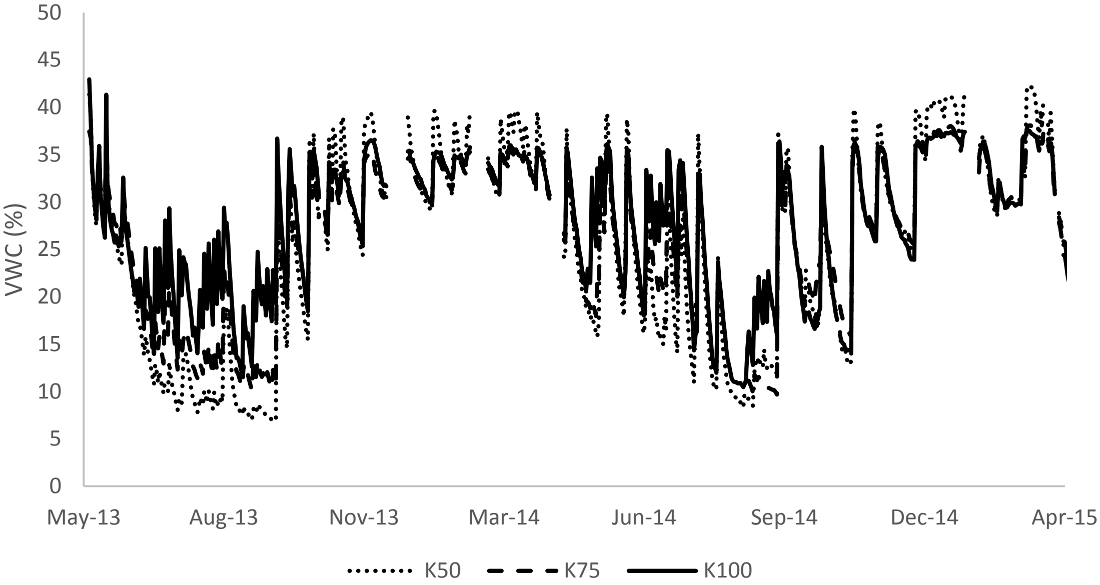

Fig. B.2 Volumetric water content at the 10 cm depth.

APPENDIX C

COMPLETE DATASET – RUNOFF CHEMISTRY

Table C.1. All measured and estimated nutrient concentrations and runoff depths.

Date	**Plot**	**NO_3-N**	**NH_4-N**	**DON**	**TDN**	**Runoff**
		------------------------------mg L^{-1}------------------------------				mm
5/9/2013	**1**	3.12	2.32	9.13	14.57	35.92
	2	2.60	1.24	8.14	11.98	40.34
	3	4.09	1.66	8.66	14.40	34.78
	4	1.27	1.66	10.64	13.57	50.08
	5	0.53	0.28	2.39	3.20	54.19
	6	3.32	1.40	9.03	13.74	45.30
	7	2.56	4.61	9.44	16.61	31.04
	8	0.43	0.39	2.58	3.40	33.88
	9	3.82	8.27	6.07	18.16	69.01
	10	0.97	6.33	8.07	15.38	69.01
	11	1.33	9.16	7.70	18.19	69.01
	12	1.02	9.51	7.37	17.90	69.01
	13	0.77	7.21	5.25	13.23	44.39
	14	0.58	0.49	2.73	3.79	69.01
	15	0.60	7.40	4.63	12.62	69.01
	16	0.52	0.66	2.32	3.50	56.66
	17	0.48	8.14	5.00	13.61	32.82
	18	0.74	6.14	3.11	9.99	43.81
	19	0.42	1.63	8.16	10.21	30.13
	20	0.85	6.22	2.77	9.84	31.17
	21	0.59	0.52	1.95	3.07	31.67
	22	1.12	6.91	4.56	12.58	41.02
	23	0.32	0.52	2.43	3.26	31.85
	24	0.89	3.13	7.96	11.98	30.93
5/10/2013	**1**	1.21	0.80	4.53	6.54	4.84
	2	1.27	0.98	6.17	8.41	4.88
	3	0.75	0.58	6.24	7.57	4.46
	4	0.61	0.80	7.71	9.11	3.99
	5	0.24	0.51	6.19	6.94	7.53
	6	0.84	0.91	5.87	7.62	4.56
	7	0.99	1.54	6.02	8.54	3.31
	8	0.19	1.90	5.37	7.45	3.07
	9	1.07	0.56	5.54	7.17	7.33
	10	0.39	0.62	5.70	6.71	8.14
	11	0.45	0.50	4.93	5.87	6.51
	12	0.35	0.50	5.16	6.00	7.57
	13	0.25	0.51	7.10	7.87	6.22
	14	0.20	0.40	4.16	4.77	9.50
	15	0.26	0.57	5.99	6.82	7.06
	16	0.18	1.90	5.24	7.33	6.83
	17	0.22	0.43	5.18	5.83	6.51
	18	0.24	0.50	5.79	6.53	8.30
	19	0.21	0.51	4.58	5.29	6.49
	20	0.37	0.60	5.16	6.12	6.06
	21	0.17	0.50	4.78	5.46	6.22
	22	0.47	0.67	4.58	5.72	6.30
	23	0.18	2.13	4.51	6.82	4.42
	24	0.34	0.61	3.67	4.62	4.07
5/16/2013	**1**					5.77
	2					5.27
	3					5.06
	4					4.67
	5					6.18
	6					5.19
	7					4.56
	8					4.70
	9					7.32
	10					7.85
	11					7.12
	12					8.62
	13					7.03
	14					10.37
	15					7.23
	16					7.31

Date	Plot	NO_3-N	NH_4-N	DON	TDN	Runoff
		-----------------------------mg L^{-1}-----------------------------				mm
	17					6.88
	18					8.73
	19					6.89
	20					7.04
	21					6.69
	22					7.59
	23					5.37
	24					5.71
5/21/2013	**1**					1.51
	2					1.45
	3					0.40
	4					0.56
	5					0.35
	6					0.45
	7					1.46
	8					1.40
	9					1.89
	10					1.14
	11					0.64
	12					1.48
	13					1.09
	14					1.86
	15					1.72
	16					3.38
	17					2.16
	18					3.12
	19					2.71
	20					1.69
	21					2.06
	22					1.59
	23					0.72
	24					1.16
6/2/2013	**1**	0.94	0.56	2.38	3.88	0.61
	2	1.30	0.58	2.59	4.48	3.77
	3	1.31	0.46	4.31	6.07	1.17
	4	0.57	0.70	2.88	4.15	2.05
	5	0.45	0.76	2.57	3.78	2.19
	6	1.18	1.13	2.81	5.12	1.32
	7	0.76	0.82	3.11	4.70	1.67
	8	0.28	0.57	2.19	3.04	1.93
	9	0.70	1.98	1.63	4.32	6.76
	10	0.36	0.45	1.55	2.36	1.97
	11	0.44	0.49	2.02	2.96	0.46
	12	0.27	0.65	1.50	2.42	2.48
	13	0.24	0.52	2.87	3.64	4.61
	14	0.27	0.85	2.29	3.41	6.85
	15	0.27	0.37	1.86	2.50	5.06
	16	0.26	0.37	1.35	1.99	4.76
	17	0.21	0.44	1.56	2.21	4.14
	18	0.21	0.39	1.92	2.53	7.59
	19	0.21	0.46	1.68	2.34	4.74
	20	0.37	0.69	1.51	2.57	3.71
	21	0.41	0.51	1.86	2.78	3.49
	22	0.40	0.60	2.91	3.91	0.82
	23	0.31	0.92	2.13	3.35	3.22
	24	0.28	2.58	2.94	5.80	1.79
8/13/2013	**1**	2.59	0.27	2.09	4.95	0.10
	2	0.47	0.15	2.11	2.73	3.02
	3	0.97	0.17	2.54	3.69	0.39
	4	0.89	0.23	2.09	3.21	0.81
	5	1.99	0.26	6.04	8.29	3.21
	6	1.48	0.25	5.31	7.05	1.16
	7	1.64	0.32	4.94	6.90	0.74
	8	0.54	0.24	3.22	4.00	0.24
	9	1.90	0.23	6.15	8.28	5.42
	10	0.64	0.30	2.90	3.84	0.71
	11	1.30	0.41	6.29	7.99	0.05
	12	0.74	0.24	5.42	6.40	0.73
	13	0.27	0.19	1.15	1.61	1.51
	14	0.28	0.24	6.31	6.83	16.38
	15	1.01	0.36	7.54	8.90	10.22
	16	0.72	0.26	5.75	6.74	0.40
	17	0.52	0.23	4.32	5.07	3.02

Date	**Plot**	**NO_3-N**	**NH_4-N**	**DON**	**TDN**	**Runoff**
		------------------------------mg L^{-1}------------------------------				mm
	18	0.35	0.20	4.77	5.33	5.84
	19	0.28	0.20	4.26	4.74	2.15
	20	0.65	0.24	4.52	5.41	1.06
	21	0.43	0.24	5.41	6.08	2.48
	22	2.03	0.23	4.26	6.52	0.35
	23	0.71	0.18	2.71	3.60	0.55
	24	0.62	0.34	5.23	6.19	0.43
9/20/2013	**1**	7.35	1.88	7.95	17.18	2.26
	2	1.72	0.48	4.08	6.29	10.66
	3	3.25	0.62	3.86	7.73	3.34
	4	2.67	0.62	4.03	7.32	4.41
	5	2.97	0.95	5.37	9.29	10.15
	6	5.02	1.02	5.85	11.89	8.14
	7	1.51	0.57	2.16	4.24	4.00
	8	0.42	0.65	4.00	5.07	4.93
	9	2.52	0.64	4.84	8.00	19.11
	10	4.34	0.48	4.93	9.75	6.81
	11	4.75	0.58	5.58	10.90	2.82
	12	2.60	0.54	4.81	7.95	5.94
	13	1.83	0.50	4.14	6.48	7.74
	14	0.91	0.93	6.50	8.35	24.26
	15	3.23	0.86	7.05	11.14	19.35
	16	0.26	0.43	3.95	4.64	13.38
	17	0.60	0.40	3.57	4.56	11.28
	18	0.43	0.47	3.29	4.18	20.68
	19	0.31	0.43	2.90	3.65	12.08
	20	2.67	0.68	4.34	7.68	7.84
	21	0.46	0.74	4.17	5.38	15.35
	22	3.51	0.65	5.23	9.39	3.30
	23	0.53	0.54	3.39	4.45	7.17
	24	2.39	0.51	4.06	6.96	11.09
9/29/2013	**1**	0.77	2.82	3.56	7.14	5.15
	2	1.27	0.24	1.41	2.92	6.95
	3	2.17	0.24	2.13	4.54	3.31
	4	1.73	0.40	1.88	4.01	3.59
	5	0.94	0.73	3.41	5.08	6.97
	6	3.27	1.04	2.99	7.30	5.60
	7	1.51	0.54	1.80	3.86	4.54
	8	0.25	0.35	1.76	2.36	3.81
	9	2.41	0.29	3.25	5.95	9.06
	10	2.24	0.23	2.63	5.09	8.42
	11	2.91	0.24	2.98	6.12	7.55
	12	1.42	0.22	2.89	4.53	8.24
	13	1.22	0.32	1.88	3.42	6.39
	14	0.98	0.41	3.59	4.97	17.99
	15	1.90	0.41	2.91	5.22	12.60
	16	0.23	0.31	2.82	3.37	10.86
	17	0.28	0.19	2.42	2.90	10.82
	18	0.38	0.21	2.10	2.70	14.20
	19	0.28	0.21	2.20	2.69	9.51
	20	0.90	0.25	1.96	3.10	6.19
	21	0.35	1.51	2.75	4.60	9.30
	22	0.98	0.29	2.29	3.57	6.93
	23	0.34	0.24	1.74	2.32	5.22
	24	1.97	0.43	2.38	4.79	8.51
10/13/2013	**1**	3.06	1.00	2.73	6.79	23.19
	2	4.45	0.46	1.59	6.50	40.13
	3	4.26	0.52	1.43	6.20	12.53
	4	2.01	1.02	2.50	5.53	14.04
	5	1.72	0.40	1.08	3.20	15.47
	6	5.31	0.75	1.75	7.82	12.67
	7	1.64	0.69	2.31	4.63	16.86
	8	0.55	0.38	1.65	2.58	15.09
	9	3.72	0.55	1.56	5.84	50.69
	10	4.09	0.61	1.65	6.36	35.91
	11	2.43	0.61	1.81	4.85	40.13
	12	2.34	0.58	1.79	4.71	46.47
	13	3.39	0.55	1.81	5.74	35.91
	14	1.68	0.51	1.35	3.54	46.47
	15	2.01	0.49	1.29	3.78	50.69
	16	0.77	0.43	1.60	2.80	35.91
	17	0.75	0.48	1.66	2.88	27.46
	18	0.99	0.32	0.97	2.28	25.35

Date	Plot	NO_3-N	NH_4-N	DON	TDN	Runoff
		------------------------------mg L^{-1}------------------------------				mm
	19	0.56	0.31	0.98	1.86	25.35
	20	2.27	0.38	1.41	4.05	21.12
	21	0.79	0.36	1.40	2.55	16.90
	22	1.97	0.60	1.75	4.32	21.12
	23	0.83	0.42	1.39	2.63	23.23
	24	2.77	0.51	1.09	4.36	23.23
10/27/2013	**1**	5.19	0.63	1.33	7.14	6.71
	2	0.98	0.44	2.86	4.29	6.23
	3	4.36	0.57	1.88	6.81	4.54
	4	2.90	0.55	2.05	5.49	4.14
	5	2.55	0.58	2.43	5.57	6.33
	6	5.60	0.48	1.83	7.92	3.21
	7	2.81	0.63	2.76	6.20	5.09
	8	1.06	0.46	2.45	3.97	4.92
	9	1.26	0.50	3.28	5.04	8.86
	10	3.39	0.55	2.33	6.27	11.95
	11	3.96	0.60	2.40	6.95	10.43
	12	2.71	0.61	2.74	6.05	11.53
	13	2.20	0.53	2.61	5.34	8.41
	14	1.51	0.50	1.91	3.92	13.19
	15	2.38	0.51	1.72	4.61	8.76
	16	0.95	0.46	2.62	4.03	9.82
	17	1.21	0.60	3.19	5.01	10.89
	18	0.46	0.43	2.63	3.53	11.44
	19	1.19	0.51	2.68	4.38	8.98
	20	2.21	0.55	2.69	5.44	8.67
	21	1.21	0.49	2.07	3.76	9.12
	22	2.84	0.63	2.98	6.45	5.16
	23	1.07	0.47	2.04	3.58	7.65
	24	4.78	0.58	2.29	7.66	8.02
10/31/2013	**1**	3.22	0.78	4.10	8.10	4.66
	2	1.77	0.62	3.86	6.25	8.74
	3	2.71	0.70	4.31	7.73	3.23
	4	1.80	0.68	3.75	6.23	4.39
	5	1.51	0.61	2.99	5.11	9.98
	6	2.45	0.63	3.63	6.71	6.61
	7	1.74	0.78	4.51	7.03	3.59
	8	0.66	0.57	3.27	4.50	5.76
	9	2.11	0.65	4.19	6.95	15.67
	10	2.11	0.68	4.32	7.11	8.01
	11	2.46	0.74	4.69	7.89	4.26
	12	1.68	0.75	4.44	6.87	6.91
	13	1.37	0.66	4.03	6.06	7.27
	14	1.17	0.64	4.39	6.20	20.12
	15	0.95	0.95	4.22	6.12	14.49
	16	0.59	0.57	3.41	4.57	11.42
	17	0.75	0.74	4.18	5.68	10.81
	18	0.80	0.59	3.68	5.07	16.63
	19	0.74	0.63	3.60	4.97	10.59
	20	1.37	0.68	4.13	6.18	7.29
	21	0.83	0.53	3.86	5.22	12.22
	22	1.77	0.78	4.78	7.32	3.16
	23	0.67	0.58	2.81	4.07	6.10
	24	1.90	0.57	3.18	5.65	9.97
11/26/2013	**1**	3.03	0.47	3.45	6.95	
	2	1.66	0.37	3.32	5.36	
	3	2.55	0.42	3.65	6.62	
	4	1.69	0.41	3.24	5.34	
	5	0.65	0.20	2.12	2.98	
	6	2.64	0.49	3.52	6.66	
	7	1.64	0.47	3.92	6.03	
	8	0.62	0.34	2.90	3.86	
	9	1.98	0.39	3.59	5.96	
	10	1.98	0.41	3.70	6.10	
	11	2.31	0.45	4.00	6.76	
	12	1.58	0.45	3.85	5.89	
	13	1.29	0.40	3.51	5.20	
	14	1.23	0.39	3.36	4.97	
	15	1.40	0.68	4.70	6.78	
	16	0.55	0.34	3.02	3.92	
	17	0.71	0.45	3.71	4.87	
	18	0.75	0.35	3.24	4.34	
	19	0.70	0.38	3.18	4.26	

Date	Plot	NO_3-N	NH_4-N	DON	TDN	Runoff
		------------------------------mg L^{-1}------------------------------				mm
	20	1.29	0.41	3.59	5.30	
	21	0.70	0.41	3.33	4.44	
	22	1.66	0.47	4.15	6.28	
	23	0.63	0.35	2.51	3.49	
	24	1.54	0.36	2.76	4.66	
12/22/2013	**1**	15.33	0.57	2.87	18.77	9.64
	2	7.89	1.09	2.08	11.06	3.88
	3	18.17	1.67	0.54	20.38	1.15
	4	2.89	1.55	4.13	8.56	2.13
	5	2.30	0.79	3.63	6.72	10.46
	6	6.99	0.79	0.89	8.67	2.42
	7	3.86	0.98	5.66	10.50	0.94
	8	1.56	0.44	3.76	5.76	11.32
	9	10.06	1.20	1.41	12.68	4.38
	10	13.52	1.67	3.69	18.88	11.19
	11	7.58	0.90	3.32	11.80	6.10
	12	7.68	0.54	3.00	11.22	6.94
	13	2.83	1.53	4.09	8.45	4.20
	14	4.02	1.26	4.12	9.40	13.23
	15	3.75	0.78	3.05	7.59	5.08
	16	0.61	1.66	3.64	5.91	3.69
	17	0.92	1.57	5.35	7.84	4.72
	18	2.93	1.14	4.67	8.74	6.63
	19	1.24	1.41	4.19	6.84	3.43
	20	8.91	1.72	5.85	16.48	1.99
	21	1.87	1.16	4.66	7.69	2.70
	22	6.95	0.74	5.98	13.66	0.01
	23	0.99	0.94	3.54	5.47	1.19
	24	3.68	0.84	2.69	7.22	3.47
1/14/2014	**1**	20.11	6.68	0.95	27.74	6.78
	2	7.51	3.82	4.34	15.67	3.64
	3	21.63	5.18	-2.96	23.85	1.08
	4	18.65	5.77	0.91	25.33	7.02
	5	3.42	5.75	2.90	12.07	6.52
	6	10.25	5.31	1.19	16.76	1.54
	7	2.28	7.57	7.09	16.94	1.71
	8	0.65	9.44	3.49	13.59	2.93
	9	16.41	3.02	2.19	21.62	3.68
	10	16.56	4.99	0.98	22.53	6.47
	11	14.77	5.55	-0.78	19.54	3.51
	12	12.07	6.19	1.21	19.48	4.59
	13	13.12	5.34	0.99	19.45	4.52
	14	4.53	5.57	3.51	13.61	7.82
	15	5.26	4.84	3.55	13.65	3.57
	16	1.62	2.05	3.73	7.40	2.66
	17	0.21	7.79	3.66	11.66	3.70
	18	2.11	5.24	3.25	10.60	5.75
	19	1.79	3.27	3.86	8.92	3.00
	20	10.61	5.31	3.36	19.28	1.92
	21	0.73	7.63	1.87	10.23	2.42
	22	11.05	6.28	3.97	21.30	0.00
	23	1.11	4.80	3.84	9.75	1.90
	24	5.40	5.69	2.86	13.95	1.86
3/8/2014	**1**	28.75	1.78	2.15	32.67	10.36
	2	25.14	1.28	2.64	29.06	6.56
	3	28.48	1.10	2.24	31.81	3.02
	4	30.81	0.95	-0.92	30.84	3.57
	5	11.91	1.10	3.82	16.82	9.96
	6	33.87	1.03	-7.18	27.73	3.42
	7	30.39	1.98	1.32	33.69	3.60
	8	13.66	1.48	2.20	17.34	4.74
	9	31.80	1.20	3.57	36.57	5.73
	10	35.54	0.97	3.02	39.53	10.61
	11	31.90	1.13	3.39	36.42	6.58
	12	31.24	1.09	2.39	34.72	7.04
	13	28.24	1.00	2.53	31.76	5.95
	14	17.27	0.89	4.21	22.37	11.12
	15	15.12	0.77	2.37	18.27	5.54
	16	8.15	0.72	3.35	12.21	5.45
	17	18.85	1.18	2.68	22.71	9.74
	18	14.69	1.35	2.61	18.65	10.25
	19	13.21	1.07	3.40	17.68	6.24
	20	28.19	1.66	2.52	32.37	5.26

Date	**Plot**	**NO_3-N**	**NH_4-N**	**DON**	**TDN**	**Runoff**
		------------------------------mg L^{-1}------------------------------				mm
	21	19.60	0.88	4.23	24.71	4.66
	22	19.22	1.44	10.32	30.98	4.56
	23	22.68	1.08	3.28	27.05	3.26
	24	26.90	1.43	2.63	30.95	5.22
5/9/2014	**1**	10.33	1.06	0.58	11.97	8.39
	2	5.47	0.51	0.88	6.86	11.21
	3	6.31	0.53	0.65	7.49	5.28
	4	3.39	0.38	0.85	4.63	5.14
	5	2.14	0.40	1.19	3.73	11.72
	6	3.05	0.43	0.97	4.46	10.83
	7	7.42	0.66	0.59	8.67	5.21
	8	2.70	0.51	1.47	4.68	5.95
	9	6.17	0.38	0.39	6.94	12.05
	10	3.70	0.41	1.04	5.15	7.50
	11	7.48	0.48	0.53	8.49	2.51
	12	5.62	0.49	0.64	6.75	4.97
	13	3.66	0.41	0.82	4.89	5.96
	14	2.80	0.37	1.13	4.30	12.69
	15	2.06	0.58	1.56	4.20	10.18
	16	1.97	0.33	1.65	3.95	8.22
	17	3.06	0.49	1.42	4.98	5.50
	18	2.94	0.36	1.34	4.63	12.26
	19	2.80	0.39	1.23	4.42	7.38
	20	3.57	0.44	1.09	5.10	6.86
	21	1.94	0.43	1.11	3.48	7.05
	22	5.03	0.53	1.02	6.58	5.87
	23	3.81	0.88	1.57	6.25	5.88
	24	3.73	0.57	1.43	5.73	9.00
5/13/2014	**1**	3.70	0.38	1.07	5.15	38.09
	2	2.02	0.27	0.87	3.16	33.17
	3	1.97	0.26	0.70	2.93	27.30
	4	1.36	0.27	0.94	2.57	26.51
	5	0.70	0.31	1.00	2.01	42.03
	6	1.54	0.28	1.01	2.83	29.54
	7	2.00	0.27	0.81	3.08	25.46
	8	1.21	0.28	1.20	2.68	33.64
	9	1.41	0.31	1.37	3.08	31.99
	10	1.60	0.23	1.13	2.97	39.86
	11	2.10	0.27	1.10	3.46	30.79
	12	1.82	0.26	0.73	2.81	34.90
	13	0.97	0.29	1.07	2.33	26.89
	14	0.92	0.26	1.26	2.45	44.38
	15	0.77	0.25	1.15	2.18	29.36
	16	0.75	0.29	1.61	2.65	27.77
	17	0.86	0.30	1.04	2.20	30.10
	18	1.14	0.28	1.20	2.63	35.48
	19	0.70	0.25	1.11	2.05	28.25
	20	1.06	0.23	1.02	2.30	25.28
	21	0.60	0.24	0.81	1.65	23.55
	22	1.57	0.25	0.53	2.36	34.35
	23	0.95	0.29	0.50	1.75	21.61
	24	1.37	0.28	1.42	3.07	26.96
5/27/2014	**1**	8.27	0.90	6.15	15.33	18.93
	2	5.82	0.87	8.57	15.27	13.31
	3	5.80	0.61	7.12	13.53	7.95
	4	4.13	0.68	7.46	12.27	6.89
	5	1.03	0.26	4.74	6.03	14.55
	6	4.42	0.66	7.42	12.50	8.89
	7	5.76	0.91	7.74	14.42	10.94
	8	1.33	0.44	1.74	3.51	15.00
	9	6.80	1.02	7.34	15.16	16.06
	10	5.96	0.77	6.90	13.63	14.83
	11	5.69	0.77	7.55	14.01	11.14
	12	5.74	0.85	9.05	15.63	9.88
	13	3.68	0.74	9.32	13.75	6.29
	14	1.09	0.34	1.30	2.74	17.58
	15	4.39	0.85	7.98	13.22	14.58
	16	0.91	0.25	1.35	2.50	14.44
	17	4.35	0.97	9.32	14.64	21.74
	18	4.24	0.95	8.25	13.44	19.84
	19	3.53	0.96	10.35	14.84	13.44
	20	3.59	0.69	7.35	11.63	10.96
	21	1.06	0.29	1.12	2.47	10.39

Date	Plot	NO_3-N	NH_4-N	DON	TDN	Runoff
		------------------------------mg L^{-1}------------------------------				mm
	22	4.55	0.67	7.63	12.86	16.97
	23	1.57	0.33	1.04	2.94	12.86
	24	6.67	1.08	6.35	14.10	12.56
5/28/2014	**1**	1.81	0.30	2.51	4.62	11.22
	2	1.05	0.23	2.40	3.69	8.55
	3	1.38	0.22	2.25	3.85	8.27
	4	1.10	0.24	2.73	4.08	8.23
	5	0.31	0.19	0.89	1.39	11.26
	6	1.10	0.20	2.32	3.62	8.84
	7	1.52	0.27	2.38	4.17	8.68
	8	0.39	0.25	1.28	1.91	9.92
	9	1.41	0.24	2.56	4.22	9.51
	10	1.12	0.51	3.08	4.70	12.29
	11	1.26	0.28	3.02	4.56	10.58
	12	1.14	0.28	2.88	4.30	10.72
	13	0.92	0.23	2.83	3.98	7.08
	14	0.41	0.21	0.75	1.37	12.27
	15	1.09	0.26	2.50	3.85	9.83
	16	0.30	0.20	1.10	1.60	9.71
	17	1.06	0.30	3.01	4.37	10.13
	18	1.26	0.26	2.71	4.23	11.25
	19	0.89	0.25	2.67	3.81	9.06
	20	0.98	0.23	2.35	3.57	8.98
	21	0.39	0.19	0.74	1.33	7.53
	22	1.20	0.28	2.61	4.09	11.66
	23	0.46	0.28	0.73	1.47	8.88
	24	1.50	0.27	2.71	4.48	8.73
6/23/2014	**1**					0.53
	2					1.42
	3					0.00
	4					0.00
	5					0.00
	6					0.00
	7					0.02
	8					0.00
	9					0.14
	10					0.23
	11					0.02
	12					0.00
	13					0.03
	14					0.00
	15					0.17
	16					0.14
	17					0.02
	18					0.06
	19					0.27
	20					0.52
	21					0.16
	22					0.05
	23					0.62
	24					0.05
6/25/2014	**1**	1.21	0.43	3.60	5.24	0.23
	2	0.58	0.32	2.97	3.87	0.07
	3	1.02	0.39	3.59	5.00	0.00
	4	0.36	0.60	1.97	2.92	0.01
	5	0.37	0.27	4.59	5.24	0.01
	6	0.63	0.41	5.36	6.40	0.00
	7	0.66	0.43	3.46	4.55	0.10
	8	0.25	0.32	2.35	2.91	0.00
	9	1.02	0.35	1.74	3.11	0.78
	10	0.79	0.38	3.43	4.60	0.02
	11	0.92	0.41	3.77	5.10	0.06
	12	0.63	0.42	3.39	4.44	0.27
	13	1.86	0.26	0.97	3.09	2.68
	14	0.32	0.29	4.50	5.12	6.22
	15	0.38	0.40	4.70	5.48	0.68
	16	0.22	0.32	2.42	2.96	0.57
	17	0.28	0.41	2.98	3.67	1.72
	18	0.23	0.31	4.11	4.65	0.59
	19	0.43	0.37	1.67	2.47	1.40
	20	0.52	0.38	3.10	4.00	1.18
	21	0.25	0.32	4.45	5.01	0.08
	22	0.66	0.43	3.64	4.74	2.53

Date	Plot	NO_3-N	NH_4-N	DON	TDN	Runoff
		-----------------------------mg L^{-1}-----------------------------				mm
	23	0.25	0.33	2.05	2.63	0.74
	24	0.33	0.44	4.56	5.33	0.87
6/26/2014	**1**					0.09
	2					0.29
	3					0.00
	4					0.01
	5					0.00
	6					0.00
	7					0.02
	8					0.00
	9					0.29
	10					0.41
	11					0.01
	12					0.00
	13					0.14
	14					0.52
	15					1.67
	16					0.00
	17					0.22
	18					0.18
	19					0.51
	20					1.04
	21					0.24
	22					0.00
	23					1.81
	24					0.07
7/5/2014	**1**	1.94	3.75	6.41	12.10	0.00
	2	0.45	1.58	4.27	6.30	0.00
	3	1.63	3.38	6.52	11.53	0.00
	4	1.09	3.25	4.96	9.30	0.00
	5	0.68	2.75	4.12	7.55	0.00
	6	2.77	6.25	9.66	18.67	0.00
	7	1.05	3.74	5.71	10.50	0.00
	8	0.40	2.75	3.58	6.72	0.00
	9	0.58	1.75	4.90	7.22	0.15
	10	1.27	3.26	6.09	10.62	0.00
	11	1.48	3.55	6.74	11.77	0.00
	12	1.01	3.61	5.63	10.26	0.00
	13	0.82	3.17	5.05	9.05	0.00
	14	0.58	2.74	3.94	7.26	0.00
	15	1.65	5.88	8.42	15.94	0.12
	16	0.36	2.72	3.74	6.82	0.00
	17	0.45	3.58	4.45	8.48	0.04
	18	0.21	1.55	3.81	5.57	0.02
	19	0.45	3.03	3.94	7.42	0.07
	20	0.83	3.26	5.13	9.22	0.25
	21	0.46	2.90	3.64	7.00	0.00
	22	1.06	3.74	6.12	10.93	0.02
	23	0.40	2.81	2.86	6.07	0.22
	24	1.46	6.68	7.40	15.54	0.00
7/7/2014	**1**	2.82	3.56	16.70	23.08	0.04
	2	1.55	2.81	13.43	17.79	0.02
	3	2.38	3.21	16.41	22.00	0.00
	4	1.58	3.09	13.07	17.74	0.00
	5	3.00	0.36	3.34	6.70	0.03
	6	2.13	3.33	16.28	21.74	0.00
	7	1.53	3.55	14.95	20.03	0.01
	8	0.21	18.14	8.76	27.11	0.12
	9	1.85	2.98	14.98	19.81	0.12
	10	1.85	3.09	15.32	20.26	0.11
	11	2.15	3.38	16.93	22.46	0.00
	12	1.47	3.43	14.66	19.57	0.00
	13	1.20	3.02	13.05	17.26	0.02
	14	2.56	0.37	3.60	6.53	0.03
	15	1.26	3.08	14.53	18.87	0.56
	16	0.22	17.45	9.49	27.16	0.00
	17	0.66	3.40	12.12	16.18	0.02
	18	0.70	2.68	11.06	14.43	0.00
	19	0.65	2.88	10.62	14.15	0.19
	20	1.20	3.10	13.29	17.60	0.52
	21	2.10	0.40	3.70	6.20	0.00
	22	1.55	3.56	15.74	20.85	0.06
	23	0.20	19.41	5.48	25.08	0.82

Date	Plot	NO_3-N	NH_4-N	DON	TDN	Runoff
		------------------------------mg L^{-1}------------------------------				mm
	24	1.14	3.28	13.16	17.58	0.00
7/18/2014	**1**	1.20	0.37	1.00	2.57	79.62
	2	0.53	0.42	2.19	3.14	109.55
	3	0.84	0.44	2.68	3.96	77.87
	4	0.57	0.39	2.94	3.90	109.55
	5	0.44	0.32	1.76	2.52	109.55
	6	0.73	0.40	3.55	4.68	109.55
	7	0.49	0.33	2.82	3.64	109.55
	8	0.36	0.33	2.96	3.65	107.52
	9	0.64	0.30	2.72	3.66	109.55
	10	0.60	0.34	1.89	2.83	109.55
	11	1.01	0.41	1.72	3.14	109.55
	12	0.70	0.35	2.09	3.14	55.14
	13	0.38	0.27	2.55	3.20	109.55
	14	0.34	0.25	1.64	2.23	109.55
	15	0.47	0.32	3.06	3.84	109.55
	16	0.48	0.29	2.25	3.02	109.55
	17	0.52	0.31	1.93	2.76	109.55
	18	0.43	0.25	1.42	2.10	109.55
	19	0.48	0.32	2.01	2.81	107.01
	20	0.46	0.36	3.53	4.35	109.55
	21	0.31	0.27	1.22	1.80	68.82
	22	0.44	0.30	2.37	3.11	90.54
	23	0.34	0.27	1.47	2.08	58.71
	24	0.43	0.30	2.77	3.50	56.73
9/15/2014	**1**	0.93	0.92	1.69	3.54	27.24
	2	0.31	0.44	1.16	1.91	27.76
	3	0.47	0.49	1.23	2.19	13.65
	4	0.46	0.57	1.31	2.34	23.80
	5	0.29	0.51	1.46	2.26	61.44
	6	0.62	0.63	2.26	3.51	48.34
	7	0.65	1.43	2.66	4.74	27.39
	8	0.25	0.56	1.44	2.25	31.75
	9	0.44	0.54	1.51	2.49	42.03
	10	0.62	0.53	1.62	2.77	29.86
	11	1.48	0.61	1.88	3.97	26.15
	12	1.05	0.62	1.57	3.24	32.15
	13	0.30	0.46	1.14	1.90	29.03
	14	0.29	0.67	1.83	2.79	44.28
	15	0.43	0.53	1.79	2.75	39.58
	16	0.42	0.50	1.83	2.75	46.94
	17	0.60	0.49	1.64	2.73	40.15
	18	0.33	0.49	1.65	2.47	49.50
	19	0.36	0.51	1.49	2.36	39.04
	20	0.32	0.34	1.28	1.94	30.66
	21	0.26	0.45	1.33	2.04	30.75
	22	0.46	0.57	1.61	2.64	44.30
	23	0.26	0.38	0.92	1.56	20.99
	24	0.29	0.33	0.93	1.55	32.39
9/19/2014	**1**					0.00
	2					0.00
	3					0.00
	4					0.00
	5					0.04
	6					0.07
	7					0.15
	8					0.03
	9					0.05
	10					0.04
	11					0.05
	12					0.00
	13					0.00
	14					0.06
	15					0.14
	16					0.02
	17					0.01
	18					0.06
	19					0.04
	20					0.00
	21					0.04
	22					0.20
	23					0.00
	24					0.00

Date	Plot	NO_3-N	NH_4-N	DON	TDN	Runoff
		-----------------------------mg L^{-1}-----------------------------				mm
10/2/2014	**1**					0.45
	2					0.16
	3					0.13
	4					0.06
	5					0.29
	6					0.15
	7					0.28
	8					0.22
	9					0.22
	10					0.16
	11					0.20
	12					0.11
	13					0.24
	14					0.13
	15					0.38
	16					0.27
	17					0.27
	18					0.32
	19					0.27
	20					0.19
	21					0.16
	22					0.40
	23					0.17
	24					0.18
10/11/2014	**1**					0.00
	2					0.00
	3					0.00
	4					0.00
	5					0.05
	6					0.04
	7					0.03
	8					0.01
	9					0.00
	10					0.00
	11					0.00
	12					0.00
	13					0.00
	14					0.00
	15					0.04
	16					0.00
	17					0.00
	18					0.00
	19					0.01
	20					0.00
	21					0.00
	22					0.02
	23					0.00
	24					0.00
10/13/2014	**1**	1.88	0.52	3.29	5.69	1.04
	2	0.51	0.26	1.78	2.55	0.36
	3	1.80	0.60	3.80	6.20	0.21
	4	0.83	0.57	2.93	4.34	0.29
	5	0.76	0.48	3.42	4.66	0.77
	6	1.48	0.42	3.38	5.27	0.33
	7	1.05	0.42	2.90	4.37	0.77
	8	0.33	0.28	2.54	3.14	0.42
	9	0.65	0.29	1.99	2.92	1.15
	10	1.70	0.59	3.68	5.97	0.82
	11	1.44	0.49	3.61	5.54	0.38
	12	1.05	0.39	2.84	4.28	0.37
	13	0.57	0.56	2.81	3.94	0.56
	14	0.52	0.48	3.04	4.04	0.40
	15	0.92	0.39	3.16	4.47	1.74
	16	0.36	0.27	2.62	3.25	3.42
	17	0.54	0.38	2.56	3.48	1.18
	18	0.31	0.26	1.61	2.18	1.21
	19	0.35	0.52	2.59	3.46	0.52
	20	0.88	0.61	3.52	5.01	0.43
	21	0.66	0.56	3.83	5.05	0.44
	22	1.03	0.52	3.59	5.14	1.04
	23	0.31	0.30	2.30	2.91	0.50
	24	0.78	0.44	3.16	4.39	0.53
11/6/2014	**1**	2.20	0.35	3.90	6.44	0.00

Date	Plot	NO_3-N	NH_4-N	DON	TDN	Runoff
		------------------------------mg L^{-1}------------------------------				mm
	2	0.88	0.21	2.95	4.05	0.08
	3	1.68	0.33	4.18	6.18	0.00
	4	0.41	0.25	3.23	3.89	0.00
	5	0.38	0.31	3.26	3.95	0.24
	6	1.68	0.33	5.16	7.17	3.08
	7	0.46	0.19	3.45	4.10	0.32
	8	0.18	0.25	3.23	3.66	0.06
	9	0.90	0.22	3.83	4.95	1.58
	10	1.88	0.26	3.84	5.98	0.87
	11	3.45	0.28	3.94	7.67	0.98
	12	0.46	0.18	3.38	4.02	0.41
	13	0.30	0.28	2.79	3.37	0.76
	14	0.27	0.32	3.27	3.86	2.09
	15	0.98	0.23	3.04	4.25	1.12
	16	0.17	0.24	3.11	3.52	3.08
	17	0.21	0.19	2.90	3.30	4.27
	18	0.51	0.22	2.41	3.14	1.83
	19	0.18	0.18	3.08	3.44	0.45
	20	0.56	0.43	3.80	4.79	0.23
	21	0.30	0.36	3.06	3.72	0.51
	22	0.55	0.36	3.39	4.30	1.32
	23	0.17	0.27	2.95	3.39	0.00
	24	0.87	0.31	3.79	4.96	0.02
11/23/2014	**1**	4.46	0.79	4.39	9.64	
	2	1.05	0.74	2.58	4.37	
	3	2.12	0.49	2.86	5.47	
	4	1.52	0.72	2.56	4.80	
	5	0.94	0.41	2.90	4.25	
	6	1.72	0.56	3.17	5.45	
	7	0.81	0.60	3.29	4.70	
	8	0.42	0.50	3.54	4.46	
	9	0.98	0.70	3.22	4.90	
	10	1.82	0.55	3.09	5.46	
	11	2.45	0.51	3.04	6.00	
	12	1.66	0.82	3.35	5.83	
	13	0.95	0.45	2.96	4.36	
	14	0.72	0.62	2.86	4.20	
	15	0.91	0.42	2.36	3.69	
	16	0.41	0.48	2.27	3.16	
	17	0.43	0.91	2.68	4.02	
	18	0.46	0.46	2.65	3.57	
	19	0.48	0.44	2.95	3.87	
	20	0.89	0.45	2.74	4.08	
	21	0.51	0.42	2.29	3.22	
	22	1.30	0.54	2.89	4.73	
	23	0.64	0.52	2.80	3.96	
	24	0.79	0.64	2.91	4.34	
12/19/2014	**1**	6.46	0.33	2.42	9.21	13.58
	2	0.99	0.25	2.53	3.77	31.69
	3	3.88	0.37	2.19	6.44	20.99
	4	1.58	0.35	2.78	4.70	29.22
	5	2.38	0.28	1.99	4.65	34.57
	6	2.72	0.27	2.33	5.32	10.70
	7	1.57	0.30	3.74	5.62	12.35
	8	0.38	0.65	3.51	4.54	26.75
	9	2.13	0.20	2.17	4.50	10.70
	10	3.10	0.38	2.37	5.85	5.76
	11	3.14	0.28	2.05	5.47	7.41
	12	2.18	0.24	2.75	5.17	8.23
	13	1.81	0.30	2.30	4.41	9.46
	14	1.52	0.40	2.29	4.21	0.00
	15	1.50	0.28	2.22	4.00	7.82
	16	0.21	0.29	2.13	2.63	27.57
	17	0.73	0.29	3.56	4.58	6.58
	18	0.26	0.33	2.42	3.01	16.46
	19	0.44	0.34	3.09	3.87	18.11
	20	1.72	0.38	3.19	5.29	12.76
	21	0.91	0.49	2.62	4.02	31.69
	22	2.04	0.44	2.77	5.25	4.94
	23	0.70	1.49	4.84	7.03	25.10
	24	1.22	0.47	3.83	5.52	4.94
12/31/2014	**1**	1.28	0.63	5.03	6.94	0.00
	2	0.41	0.26	3.99	4.66	0.00

Date	**Plot**	**NO_3-N**	**NH_4-N**	**DON**	**TDN**	**Runoff**
		------------------------------mg L^{-1}	------------------------------			mm
	3	1.19	0.52	5.42	7.13	0.00
	4	0.52	0.72	5.17	6.42	0.00
	5	0.32	0.90	6.02	7.24	0.00
	6	0.71	0.78	6.38	7.87	0.00
	7	0.28	2.76	7.21	10.25	0.00
	8	0.31	0.43	3.89	4.63	0.00
	9	0.42	0.15	5.25	5.82	0.56
	10	0.92	0.54	5.30	6.76	0.30
	11	0.88	0.56	4.83	6.27	0.13
	12	0.44	0.90	5.00	6.34	0.28
	13	0.40	0.71	5.15	6.25	0.19
	14	0.30	1.03	6.09	7.42	0.73
	15	0.42	0.72	5.69	6.84	1.33
	16	0.30	0.41	3.90	4.61	0.45
	17	0.10	7.72	6.09	13.91	0.07
	18	0.23	0.50	2.99	3.72	0.64
	19	0.22	0.68	4.23	5.12	0.23
	20	0.58	0.53	4.65	5.76	0.52
	21	0.21	1.04	5.67	6.92	0.21
	22	0.72	0.62	4.87	6.22	1.58
	23	0.41	0.51	3.80	4.72	0.51
	24	0.38	0.77	5.22	6.37	0.24
1/1/2015	**1**					0.00
	2					0.00
	3					0.00
	4					0.00
	5					0.59
	6					0.03
	7					0.00
	8					0.02
	9					15.92
	10					14.16
	11					13.20
	12					15.92
	13					10.70
	14					15.92
	15					15.92
	16					15.92
	17					1.92
	18					13.55
	19					3.13
	20					10.65
	21					6.12
	22					15.92
	23					8.40
	24					5.35
1/3/2015	**1**	1.39	0.24	1.63	3.26	9.74
	2	0.68	0.22	1.37	2.27	10.41
	3	1.19	0.22	2.16	3.57	0.10
	4	0.70	0.30	1.23	2.23	8.63
	5	0.44	0.17	1.31	1.92	12.50
	6	0.54	0.20	1.40	2.14	11.32
	7	0.40	0.25	1.51	2.16	8.33
	8	0.21	0.21	2.14	2.56	13.41
	9	0.78	0.38	2.88	4.04	22.01
	10	0.94	0.27	2.66	3.87	22.88
	11	0.80	0.22	1.83	2.85	24.23
	12	0.69	0.22	1.78	2.69	25.26
	13	0.54	0.20	1.75	2.49	19.76
	14	0.63	0.40	2.35	3.38	25.60
	15	0.69	0.20	2.19	3.08	25.32
	16	0.23	0.22	2.32	2.77	25.73
	17	0.34	0.29	2.04	2.67	16.79
	18	0.29	0.20	2.16	2.65	23.86
	19	0.34	0.17	1.92	2.43	17.65
	20	0.50	0.19	1.75	2.44	21.31
	21	0.34	0.23	2.07	2.64	18.03
	22	0.79	0.20	2.30	3.29	27.51
	23	0.29	0.20	1.90	2.39	18.09
	24	0.41	0.22	1.69	2.32	20.66
1/12/2015	**1**	0.27	2.42	1.24	3.93	10.67
	2	0.23	1.44	1.02	2.69	10.74
	3	0.40	1.19	1.97	3.56	0.00

Date	Plot	NO_3-N	NH_4-N	DON	TDN	Runoff
		-----------------------------mg L^{-1}-----------------------------				mm
	4	0.24	1.84	0.94	3.02	9.79
	5	0.20	1.07	1.06	2.33	14.62
	6	0.19	1.35	1.13	2.67	11.60
	7	0.19	0.96	1.24	2.39	9.13
	8	0.20	0.42	1.64	2.26	15.35
	9	0.25	1.25	1.65	3.15	24.66
	10	0.23	1.53	1.59	3.35	28.56
	11	0.23	1.65	1.41	3.29	25.36
	12	0.23	1.37	1.53	3.13	27.77
	13	0.21	1.22	1.52	2.95	20.38
	14	0.23	0.93	1.51	2.67	23.45
	15	0.21	1.25	1.61	3.07	28.47
	16	0.19	0.60	1.55	2.34	30.17
	17	0.18	0.63	1.23	2.04	18.99
	18	0.19	0.57	1.49	2.25	26.86
	19	0.20	0.60	1.50	2.30	20.63
	20	0.22	0.97	1.56	2.75	23.44
	21	0.20	0.62	1.61	2.43	20.52
	22	0.31	1.12	1.90	3.33	30.28
	23	0.21	0.60	1.40	2.21	18.93
	24	0.13	1.43	1.01	2.58	23.55
1/23/2015	**1**	3.25	0.23	0.81	4.29	11.13
	2	2.14	0.25	0.94	3.33	11.61
	3	4.07	0.22	0.62	4.91	48.34
	4	2.27	0.26	0.90	3.43	9.06
	5	1.77	0.21	1.04	3.02	14.91
	6	2.57	0.21	0.96	3.74	11.27
	7	1.44	0.23	1.24	2.91	9.83
	8	0.54	0.21	1.81	2.56	17.70
	9	1.51	0.29	1.91	3.71	32.78
	10	1.72	0.26	1.79	3.77	36.41
	11	1.80	0.23	1.32	3.35	33.13
	12	1.82	0.39	1.70	3.91	38.71
	13	1.47	0.25	1.65	3.37	26.88
	14	1.11	0.25	1.99	3.35	30.03
	15	1.59	0.22	1.33	3.14	40.37
	16	0.74	0.20	1.43	2.37	39.21
	17	0.86	0.30	1.66	2.82	24.30
	18	0.73	0.23	1.82	2.78	34.85
	19	0.74	0.21	1.97	2.92	26.17
	20	1.34	0.26	1.65	3.25	30.20
	21	0.72	0.24	1.65	2.61	26.36
	22	1.34	0.25	1.80	3.39	42.15
	23	0.69	0.24	1.71	2.64	25.54
	24	1.08	0.23	1.74	3.05	27.02
3/11/2015	**1**	0.87	0.15	1.56	2.58	19.40
	2	0.39	0.11	1.10	1.60	20.28
	3	0.58	0.14	1.09	1.81	56.74
	4	0.55	0.10	0.81	1.46	16.13
	5	0.38	0.07	1.14	1.59	26.84
	6	0.44	0.04	1.14	1.62	19.71
	7	0.21	0.05	1.18	1.44	16.40
	8	0.13	0.10	1.58	1.81	29.51
	9	0.50	0.15	1.90	2.55	57.59
	10	0.57	0.22	2.11	2.90	61.33
	11	0.53	0.11	1.73	2.37	58.88
	12	0.48	0.14	1.90	2.52	68.08
	13	0.51	0.25	1.02	1.78	48.67
	14	0.38	0.15	1.95	2.48	54.06
	15	0.52	0.10	1.42	2.04	61.47
	16	0.19	0.14	1.53	1.86	65.06
	17	0.25	0.17	1.74	2.16	82.91
	18	0.28	0.12	1.73	2.13	62.90
	19	0.26	0.24	1.74	2.24	44.45
	20	0.43	0.20	1.74	2.37	51.56
	21	0.25	0.14	2.01	2.40	46.14
	22	0.48	0.24	2.30	3.02	77.08
	23	0.23	0.16	1.27	1.66	52.38
	24	0.28	0.14	1.81	2.23	55.27
3/22/2015	**1**	0.84	0.56	3.22	4.62	0.21
	2	0.45	0.69	2.87	4.01	0.48
	3	1.17	0.86	2.76	4.79	0.76
	4	1.50	0.83	2.15	4.48	0.83

Date	Plot	NO_3-N	NH_4-N	DON	TDN	Runoff
		------------------------------mg L^{-1}------------------------------				mm
	5	0.75	0.47	1.84	3.06	2.11
	6	0.97	0.36	2.82	4.15	1.08
	7	0.63	1.23	2.23	4.09	0.40
	8	0.23	1.98	2.85	5.06	1.03
	9	0.47	0.94	3.22	4.63	11.62
	10	0.63	0.64	2.77	4.04	13.33
	11	0.69	0.31	2.81	3.81	10.36
	12	0.45	0.58	2.57	3.60	13.30
	13	0.41	2.15	2.27	4.83	8.64
	14	0.64	0.88	2.36	3.88	11.36
	15	0.68	0.35	2.41	3.44	14.31
	16	0.21	0.79	2.35	3.35	16.02
	17	0.20	0.97	2.62	3.79	20.04
	18	0.28	0.57	2.62	3.47	12.89
	19	0.43	1.61	2.59	4.63	6.87
	20	0.85	1.25	2.43	4.53	10.43
	21	0.16	14.69	3.30	18.15	7.79
	22	0.43	0.91	3.51	4.85	17.48
	23	0.36	1.81	2.57	4.74	10.71
	24	0.21	8.35	1.55	10.11	11.12