5-2009

ROOT-ZONE CHARACTERISTICS AND BERMUDAGRASS RESPONSE TO SALINE WATER DELIVERED BY SUBSURFACE DRIP IRRIGATION

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ROOT-ZONE CHARACTERISTICS AND BERMUDAGRASS RESPONSE TO SALINE WATER DELIVERED BY SUBSURFACE DRIP IRRIGATION

A Thesis
Presented to
the Graduate School of
Clemson University

In Partial Fulfillment
of the Requirements for the Degree
Master of Plant and Environmental Science

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by
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May 2009

Accepted by:
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ABSTRACT

Population growth and recurring drought conditions have placed high demands on freshwater resources in South Carolina. Thus, turfgrass irrigation management practices that reduce freshwater use while maintaining quality turfgrass need to be identified. Previous research in the arid Southwest USA documents water conservation on bermudagrass by using saline water sources and subsurface drip irrigation (SDI) systems. A field-scale facility was constructed in Florence, SC, to evaluate 'Tifway' bermudagrass (*Cynodon dactylon* (L.) Pers. X C. *transvaalensis* Burtt Davy) quality, growth, and root-zone characteristics when subjected to saline (3.15 dS m^{-1}) or freshwater (0.07 dS m^{-1}) irrigation, SDI lines spaced 41 or 81 cm, and irrigated to replace 65 or 100% ETp. For eight-week periods during the summer months of 2007 and 2008, weekly quality was monitored visually and by documenting the spectral reflectance of a near-infrared and a red wavelength. Growth was assessed by clipping yields, stolon counts, and root mass determinations. Soil electrical conductivity (ECe) was assessed for three soil depths at pre, mid, and post experiment each year. Turfgrass average quality scores were acceptable each year even though the 2007 experiment encompassed an extreme drought period. Observed wilt during the 2007 experiment suggests that additional saline water, or cycling with freshwater may be necessary during extreme drought periods. Post experiment shoot density and root mass as well as mid and post experiment ECe were greater from saline irrigated bermudagrass than freshwater irrigated bermudagrass in 2007. There was minimal influence from factor treatments, and only for post-experiment

measurements in 2008. These results suggest that saline water can be applied at reduced volumes through a SDI system during periods of high freshwater demand to maintain quality bermudagrass.

This experiment also evaluated the relationship between the qualitative (visual) and quantitative (spectral reflectance) assessment of quality and the relationship of spectral reflectance to primary stress factors (soil moisture and soil salinity). The two forms of quality assessment were positively correlated for both experiments. Spectral reflectance was not as consistently correlated with soil moisture during the 2007 experiment as compared to 2008. However, spectral reflectance was positively correlated with ECe during the 2007 experiment in which drought persisted, but not in the 2008 experiment. Monitoring spectral reflectance allows for assessment of turf response to primary stress variables.

ACKNOWLEDGEMENTS

Special appreciation and gratitude is extended to my major advisor, Dr. Dara M. Park and committee members: Dr. Lambert B. McCarty, Dr. Haibo Liu, Dr. Joe E. Toler, and Dr. Kenneth C. Stone for their teaching and counsel in course work and expertise in conducting this research project. I also would like to thank staff and student interns of Clemson University's Pee Dee Research & Education Center in Florence, SC. Special appreciation is further extended to staff of USDA – Coastal Plains Research Center, Florence, SC; Revels Turf and Tractor, Myrtle Beach, SC; Harrells, and the SC Turfgrass Association for their support in executing this research project.

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CHAPTER ONE

Literature Review

Introduction

In 2003, approximately 153 million people (representing 53 percent of the nation's population) lived in the 673 U.S. coastal counties with a projected increase by 7 million by the year 2008 (Crossett et al., 2006). The desire to live in coastal areas has resulted in urban development around fragile coastal ecosystems. The primary concerns are that population growth in these areas has put a strain on potable freshwater sources (Thomas et al., 2006). One way to reduce freshwater for non-essential uses is by using poorer quality sources (Dean-Knox et al., 1998).

The golf course industry has a strong presence in the state of South Carolina. *Golf Digest* ranks South Carolina among the nation's top five golf states (Flowers, 2006). South Carolina has over 375 golf courses statewide, with the majority located within the coastal areas (Flowers, 2006). These populated areas account for 18% of the state's population (U.S. Census Bureau, 2006) and is projected to average an increase of 10 to 12% by 2008 (Crossett et al., 2006). Additionally, 88% of out-of-state golfers spend vacations in the coastal areas of Myrtle Beach, Charleston, and Hilton Head Island (Flowers, 2006). In 2005, water capacity use for golf course irrigation from the four coastal-bound, South Carolina counties (Horry, Georgetown, Charleston, and Beaufort) totaled 7.6 million gallons alone from ground and surface water sources (Childress and Butler, 2006). Golf courses in these areas represent 76% of reported potable or ground water use in South Carolina (Childress and Butler, 2006). Recognizing the need to conserve potable water for human consumption, especially in high density areas such as along the coast, golf courses have begun using alternative methods for golf course irrigation. Methods include monitoring capacity usage, altering management practices to efficiently use water, developing and utilizing more stress (salt and drought) tolerant grasses, improving irrigation systems, and using lower quality water sources (Watson and Carrow, 1994). Of these methods, the last two are most promising for reducing potable water use for irrigation of turfgrass areas. Turfgrass managers in the future may need to install irrigation systems that are more water use efficient (increased irrigation uniformity) than current irrigation systems. An example is using point emitters in subsurface irrigation which flow directly to the root-zone, thus eliminating surface runoff (Suarez-Rey et al., 2000). Also by identifying alternative water sources for irrigation, the use of potable water can be considerably reduced. Currently, turfgrass managers of golf courses located in coastal areas are interested in using brackish or saline water sources for irrigation (Marcum, 2004). The National Golf Foundation reports approximately 13% of golf courses nationwide and 34% in the Southwest alone currently use effluent water as an irrigation source (Huck et al., 2000).

Saline Water Sources for the Irrigation of Turfgrass

Examples of saline water sources include seawater, reclaimed water (sewage effluent), brackish surface and groundwater caused by either salt leaching or salt water intrusion and/or other sources (Marcum, 2004). These sources can be further classified based on electrical conductivity, total dissolved solids, residual sodium carbonate and sodium absorption ratio (Mitra, 2000). Saline water is a good conductor of electricity and is typically measured by either its electrical conductivity (EC), which measures ion concentration in decisiemens per meter (dS m^{-1}) or total dissolved solids (or salts), which is reported in parts per million (McCarty et al., 2003). The U.S. Geological Survey classifies saline water having TDS between 1,000 and 35,000 ppm.

Past research on the successful use of waters containing high levels of soluble salts for irrigation of crops during the last 50 years in the USA (Rhoades, 1983; Pasternak et al., 1986; Gratten et al., 1987; Broadbent et al., 1988; Rhoades et al., 1989) suggest it to be considered as a supplemental source of irrigation for turfgrass, especially at high salinity levels (Dean et al., 1996; Dean-Knox, 1998). One study compared canola (*Brassica napus* cv. Cyclone), field pea (*Pisum sativum* cv. green seed Radley and cv. yellow-seed Carneval), and Othello pinto dry bean (*Phaseolus vulgari*s cv. Othello), to durum wheat (*Triticum turgidum* cv. Kyle) that was germinated in a saline media (Steppuhn et al., 2001). The results indicated that durum wheat survived moderate (11.2 dS m^{-1}) and severe (24.9 dS m^{-1}) salinity better than the other crops. Other salinity-tolerance studies document satisfactory yields from *Portulaca oleraciea* L. (a halophyte), wheat, and nine leafy vegetable crops when irrigated with saline water (Grieve and Suarez, 1997; Grieve et al., 1999 and 2001; Steppuhn et al., 2005).

Research documenting the potential of irrigating turfgrasses with water high in soluble salts has primarily been conducted in the arid and semiarid regions of the United States, where irrigation water availability and water conservation are major concerns for the turfgrass industry (Shearman, 2006). In this region, water pricing has been an effective strategy and conservation tool (Leskys et al., 1999), yet it is common for golf courses that use a municipal water source to have water bills of one million dollars per year (Dean et al., 1996). Thus in order to reduce costs and conserve potable water, the use of saline water has been suggested as a potential water source for turfgrass irrigation.

In an experiment in Las Vegas, NV, where water restrictions are being mandated to conserve potable water for human consumption, a cyclic irrigation study using saline groundwater from a shallow saline aquifer was conducted on sports field bermudagrass, *Cynodon sp*. (Schaan et al., 2003). Results of the study concluded that soil salinity cycled up (as high as 24 dS m^{-1}) and down (baseline values of 4.0-10 dS m^{-1}) in response to substitution (saltwater) periods, but the duration in which soil salinity exceeded salt tolerance threshold values for bermudagrass were short in all treatments (Schaan et al., 2003). Other notable results of the experiment were the lack of change in turfgrass color, cover, and plant water status which indicates that cyclic irrigation is feasible on large turfgrass areas in an urban setting (Schaan et al., 2003).

In Colorado, container and hydroponics experiments were performed to evaluate the growth responses of four turfgrass species ('Challenger' Kentucky bluegrass (*Poa pratensis* L.), 'Arid' tall fescue (*Festuca arundinacea* Schreb), 'Fults' alkaligrass (*Puccinellia distans* (L.) Parl.) and a saltgrass collection (*Distichlis spicata* (Torr.) Beetle) to salinity (Alshammary et al., 2004). The grasses were irrigated with different salinity levels and authors concluded that salinity caused root cortex cells to collapse in

Kentucky bluegrass at 14.1 dS m^{-1} and in tall fescue at 23.5 dS m^{-1}, but saltgrass had only a few cells collapse even at 23.5 dS m^{-1} (Alshammary et al., 2004).

In studies conducted in the Southwest, bermudagrass was maintained with adequate quality when saline water was used for irrigation (Dean et al., 1996; Dean-Knox et al., 1998), and when irrigations were based on an evapotranspiration (ET) feedback system with adequate leaching and high uniformity of application (Leskys et al., 1999). Dean et al., (1996) and Dean-Knox et al., (1998) concluded that saline water should be considered as a supplemental source.

Thomas et al., (2006) conducted an experiment on the use of type I recycled water for maintaining Tifway bermudagrass (*Cynodon dactylon* (L.) Pers. X *C. transvaalensis* Burtt Davy) and 'Jamur' zoysiagrass (*Zoysia japonica* Steud.) irrigation using an above ground sprinkler system in San Antonio, TX. They documented that although there was an increase in soil electrical conductivity (EC) from 0.2518 dS m^{-1} in one treatment to 0.3132 and 0.3171 dS m^{-1} in other treated turfgrass, they observed that the soil sodium concentrations were not negatively affected by the use of recycled water and turfgrass quality was not adversely affected (quality scores of 5 or greater during growing season on a scale of 3 to 9), (Thomas et al., 2006).

In Australia, Rogers (2002) reported a reduction in the yield of perennial pasture grasses when saline water with concentrations greater than 0.8-1.2 dS m^{-1} was applied. However, Rogers (2002) documented that this was due to the frequency of salt application throughout the season and concluded that farmers should monitor the salinity levels to avoid an escalation of Na^+ and Cl^- to prevent consequence of reductions in herbage production.

Influence of Saline Water on Plant Function and Soil Structure

While the above mentioned experiments document the potential of using saline water for irrigating turfgrass, special considerations must be made in regards to the management of turfgrass systems to adjust for the increase in salinity. In order to do this, the influence by saline water on turfgrass functions must first be understood. More specifically, the total salinity, sodium concentration, and bicarbonate concentration are of concern. Total salinity is related to the various salts that are found in saline water and soil solution with the most common being sodium, potassium, calcium, and magnesium associated with anions chloride, sulfate, and carbonate/bicarbonate (Rhoades, 1972). Harmful effects of salinity on turfgrass growth include osmotic stress, ion toxicity, and nutritional imbalances (Carrow et al., 2001; McCarty et al., 2003, Dean-Knox et al., 1998). Soil texture can influence sodium accumulation since sodium can replace calcium on the cation exchange site (Brady and Weil, 2002). This may result in soil structure deterioration known as dispersion or deflocculation of clay particles (Carrow et al., 2001). Salts can quickly accumulate in the soil profile when irrigating with saline water, particularly when evaporative demand is high (Marcum, 2004). This is because water is evaporated and the salts precipitate out and are left behind in the soil medium. When excess salts increase the concentration of the soil solution, the osmotic gradient changes from high to low, making it more difficult for plants to take in water (Mitra, 2000).

Reduced growth rate, increased wilting, and reduced leaf size and area are common as a result of this water deficit (McCarty et al., 2003). Plasmolysis can occur at very high salt concentrations in the soil, in which osmotic potential reverses the direction of water flow from plant cells into the soil solution and the cells collapse, eventually killing the plant (Mitra, 2000).

Soil salinity is characterized based upon electrical conductivity, sodium absorption ratio and exchangeable sodium percentage (Mitra 2000; Brady and Weil, 2002). Increased Na^+ concentrations can be hazardous on the dispersion of soil colloids, ultimately decreasing soil structure. Loss of structure results in compaction-prone soils (high traffic areas such as golf greens) resulting in anaerobiosis, poor aeration and reduced infiltration rates, and loss of rooting (Mitra, 2000, Marcum, 2004). Anaerobiosis has the effect of increasing the transport of salts to shoots, and decreasing plant growth and survival (Barrett-Lennard, 2003). Higher levels of sodium will also affect the sodium absorption ratio (SAR), as it relates the concentration of Na^+ to calcium (Ca^{+2}) and magnesium (Mg^{+2}) ions, and is the most important parameter for measuring sodium accumulation (Mitra, 2000). Ions that can increase in concentration and become toxic when there is inadequate leaching with quality water, poor soil permeability, and during high evaporation periods include: sodium, boron, chloride, chlorine, fluoride, and heavy metals (Carrow and Duncan, 1988; McCarty et al., 2003).

Bicarbonate (HCO_3^-) and carbonate (CO_3^{2-}) ions are found in water with a high pH and results primarily from carbonic acid, which is formed when carbon dioxide from microbial and root respiration combines with water (McCarty et al., 2003). Bicarbonates in water and soil affect soil permeability as these ions form insoluble precipitate with calcium and/or magnesium, potentially leaving one of two situations: (a) in the presence of Na^+, the Na^+ will be left to dominate the soil colloid exchange complex, or (b) if no Na^+ is present and the Mg^{+2} and Ca^{+2} is complexed, then there are no ions to bind soil colloids together; regardless of the situation, the outcome is the same for fine textured soils, in which soil porosity and infiltration decreases (Harivandi et al., 1994). Bicarbonate problems can be adequately addressed by blending irrigation waters, applying an acidifying fertilizer, acidifying the water, and/or applying gypsum or sulfur (Watson and Carrow, 1994).

Managing Salinity in Turfgrass Systems

Ayers and Westcot (1985) defines a salinity problem as a condition where the salts in solution within the crop root-zone accumulate in concentrations to which crop yield decreases. In general, salinity slows the rate of crop growth, resulting in plants with smaller leaves, shorter stature, and reduced economic yield (Shannon et al., 1994). While turfgrass growers may not be as concerned in yield reductions, they are very concerned about reductions in turf quality (color and canopy cover) and health (Dean et al., 1996).

Salt tolerant plants including bermudagrass have adapted to minimize the detrimental effects of salinity by producing an extensive root system and salt secreting glands on the leaf surface (Liphschitz and Waisel, 1974; Oross and Thomson, 1982; Gould and Shaw, 1983; Marcum and Murdoch, 1990; Marcum et al., 1998).

Irrigation water from saline sources will have greater turfgrass management costs compared to if a good quality irrigation source was used (Marcum, 2004). Increase in costs are associated with: higher water use for leaching, cultivation programs to maintain water infiltration, percolation and drainage, disposal of salts, amendment(s) needs for the soil and water, monitoring, greater fertilization of any nutrients leached by wastewater, and over-seeding costs (Huck et al., 2000).

Infiltration, percolation, and drainage are important water movement factors and thus influence managing salinity in turfgrass systems. Infiltration can be enhanced on salt affected soils by cultivation (core aeration, slicing, spiking, and solid tine coring) and adding amendments such as acidification of the irrigation water and soil (Carrow and Duncan, 1998). Percolation involves water that moves through the root-zone and is important to leach salts beyond the root system (Carrow and Duncan, 1998). Percolation can be improved by subsurface (25 to 60 cm) cultivation by similar methods for increasing infiltration as well as possible injections of gypsum or other amendments to the subsoil (Carrow and Duncan, 1998). In order to have a better soil structure and increased soil stability, the soil should be flocculated with polyvalent cations such as calcium and magnesium (Mitra, 2000). The more complex drainage concerns are managed by scheduling periodic drainage of the salts below the root-zone by using quality water, using the minimal leaching requirement, improving the efficiency of the irrigation system, and the installation of subsurface drainage (Carrow and Duncan, 1998).

Previous studies of using recycled water for irrigation indicate that the major constituents of concern with leachate include total salts, calcium, chloride, magnesium, nitrogen, phosphorus, potassium, and sodium (Pepper and Mancino, 1994). High sodium concentrations are of particular concern and usually require the use of a leaching factor and periodic gypsum applications to prevent salt accumulation in the soil (Hayes et al., 1990). To remediate excessive salt accumulation, a quality water source is needed to leach the salts out of the root-zone and is the most important strategy of any management plan for salt affected sites (Carrow and Duncan, 1998). To perform this, the leaching factor (LF) and leaching requirement (LR) must be determined. The LF is the factor of water that infiltrates the soil surface and moves through the root-zone (Carrow and Duncan, 1998). The LR is the minimum amount of water that must pass through the root-zone to control salts within an acceptable level (Carrow and Duncan, 1998). Bowman et al., (1989, 1998) and Geron et al., (1993) indicate that leaching is controlled by turfgrass biology, most noted is the development of enhanced nitrogen uptake and a very dense root system. For turfgrass applications, the LF is that fraction of water applied above that needed to meet turfgrass evapotranspiration (ET) needs (Carrow and Duncan, 1998). The ET can be high due to increase temperatures and/or coastal winds, especially during establishment when soil evaporation is excessive (Duncan et al., 2000). Leaching requirement can be expressed as: LR= ECiw/ECdw where ECiw is the electrical conductivity of irrigation water and ECdw is the maximum acceptable salinity for the specified crop (Brady and Weil, 2002).

In Nevada, Leskys et al., (1999) performed an experiment to evaluate the response of ‘Monarch’ tall fescue, (*Festuca arundincea* Schreb.) to saline irrigation water (2.5 dS m^{-1}) when varying LF of 0.05, 0.15, 0.25 were applied while the Christiansen uniformity coefficient (CUC) was set at 0.65, 0.75, or 0.85. CUC is an average measurement of irrigation uniformity used in the turfgrass industry that ensures the same irrigation volumes are equally applied below and above a calculated mean (Zoldoske and Soloman, 1988). Leskys et al., (1999) determined that as long as CUC was high, acceptable turfgrass was maintained when low LFs were imposed.

Salt Tolerance of Bermudagrass

Cynodon sp. (bermudagrass) is the most utilized turfgrass in warm regions world-wide. Introduced to the United States from Africa in 1751, (Alderson & Sharp, 1995) bermudagrass has been recognized as being both drought and salt tolerant (Harivandi et al., 1992; Carrow, 1996; Duble, 1996).

In a greenhouse experiment, the effects of sodium chloride in solution were tested on various cultivars of *Cynodon* cultivars to determine salt tolerant cultivars. Top growth decreased 22%, but root growth increased 270% at the highest salt level. Differences between cultivars were measured by the rate of decrease in top growth with increased salinity and it was determined that 'Tifdwarf' and 'Tifgreen' were the most salt tolerant of the bermudagrasses tested (Dudeck et al., 1983). Marcum and Pessarakli (2006) also found that shoot dry weight of all cultivars decreased linearly with increasing salinity. In an experiment that focused on soil matric and osmotic potentials of the tall fescue (*Festuca arundinacea* Schreber) cultivar 'Monarch' and bermudagrass, (*Cynodon dactylon* L. 'Numex Sahara'), it was determined that water with a salinity level of 6.0 dS m^{-1} could be used as a supplemental irrigation source, if irrigation practices were designed to minimize soil water deficit (Dean-Knox et al., 1998).

Under small-scale controlled studies, bermudagrass has been shown to be more salt tolerant than many agricultural crops (Maas and Hoffman, 1977; Hoffman et al., 1983; Peacock et al., 1993; Marcum and Murdoch, 1994). In a salinity tolerance and salt gland excretion efficiency study, it was noted that bermudagrass may exclude saline ions in several ways: via compatible solute accumulation associated with ion compartmentalization (Marcum, 1999), exclusion at the root cortex (Leonard, 1983), and excretion by salt glands (Marcum and Murdoch, 1990; Marcum and Pessarakli, 2006). Previous research has indicated the visual appearance of bicellular leaf salt glands and salt crystals that formed on both abaxial and adaxial leaves of bermudagrass cultivars (Marcum and Pessarakli, 2006). Salinity tolerance differs with the stage of plant development (seedling, juvenile, mature) (Hughes et al., 1975).

Besides species specific tolerances, salinity tolerance is influenced by a number of environmental, edaphic, and plant factors (Marcum, 2004). Temperature and relative humidity can influence plant response to salinity (Maas, 1986). For example, plants are more sensitive to salinity under hot, dry conditions than under cool, humid circumstances, probably due to increased ET demand, favoring increased soil solution and subsequent salt uptake (Hoffman and Rawlins, 1971).

Using Subsurface Drip Irrigation to Apply Saline Water

Benefits of using a subsurface drip irrigation include reducing weed growth and the occurrence of plant diseases (Taylor et al., 2005), encouraging sturdy and deep root growth, and providing safe and efficient means of fertilizing since fertilizer is added at a single outlet allowing flow directly to the root-zone (Suarez-Rey et al., 2000). For example, an experimental subsurface drip irrigation system was used to evaluate the use of treated swine effluent on bermudagrass forage (Stone et al., 2005). The authors report that the swine effluent treatments had higher biomass yields (Stone et al., 2005). The main benefit of using subsurface irrigation is improving water use efficiency (Suarez-Rey et al., 2000). Since the water source is being directly applied to the root-zone, the potential loss of applied water by evaporation and wind drift is reduced (Taylor et al., 2005).

Some of the drawbacks to subsurface irrigation include root intrusion and precipitate clogging of the drippers; both of which are difficult to visually inspect and require turf and soil disturbance to repair (Taylor et al., 2005). Dripper flow rates also affect the likelihood of clogging (Taylor et al., 2005), because larger flow drippers (>1.5 L h^{-1} $emitter^{-1}$) experience smaller decreases from the original flow over time compared to smaller dripper sizes (0.91 L h^{-1} $emitter^{-1}$ or less) (Camp et al., 1997). Devitt and Miller (1988) demonstrated that saline water may be applied to turfgrasses using subsurface irrigation. Salinity within the root-zone was the major limiting factor for bermudagrass growth in a sandy loam soil when a saline water source (EC=2.2 dS m^{-1}) was applied. Their research suggested that the spacing of the drip lines is important when irrigating with a saline water source to ensure uniform water content is maintained and leaching of the salts can be achieved (Devitt and Miller, 1988). In another experiment that compared subsurface drip irrigation to sprinkler irrigation for bermudagrass in Arizona, salt accumulated near the soils surface at the end of the irrigation season for the subsurface drip irrigated treatment, but it was not sufficient to influence the appearance of the turf (Suarez-Rey et al., 2000).

Project Objectives

As mentioned, previous research documents experimentation of saline water and subsurface irrigation on bermudagrass primarily in the Southwest areas of the United States. Some of the experiments occurred in closed environments using newly established grasses (in greenhouses) and did not account for all processes that are related to turfgrass under realistic conditions. For example, the experiments conducted by Dudeck et al., (1983) and Marcum and Pessarakli (2006) took place in controlled environments where levels of organic matter and associated microbial communities may not exist, and / or lack the soil textural spatial variability compared to what might be found in a natural setting.

Furthermore, the climate of the Southwest U.S. is predominantly arid in comparison to the relatively humid climate of the Southeast. Rainfall in South Carolina is fairly well distributed throughout the year, with additional rainfall accounted for during the winter months in its coastal region. These rainfall events may provide natural freshwater irrigations, pushing accumulated salts through the soil profile. Thus management recommendations in the Southeast may differ from those of the Southwest U.S. Additionally, research focusing on subsurface irrigation as a delivery mechanism and saline water as a water source for bermudagrass is limited. However, since subsurface irrigation increases water use efficiency by minimizing the potential loss of water through evaporation and wind drift, it may provide a means of conserving water while irrigating large turfgrass areas.

The goals of this research were to (a) examine responses of bermudagrass maintained in an outside Southeastern environment with subsurface irrigation used to apply fresh or saline water, (b) determine if utilizing a spectral reflectance sensor can monitor bermudagrass stress levels, and (c) develop best management practices for turfgrass managers. Specific objectives of the research included (a) determining changes in root-zone soil moisture and electrical conductivity, (b) understand bermudagrass quality and growth responses when alternative irrigation sources, volumes and delivery method are utilized, and c) understand the relationship between spectral reflectance and primary stress factors.

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CHAPTER TWO

Root-Zone Characteristics and Bermudagrass Response to Saline Water Delivered by a Subsurface Drip Irrigation

Introduction

Water conservation will help ensure that an ample supply of freshwater is available for human consumption, ecosystem integrity and sustainability of services such as recreation and businesses dependent on freshwater. Turfgrass irrigation is considered a non-essential use of freshwater, thus water restrictions may impact irrigating turfgrass during high demands of use such as in the summer months. Fine tuning irrigation volumes, alternative irrigation sources (saline water) and delivery methods (subsurface drip irrigation) need to be identified to conserve freshwater while maintaining acceptable turfgrass quality. Most of the research involving turfgrass irrigation with a saline water source, alternative delivery methods such as by subsurface drip irrigation (SDI) systems, and reduced application volumes has been conducted in the arid Southwest US. A complete review can be found in Chapter One. Overall, bermudagrass has been maintained successfully by adopting the above mentioned irrigation techniques. Minimal research has been performed on these techniques in the Southeast US, where the climate is much different than the Southwest with respect to humidity and annual rainfall. Frequent, rainfall may help leach the salts from the root-zone. Thus, there may be greater potential for success in maintaining bermudagrass in the Southeast US using the strategies employed in the Southwest US.

Objectives of the research included determining quality and growth responses from bermudagrass, and soil electrical conductivity when using: (a) subsurface drip irrigation system (SDI) with saline water compared to irrigation (SDI) with a potable water source, (b) an SDI system with wider line spacings than what is recommended for the soil texture, and (c) an irrigation amount that is less than replacing 100% ETp. With these results, SDI installation recommendations may be made and best management practices can be developed for turfgrass managers.

Methods and Materials

This research project was conducted at Clemson University's Pee Dee Research and Education Center (PDREC) in Florence, South Carolina. A field-scale facility was constructed in 2003 on the native loamy sand soil (Bonneau series) characterized as a loamy, siliceous, subactive, thermic, Arenic Paleudult. The field was laser leveled at which time 96, 3 x 3.2 m (9.8 x 10.5 feet) plots were delineated. However, only 32 plots were used in this experiment that was conducted in a split-plot design. For each of the eight main plots arranged in four randomized complete blocks, subsurface drip irrigation (SDI) lines were installed between 15.2-20.3 cm (6-8 inches) depth using two poly-hose injection shanks mounted on a tool bar. The irrigation system for each plot consisted of individual PVC pipe manifolds for both supply and discharge. Discharge manifolds were flushed back to an adjacent storage tank. Irrigation laterals were WasteflowPC (Geoflow Inc., Corte Madera, CA) with in-line, pressure compensating labyrinth emitters spaced 0.4 m apart with each delivering 1.9 L/h, and were spaced either 41 or 81 cm (16 or 32 inches) apart in the two main plots of each block. Each main plot consisted of four sub-plots, and each sub-plot was randomly assigned an irrigation source (fresh or saline water) and volume (0.65 or 1.00 ETp).

The SDI system was controlled by a Microsoft windows based Personal Computer with a custom Visual Basic (VB) program. The VB program operated a digital output PCI board, an A/D input board, and a counter/timer board. The digital output board operated supply pumps and solenoid valves. The A/D input board read supply line pressures. The counter/timer board recorded flows. Selected treatments received saline water and control treatments received potable water. In-line screen filters were used for each water source. Flow meters were used on each water source as well as each treatment. Supply pressures were monitored using pressure transducers that were placed before and after the in-line screen filter for each water source. A 135 l (35 gal) mixing tank and 22,712 l (6,000 gal) storage tank was plumbed into the irrigation design to supply plots with the saline water.

'Tifway' (419) bermudagrass sod (*Cynodon transvaalensis* Burtt-Davy x *C. dactylon* (L.) Pers.) grown locally (Dargan Turf Farm, Darlington, SC) was installed and established using an overhead irrigation system. To monitor root-zone characteristics, soil sensors were installed (April 2007) in each plot to measure volumetric water content, temperature, and electrical conductivity (ECH_2O-TE, Decagon Devices, Pullman, Washington) at a depth of 15 cm or 6 inches). The 15 cm depth was selected based on field tests that showed greatest changes in soil salinity within the 0-15 cm (0 – 6 inches) depth compared to lower depths (Schaan et al., 2003) and a greenhouse study that documented 60% of bermudagrass roots distributed within the top 15 cm of the soil profile (Bowman et al., 2006). To mimic a worse-case scenario, the sensors were placed between drip lines where soil moisture was expected to be variable. However due to many of the sensors malfunctioning, the measurements could not be used.

The experiment was repeated over a two-year period (13 August - 5 October, 2007 and 29 July - 19 September, 2008). Before experiment initiation, soil samples were collected to determine fertilizer recommendations. To ensure no treatment influences carried-over into the second experiment, between the two experimental periods, the area was irrigated with an overhead irrigation system and granular fertilizer was applied after spring green-up. Furthermore, irrigation treatments were re-randomized to the sub-plots within each main plot. Once the experiments began, a fertilizer injection system was used to apply a complete liquid fertilizer (18-3-6 SLR) to the bermudagrass on a biweekly basis at 9.76 g N m^{-2}. The fertilizer injection system consisted of an Ozawa Precision Metering Pump (model # BL540GN) (Kerman, California), 0.64 cm tubing, and a stainless steel check valve which were plumbed into the supply line for fertilizer application. The bermudagrass was maintained as if for fairway playing conditions. This included mowing the grass at a 19 mm height of cut, three times a week (with all clippings collected) and applying the appropriate pesticides when needed.

The two SDI lateral spacing treatments (41 or 81 cm apart) were applied at the whole plot level. Two irrigation volumes (replacing either 0.65 or 1.00 ETp) and two irrigation sources (fresh and saline) were randomized at the split plot level. Determining proper irrigation volumes on ET can be difficult because many ET models over and under predict actual ET (Brown et al., 2001; Earls and Dixon, 2008) and some do not consider wide spatial variability in soil characteristics found in turfgrass systems (Dettman-Kruse et al., 2008). In this experiment, the irrigation volumes were selected based upon a study in which irrigation volumes were determined by weighing lysimeters in which irrigation was replaced to equate actual ET and a 0.25 leaching fraction. Only when these irrigation volumes were less than 65% replacement ETp (based from the modified Penman-Monteith method) was turf quality below the minimum acceptance criterion of 6.0 (Dean et al., 1996). For this study, weekly averages from three years (2004-2006) of predicted ET using the ASCE-Standardized reference ET equation (Allen et al., 2005) from a weather station located near the field were determined for July through October. Irrigation was based on these biweekly ETp values with applications being applied over three irrigations per week (Monday, Wednesday, and Friday); however, if a rain event was > 8.4 mm, the next scheduled irrigation was voided.

The freshwater source was from the local city municipality. The electrical conductivity of the saline water was based on data provided by the U.S. Geological Survey's surface water monitoring stations in the Atlantic Intracoastal Waterway in the Myrtle Beach, SC, area in which golf courses are currently using as a source of water to supplement groundwater for irrigation water. The saline stock was based on the salt composition of salt water off of the South Carolina coast (35 dS m^{-1}). Granulated salts were mixed and dissolved in a mixing tank then transferred to a storage tank for further dilution to the correct ECw (electrical conductivity of the irrigation water) concentration (~3.0 dS m^{-1}). Agitators were constructed by modifying recirculation pumps to make sure the salts were completely dissolved. Prior to an irrigation application, the agitators were switched on to re-dissolve any salt that may have precipitated out of solution.

Turfgrass quality was visually assessed weekly on a scale of 1-9 with 9=dark green turf, 1=dead/brown turf, and 6=minimally acceptable turf. Wilt, when visible, was observed visually as a percent of plot area. Soil cores were taken to determine salinity at pre, mid and post experiment time periods at soil depths of 0-10 cm (0-4 in), 10-20 cm (4-8 in), and 20-30 cm (8-12 in). A 1:2 (soil/water) salinity extraction method was used to determine soil electrical conductivity (ECe) (Rhoads, 1996). Measurements were determined with an Orion 3 Star Conductivity Meter (Thermo Electron Corporation, Beverly, Massachusetts).

To assess turfgrass growth, clipping samples were taken from a 1.5 m^2 area from each plot on Monday, Wednesday, and Friday. Clippings were weighed after drying at 60° C to determine dry-weight yields (g m^{-2}). For each year, 5.1 cm (2 in) cm diameter cores were taken to a depth of 30 cm prior to the first fertilization after spring green-up. The pelts were removed and stolons counted as a quantitative means to determine density. The remainder of the core was partitioned into 2 samples (0-15 cm and 15-30 cm), then washed of the mineral portion leaving just roots. Washed roots were ashed and weighed to determine root mass.

Climatic data were downloaded from the NRCS' Soil Climate Analysis Network (SCAN) weather station (site 2037) located at the PDREC.

Significant treatment effects on electrical conductivity, soil moisture, turfgrass quality, wilt, clipping yield, root weights, and stolon counts were identified by analysis of variance using the general linear model of SAS Software (SAS Institute, 2003). Means separation was performed using linear contrasts, with all comparisons made with an α level of 0.05.

Results and Discussion

Weather

Weather data, including weekly average air temperature, rainfall and ET were collected for the eight week experiment and compared with weather data averaged from 2004 through 2006. Rainfall is typically evenly distributed throughout the year in eastern South Carolina. In 2007, abnormally dry to severe drought conditions persisted throughout the summer (Figure 2.1). During the experiment, only eight rain events occurred for a total of 112 mm, compared to 312 mm from the previous 3-year average for the same time period (Figure 2.1b). Evapotranspiration rates were also higher for the 2007 experiment than the previous 3 year average (Figure 2.1c). The US Drought Monitor (http://drought.unl.edu/dm) confirmed and classified the geographic area at the beginning of the experiment (August 2007) as having abnormally dry conditions, which escalated to severe drought conditions by the end of the experiment (October 2007).

During the 2008 experiment, there were 15 rain events for a total of 388 mm, compared to 386 mm from the 3-year average (Figure 2.1b). Air temperatures and ET values during the 2008 experiment were similar to the 3-year average (Figure 2.1a and c).

In 2007, replacing 65% ETp resulted in a total of 118.2 mm of irrigation applied; whereas bermudagrass receiving 100% ETp received 180.9 mm of irrigation water. In 2008, replacing 100 and 65% ETp resulted in a total of 158.8 and 103.9 mm of irrigation applied, respectively.

Mean ECw of the freshwater and saline water sources for 2007 were 0.08 dS m^{-1} (range 0.07-0.09 dS m^{-1}) and 3.19 dS m^{-1} (range 2.65-3.52 dS m^{-1}) respectively, and for

2008 were 0.06 dS m^{-1} (range 0.05-0.07 dS m^{-1}) and 3.11 dS m^{-1} (range 2.78-3.34 dS m^{-1}), respectively.

2007 Experiment

Turfgrass Quality

All means of weekly visual quality scores were above the minimum acceptance criterion of 6.0, but differed significantly over the experiment (range: 7.1-7.9, mean: 7.5, $P<0.001$, Table 2.1). No treatment factor influenced quality (Table 2.2).

Bermudagrass wilt was only observed on Week 4, as bermudagrass with SDI lines spaced 81 cm apart was 75% wilted compared to 41% wilted for SDI lines spaced 41 cm apart ($P=0.0331$). In addition, examination of a significant Source by Irrigation Volume interaction revealed that bermudagrass irrigated with saline water at 100% replacement ETp had greater wilt than freshwater irrigated bermudagrass at the same volume (72 and 51% respectively, $P=0.0032$). Perhaps wilt occurred during Week 4 because the bermudagrass had not yet employed adaptive mechanisms in response to stress conditions.

Overall, bermudagrass quality did not decline below the minimum acceptance criterion of 6.0 when irrigated to replace 65% ETp, regardless of water sources. In the Southwest U.S., a salinization study was performed on tall fescue (‘Monarch’) and common bermudagrass (‘Numex Sahara’) in which a blended saline water source of 6.0 dS m^{-1} and a municipal water source of 1.1 dS m^{-1} was applied through a surface sprinkler system and irrigation volumes were based on replacing actual ET and imposing a 0.25 leaching fraction (Dean et al., 1996). It was reported that only when irrigation volumes were less than 0.65 replacement ETp did turf quality decline below the minimum acceptance level.

Soil Profile Electrical Conductivity (ECe)

Depth A

For Depth A, an examination of a significant Source X Date interaction revealed that ECe was higher for saline water irrigated bermudagrass compared to freshwater on Week 4 and Week 8 (P=<0.0001, Figure 2.2, Table 2.3). Similar trends were reported in studies by Maas (1986) and the U.S. Salinity Staff (1969) which suggest ECe increases with the length of time in which saline water is used as well as from the soil drying between irrigation events. As the capillary movement of water and evaporation increases, saline water is drawn to the soil surface where water evaporates and leaves salts in the soil. Devitt and Miller (1988) also reported an increase in salt concentrations (from 4.0 to 12.0 dS m^{-1}) at the soil surface for bermudagrass irrigated with saline water (2.2 dS m^{-1}) at 61 cm SDI line spacings over a ~14 month period.

Depth B

For Depth B, multiple interaction effects were identified including the fourth order interaction (Date X Spacing X Source X Volume; Table 2.3). Since the highest order interactions included sampling date, practical interactions are further discussed based on date for Depth B. No factor influenced ECe at Week 0 (all P values > 0.050). Water source influenced ECe at Week 4 (P<0.0001) in which saline irrigation resulted in

ECe of 0.057 dS m^{-1}, which was higher than from freshwater irrigations (0.027 dS m^{-1}). By the end of the experiment (Week 8), the Source X Spacing X Volume interaction was significant (P=0.0379). For each Spacing and Volume combination, higher ECe was documented from saline irrigated bermudagrass compared to freshwater irrigated bermudagrass (P≤0.0007 for all four comparisons). In addition, the volume applied significantly influenced ECe when saline water was applied at the 41 cm spaced lines. Only at this combination did increasing irrigation volume result in an increase in ECe (Figure 2.3). Finally, replacing 100% ETp using saline water resulted in higher ECe when applied through the 41 cm lines compared to the 81 cm spaced lines (P<0.0001).

Depth C

Although a fourth order interaction did not occur for Depth C (P=0.1716), significant differences were noted for three third order interactions, all of which included Date (Table 2.3). Thus, practical interactions are further discussed based on date for Depth C. No factor influenced ECe at Week 0 (all P values > 0.050). Water source influenced ECe at Week 4 (P<0.0001) in which saline irrigation resulted in ECe of 0.060 dS m^{-1}, which was higher than ECe from freshwater irrigations (0.027 dS m^{-1}). At the end of the experiment, the significant Spacing x Source interaction identified that applying saline water through the 41 cm spaced line resulted in higher ECe (0.12 dS m^{-1}) than when applied through the 81 cm spaced lines (0.10 dS m^{-1}, P=0.0011). The significant Source X Volume interaction identified that replacing 100% ETp with saline water resulted in higher ECe (0.13 dS m^{-1}) compared to replacing only 65% ETp (0.05 dS m^{-1}, P=0.0004). In each of these two interactions, applying saline water resulted in higher ECe compared to freshwater at each level of Spacing and Volume ($P \leq 0.0001$ for both levels for each Spacing and Volume). The 3rd interaction involving Spacing and Volume identified that replacing 100% ETp through the 41 cm lines resulted in higher ECe (0.10 dS m^{-1}) compared to replacing 65% ETp (0.08 dS m^{-1}, P=0.0010). In addition, replacing 100% ETp through 41 cm spaced lines resulted in higher ECe (0.10 dS m^{-1}) than when applied through the 81 cm spaced lines (0.07 dS m^{-1}, P=0.0005).

Matric forces of the soil system refer to the attraction or adhesion of water to the soil solids and are responsible for adsorption and capillarity which reduces the energy potential of water (Brady and Weil, 2002). Osmotic forces refer to the attraction of water to salts and other solutes in the soil solution which also reduces the potential energy of water (Brady and Weil, 2002). The fact that ECe increased with irrigation volume only when applied through the narrow spaced SDI lines suggests that (a) the irrigation water (and thus solutes) were not uniformly distributed throughout the soil profile when applied by the 81 cm spaced SDI lines and (b) that the osmotic potential was more influential than the matric. This would support why there were no differences in quality and clipping yields relative to increasing applied saline water volumes (as discussed previously and in following sections). The importance of matric and osmotic potentials when applying saline irrigation has been addressed by others (Dean et al., 1996 and Dean-Knox et al., 1998). They concluded from a field salinity experiment on bermudagrass and tall fescue that soil matric stress was more important to minimize than osmotic stress when a water deficit was created using a freshwater and saline water sources (1.1 to 6.0 dS m^{-1}, respectively). Perhaps the difference in their results and the conclusions of the present experiment is the degree of salinity of the saline water sources utilized. Even though significant differences in ECe levels were noted above, all ECe values observed in this study were less than the 9.0 dS m^{-1}, the level at which 'Tifway' bermudagrass top-growth begins to decline (Dudeck and Peacock., 1993).

Turfgrass Growth

Weekly clipping yields varied throughout the experiment ($P<0.0001$, Table 2.1); however, no significant treatment effects were detected.

Differences in weekly clipping yields may be attributable to applying fertilizer on a bi-weekly basis. For three out of the four two-week fertilization periods, clipping yields were greater for the first week following a fertilization event than the second week (Figure 2.4). Although not documented in this study, Dudeck et al. (1983) observed that bermudagrass top growth was reduced by 5% in a saline solution of 3.55 dS m^{-1}.

No differences in pre-treatment shoot density (mean = 25,123 stolons m^{-2}) or root mass (mean = 2,050 and 88 g m^{-3} for 0-15 cm and 15-30 cm soil depths, respectively) were found. Only water source influenced post treatment measurements (Table 2.4). The mean shoot density from saline irrigated bermudagrass (46,995 stolons m^{-2}) was greater compared to freshwater irrigated bermudagrass (35,172 stolons m^{-2}, $P=0.0066$). Root mass in the 15-30 cm depth was also greater from saline irrigated bermudagrass (197 g m^{-3}) compared to freshwater irrigated bermudagrass (130 g m^{-3}, $P=0.0360$). Research reports 'Tifway" bermudagrass shoots to have a threshold ECe of 9.0 dS m^{-1}, with a 5% top growth increase from ECe of 0 to 9.0 dS m^{-1} and a threshold ECe of 12 dS m^{-1} for roots with a 50% growth reduction at 42 dS m^{-1} (Dudeck and Peacock, 1993). However in their experiment, bermudagrass was irrigated from an above ground sprinkler system. The results from the 2007 experiment are in agreement with Dudeck and Peacock (1993) in which, at the end of the current experiment the highest ECe was 0.30 dS m^{-1} which resulted in a 25% increase in density compared to freshwater irrigated bermudagrass. Bermudagrass leaves contain salt glands or bladders that rid excess saline ions from shoots by excretion (Flowers et al., 1977; Liphschitz and Waisel, 1982). Perhaps the greater shoot density from the saline irrigated bermudagrass is in response to salt stress since increasing shoots results in an increase in the number of salt glands, and thus allowing the plant to excrete more salts. An increase in root growth under saline environment has been reported in halophytes (salt tolerant), including bermudagrass (Dudeck et al., 1983). This increase in root mass is an adaptive mechanism of turfgrass to the osmotic stresses in saline conditions (Rozema and Visser, 1981). The plant increases its water and ion absorbing root surface, therefore increasing its biomass (Dudeck et al., 1983; Parker, 1975; Torello and Symington, 1984; Youngner and Lunt, 1967). Additionally, saline-ion exclusion occurs at the root cortex (Leonard, 1983); therefore, an increase in roots is necessary to respond to saline conditions. Although bermudagrass does have the capability of this adaptation, there are both supporting and conflicting past research compared to our findings. Dudeck et al. (1983) documented, that root growth increased 270% for various Cynodon cultivars when irrigated with a sodium chloride of 9.9 dS m^{-1}. Peacock et al. (2004) reported that salinity (range between 1.1 and 41.5 dS m^{-1}) did not influence rooting of bermudagrass, and Bowman et al. (2006)

reported no differences in root distribution from bermudagrass that was irrigated with different salinity concentrations (0, 3.0 and 6.0 dS m^{-1}).

2008 Experiment

As mentioned previously, rainfall, temperatures, and ET in 2008 were more similar to the three year average than 2007. Thus, the weather conditions during this experiment represent more typical conditions which provide a contrast to the previous year.

Turfgrass Quality

All means of weekly visual quality scores were above the minimum acceptance criterion of 6.0 with variation in weekly means ($P<0.0001$) over the experiment (range: 7.0-8.1, mean: 7.6, Table 2.1). Source was the only treatment factor that influenced quality. Although only a 0.1 point difference, there was greater quality from freshwater irrigated bermudagrass in comparison to saline water (7.6 and 7.5, respectively, $P=0.0076$). Most turfgrass managers consider changes management strategies when there is a whole point difference detected in quality. Additionally, unlike the 2007 experiment, wilt was not observed at any time. An ample amount of rainfall, normal air temperatures and ET rates during the experiment were perhaps the reason.

Soil Profile Electrical Conductivity (ECe)

Depth A

No factor influenced ECe at Depth A (all P values > 0.050). For both Depths B and C, a Date X Spacing X Volume interaction was significant, thus, the interactions is further discussed based on date for Depths B and C.

Depth B

For Depth B, no factor influenced ECe at Week 0 or at Week 8 (all P values > 0.100). At Week 4, the significant Volume X Spacing interaction (P=0.0425) identified two specific combination effects: (1) There was higher ECe from 81 cm spaced lines (0.06 dS m^{-1}) compared to 41 m spaced lines when 100% ETp was replaced (0.04 dS m^{-1}, P=0.0162) and (2) There was higher ECe from replacing 100% ETp (0.06 dS m^{-1}) compared to when 65% ETp was replaced through 81 cm spaced lines (0.05 dS m^{-1}, P=0.0296, Figure 2.5a).

Depth C

A similar trend occurred for Depth C as for Depth B: No factor influenced ECe at Week 0 or at Week 8 for Depth C (all P values > 0.100). At Week 4, the significant Volume X Spacing interaction (P=0.0163) identified two specific combination effects: (1) There was higher ECe from 81 cm spaced lines (0.06 dS m^{-1}) compared to 41 cm spaced lines when 100% ETp was replaced (0.03 dS m^{-1}, P=0.0069), and (2) There was higher ECe from replacing 100% ETp (0.06 dS m^{-1}) compared to when 65% ETp was replaced through 81 cm spaced lines (0.04 dS m^{-1}, P=0.0226, Figure 2.5b).

In addition, ECe increased over time in Depth C due to Source (P=0.0102, Table 2.3). Examination of this interaction revealed that at Weeks 4 and 8, ECe was higher from saline irrigated bermudagrass (0.05 and 0.06 dS m^{-1}, respectively) compared to freshwater irrigated bermudagrass (0.04 dS m^{-1} for both Week 4 and 8, P=0.0185 and P=0.0044, Figure 2.6).

The more typical weather conditions during the 2008 experimental period were most likely the reason for the lack of differences from treatments. The lack of factor influences may be explained by the frequent rainfall leaching more salts through the soil profile compared to the 2007 experiment. This would also explain why the water source was a significant factor influencing ECe in Depth C and not in Depth A or B in the 2008 experiment. Even with the abundant rainfall, ECe was generally higher at the greater irrigation volume when applied through the wider line spacing. As in the 2007 experiment, all ECe values in the 2008 experiment were less than 9.0 dS m^{-1} (highest value being 0.48 dS m^{-1}), the level at which 'Tifway' bermudagrass top-growth begins to declines (Dudeck and Peacock, 1993).

Turfgrass Growth

Unlike the first year experiment in which bi-weekly fertilizer applications might have influenced weekly yields, fertilizer events did not appear to be a probable cause for the second experiment's differences in weekly clipping yields (Table 2.1, Figure 2.7).

Overall, the mean pre-treatment shoot density was 28,165 stolons m^{-2}, and root mass for 0-15 cm and 15-30 cm soil depths was 761 and 110 g m^{-3}, respectively (Table 2.5).

Due to the possibility of carry-over effects from the previous year's experiment, pre-treatment shoot density and root mass at the 15 – 30 cm depth were influenced by a Source X Volume interaction (Table 2.5). Examination of Source X Volume means revealed that bermudagrass irrigated with freshwater had greater shoot density at 65% replacement ETp (29,924 stolons m^{-2}) compared to 100% replacement ETp (25,358 stolons m^{-2}, P=0.0336). Additionally, bermudagrass irrigated with saline water at 100% replacement ETp had greater shoot densities (31,219 stolons m^{-2}) compared to 65% ETp (26,160 stolons m^{-2}, P=0.0202).

Root mass at the 15 – 30 cm depth was greater from bermudagrass irrigated at 100% replacement ETp with the narrow line spacing (203 g m^{-3}) compared to the same size line spacing, but irrigated at 65% replacement ETp (86 g m^{-3}, P=0.0132).

No factor or factor interactions influenced post treatment measurements shoot density (mean = 20,700 stolons m^{-2}) or root mass (mean = 797 and 141 g m^{-3} for 0-15 cm and 15-30 cm soil depths, respectively, Table 2.5).

Conclusion

Few studies have been performed in the southeastern United States that have investigated bermudagrass response to saline water delivered by a subsurface drip irrigation system in a natural environment. Most of the research has occurred in the arid, southwestern area of the United States where water shortages and salinity management have been a growing concern. This experiment investigated factor and factor combinations of water source (treatments of fresh vs saline), SDI line spacing (41 or 81 cm apart) and irrigation volumes (65% or 100% ETp) over an eight week experimental period.

The severe drought established a worst case scenario for the 2007 experiment; however, few significant differences were documented from factor and factor interactions. Since natural leaching episodes (rainfall) rarely occurred during the period, a greater concentration of salts were allowed to accumulate in the soil profile in bermudagrass irrigated with the saline water source at the higher irrigation volume of 100% replacement ETp. However, ECe values were still below hazardous levels. It is anticipated that salts would probably have leached through the soil profile under typical rainfall conditions during this period, resulting in even lower ECe. Additionally, quality scores were maintained above the acceptable criterion of 6.0 for saline irrigated bermudagrass regardless of irrigation volume or SDI spacing. The one occurrence of wilt during the experiment suggests that management of the water source and irrigation volume will be dependent on SDI line spacing. Severe wilt occurred at the wider spacing, which suggests that other factors will have to be adjusted during times of extreme drought. Perhaps applying a greater volume of saline water and/or cycle with freshwater (if available) may help reduce water stress.

Snyder (1974) indicated that 60 cm between laterals would be the maximum allowable distance required to maintain uniform appearance for bermudagrass grown on

Pompano fine sandy soil. The wide laterals for this irrigation design were 81 cm apart between spacings for the Bonneau series soil. Certainly soil texture between the two different soil types (sand versus loam) would suggest that soil texture must be considered to determine proper SDI line spacings. The first year experiment suggests that only under extreme drought conditions when wilt was apparent was there any benefit to maintaining line spacing recommendations based on soil texture.

Unlike 2007, in which a severe drought persisted throughout the experimental period, the weather conditions exhibited during the 2008 experimental period were more normal to the climate of southeastern U.S. Air temperature and ET rates were similar to previous averages and an ample amount (but normal) rainfall existed during the second experimental period. The rain events caused many scheduled irrigations to be cancelled resulting in applying less treatments to the bermudagrass. Thus it is not surprising to see even fewer treatment effects in observations and measurements. The influence of the rainfall was most apparent soil EC comparisons. Significant differences in ECe were minimal at Depths A and B compared to 2007, with source only influenced ECe at Depth C. The rain water provided a naturally leaching effect, flushing salts to the lower depth of the soil profile.

This study documents that regardless of drought intensity, during times of high water demand bermudagrass grown in the Southeastern US can be maintained with a saline water source at approximately 3.0 dS m^{-1}, applied through an SDI system with line spacings of 81 cm with an irrigation volume of 65% ETp or greater. Only during extreme drought conditions additional freshwater may need to be applied if using wider spaced laterals. As freshwater demands increases, turfgrass managers and irrigation specialists will need to implement more judicious irrigation practices. This study documents that a saline water source, SDI and irrigating to replace less that 100% ETp are three mechanisms to conserve freshwater for essential uses while not compromising turfgrass quality.

Tables

Table 2.1. Weekly quality† and clipping yields for the 2007 and 2008 experiments.

	Quality		Clipping (g m^{-2})	
Week	2007	2008	2007	2008
0	7.0 d‡	7.0 f	7.1 cd	39.2 a
1	7.1 d	7.4 de	5.2 e	15.8 c
2	7.2 cd	7.5 cd	9.4 ab	11.1 de
3	7.6 b	8.1 a	8.5 bc	8.1 fg
4	7.5 b	7.8 b	7.4 c	13.9 cd
5	7.4 bc	7.4 de	10.4 a	7.9 fg
6	7.5 b	7.6 bc	5.8 de	10.7 ef
7	7.5 b	7.3 e	7.3 de	20.8 b
8	7.9 a	7.5 cd	5.6 de	7.9 g

†Visual quality was rated on a scale of 1-9 with 1=dead, brown turfgrass, 6= minimal acceptable, and 9=green, healthy turfgrass.
‡Means followed by the same letter within a column are not significantly different at P=0.05.

Table 2.2. Degrees of freedom (df) and significance for factor and factor interactions for quality and clipping yields for the 2007 and 2008 experiments. Significant values (P< 0.05) are in bold.

		Quality		Clipping Weights	
Factor and factor interaction	df	2007	2008	2007	2008
		------------------------*P value*------------------------			
Source	1	0.2699	0.0076	0.5553	0.1425
Spacing	1	0.2035	0.2811	0.4715	0.5262
Volume	1	0.4526	0.6336	0.5544	0.5733
Week	8	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**
Source*Spacing	1	0.2109	0.7744	0.3372	0.1314
Source*Volume	1	0.0764	0.7744	0.2821	0.1876
Source*Week	8	0.1838	0.0523	0.3622	0.7741
Volume *Week	8	0.8880	0.2121	0.6550	0.7439
Source*Spacing*Volume	1	0.8144	0.0819	0.6029	0.5131
Source*Spacing*Week	8	0.1735	0.3637	0.3422	0.2202
Source*Volume*Week	8	0.4240	0.8002	0.9663	0.2174
Spacing*Volume	1	0.9792	0.2235	0.9121	0.2906
Spacing*Week	8	0.1822	0.3985	0.9863	0.9798
Spacing*Volume*Week	8	0.7234	0.7654	0.2946	0.5484
Spacing*Source*Volume*Week	8	0.7647	0.5243	0.9383	0.3448

Table 2.3. Degrees of freedom (df) and significance for factor and factor interactions for ECe in each soil depth for the 2007 and 2008 experiments. Significant values (P< 0.05) are in bold.

Factor and factor interaction	df	Depth A (0- 10 cm) 2007	Depth A (0- 10 cm) 2008	Depth B (10- 20 cm) 2007	Depth B (10- 20 cm) 2008	Depth C (20- 30 cm) 2007	Depth C (20- 30 cm) 2008
		----------------*P value*----------------					
Source	1	**<0.0001**	0.2315	**<0.0001**	0.7256	**<0.0001**	0.1976
Spacing	1	0.1457	0.2853	**0.0399**	0.5355	0.0622	0.8712
Volume	1	0.1882	0.0503	0.2563	0.1047	0.0727	0.3687
Date	2	**<0.0001**	0.9384	**<0.0001**	0.4043	**0.0003**	0.4033
Source*Spacing	1	0.24080	0.4863	0.0855	0.9882	0.1266	0.9690
Source*Volume	1	0.1312	0.2658	0.1467	0.2889	**0.0305**	0.1551
Source*Date	2	**<0.0001**	0.0834	**<0.0001**	0.1781	**<0.0001**	**0.0102**
Volume*Date	2	0.1960	0.0544	**0.0231**	0.9678	**0.0391**	0.4785
Source*Spacing* Volume	1	0.1624	0.1659	0.2393	0.6455	0.4032	0.4401
Source*Spacing* Date	2	0.3135	0.0609	**0.0009**	0.1022	**0.0203**	0.3298
Source*Volume* Date	2	0.1843	0.1476	**0.0110**	0.5562	**0.0005**	0.7236
Spacing*Volume	1	0.1521	0.4056	**0.0380**	0.2045	**0.0183**	0.2563
Spacing*Date	2	0.4607	0.0932	0.3617	0.5020	0.7244	0.2814
Spacing*Volume * Date	2	0.1761	0.2658	**0.0003**	**0.0284**	**0.0164**	**0.0158**
Spacing*Source* Volume*Date	2	0.1779	0.1196	**0.0061**	0.2163	0.1716	0.2020

Table 2.4. Degrees of freedom (df) and significance for factor and factor interactions for shoot density and root mass (0-15 and 15-30 cm) for the pre and post 2007 experiment. Significant values (P< 0.05) are in bold.

Factor and factor interaction	df	Shoots		Roots (0-15 cm)		Roots (15-30 cm)	
		Pre	Post	Pre	Post	Pre	Post
		------------------------------*P value*------------------------------					
Source	1	0.5761	**0.0066**	0.4801	0.6548	0.3638	**0.0360**
Spacing	1	0.6427	1.0000	0.3548	0.8470	0.9251	0.1223
Volume	1	0.2354	0.9246	0.2962	0.2080	0.9281	0.1996
Source*Spacing	1	0.6631	0.6484	0.3269	0.9164	0.3507	0.5129
Source*Volume	1	0.6102	0.4811	0.1190	0.0719	0.6774	0.7618
Spacing *Volume	1	0.6276	0.4255	0.6661	0.6551	0.5668	0.1218
Source*Spacing*Volume	1	0.7553	0.4715	0.1122	0.8822	0.3712	0.9819

Table 2.5. Degrees of freedom (df) and significance for factor and factor interactions for shoot density and root mass (0-15 and 15-30 cm) for the pre and post 2008 experiment. Significant values (P< 0.05) are in bold.

Factor and factor interaction	df	Shoots		Roots (0-15 cm)		Roots (15-30 cm)	
		Pre	Post	Pre	Post	Pre	Post
		------------------------------*P value*------------------------------					
Source	1	0.4646	0.5401	0.3633	0.4276	0.6722	0.1079
Spacing	1	0.6303	0.5342	0.0943	0.9730	0.0550	0.4630
Volume	1	0.8624	0.3067	0.7012	0.3608	0.1220	0.7170
Source*Spacing	1	0.1524	0.8713	0.7666	0.1956	0.1312	0.1978
Source*Volume	1	**0.0030**	0.0927	0.6986	0.1500	0.9135	0.2307
Spacing *Volume	1	0.5180	0.8969	0.8931	0.4055	**0.0359**	0.2249
Source*Spacing*Volume	1	0.3682	0.8968	0.6575	0.1048	0.1482	0.9079

<u>Figures</u>

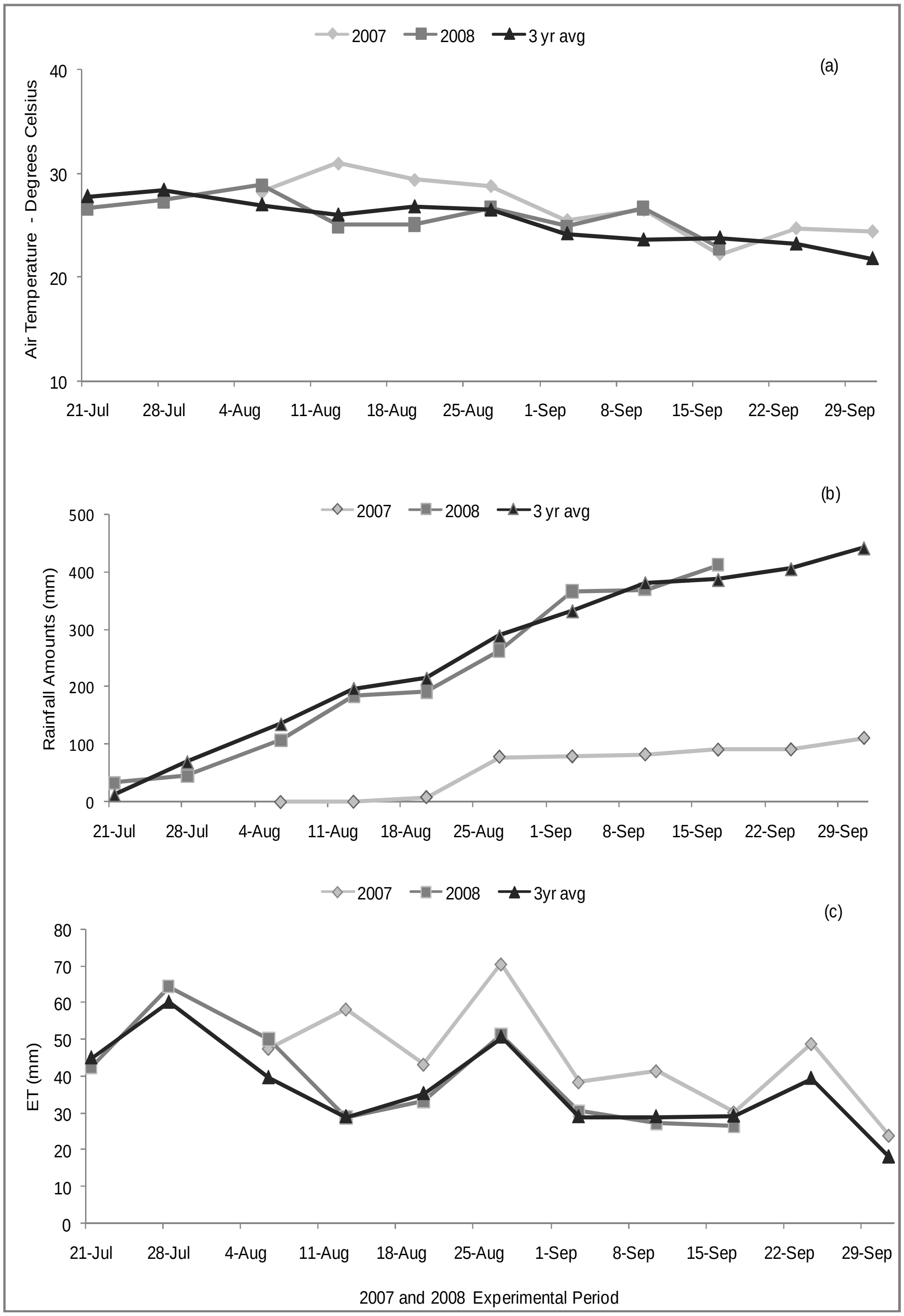


Figure 2.1. Comparison of weekly (a) mean air temperature, (b) total cumulative rainfall and (c) total ET for the 2007 and 2008 experiments compared to the previous 3 year average (2004-2006).

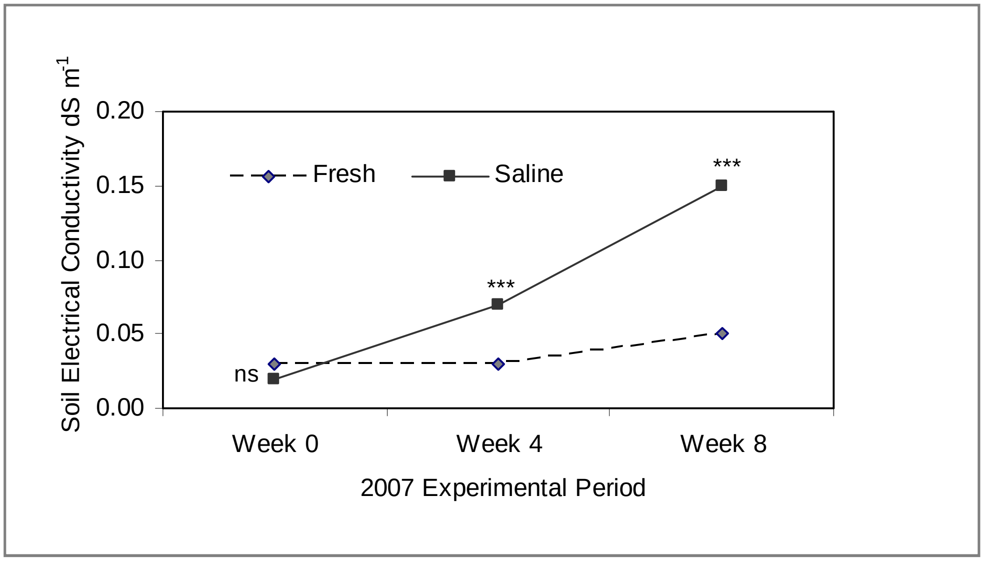


Figure 2.2 Soil electrical conductivity at Depth A increased with time for bermudagrass irrigated with saline water for the 2007 experiment.
*** and ns = $P<0.001$, and $P>0.100$, respectively.

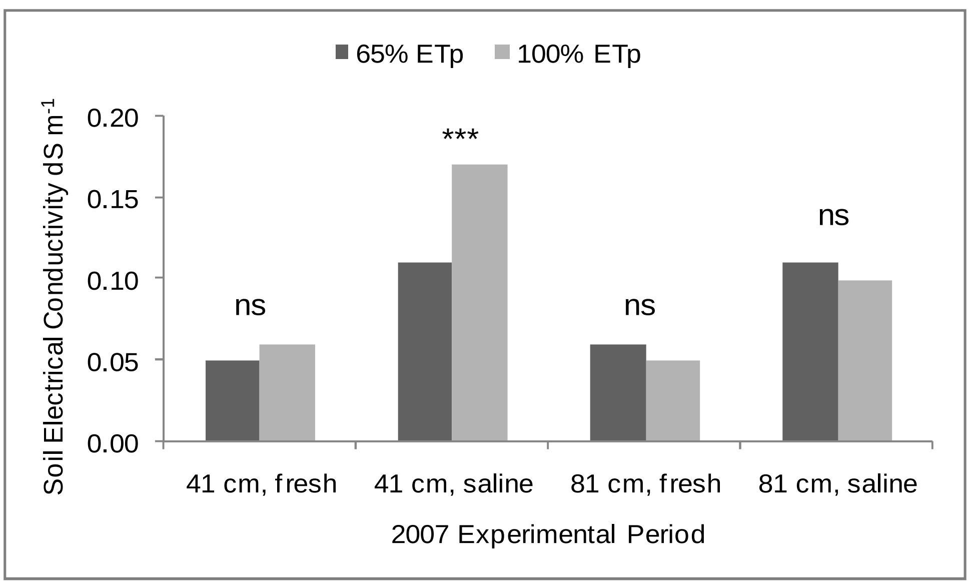


Figure 2.3. In the 2007 experiment, soil electrical conductivity values at Depth B (10-20 cm) for Week 8 were higher for saline irrigated bermudagrass with lines spaced 41 cm apart at 100% ETp, compared to the same source and line spacing at 65% ETp.
*** and ns = $P<0.001$ and $P>0.100$, respectively.

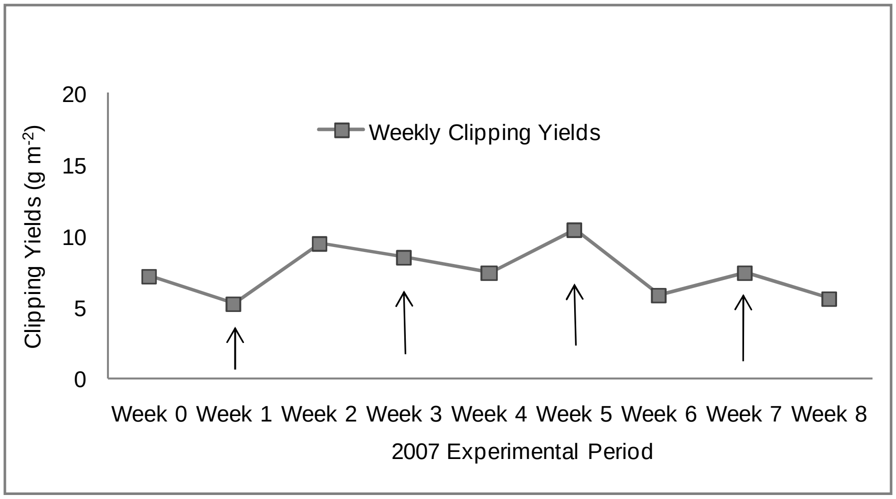
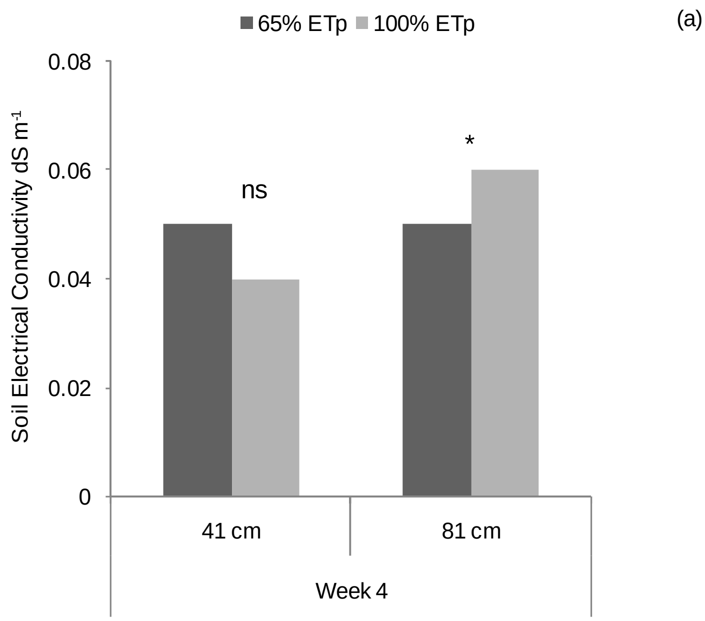


Figure 2.4. Weekly clipping yields increased following three of the four biweekly fertilizer applications in the 2007 experiment. Arrows indicate the week in which a fertilization event occurred. Bermudagrass was always fertilized through an injection system with Monday irrigations.



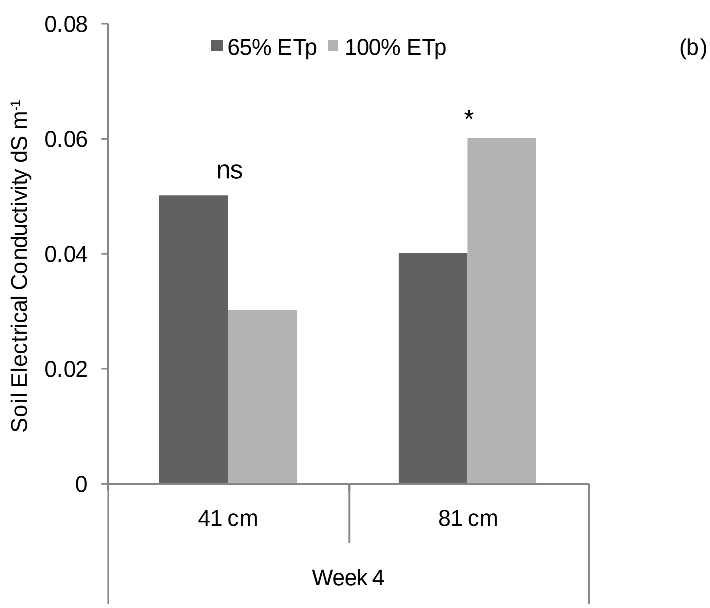


Figure 2.5. In the 2008 experiment, soil electrical conductivity values at (a) Depth B (10-20 cm) and (b) Depth C (20-30 cm) for Week 4 were higher for bermudagrass irrigated with wide spaced lines at 100% ETp, compared to 65% ETp.
* and ns = $P<0.050$ and $P>0.100$, respectively.

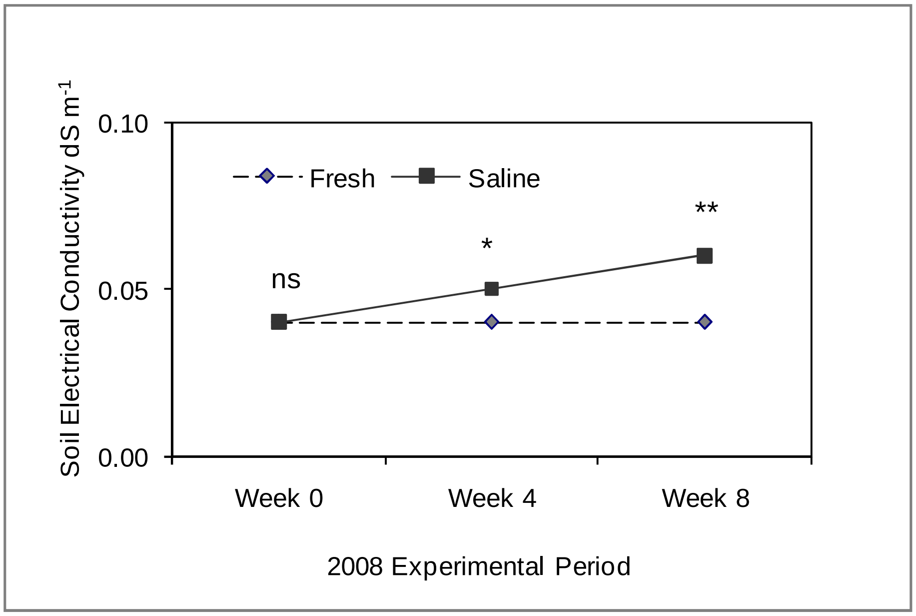


Figure 2.6. Soil electrical conductivity at Depth C increased with time for bermudagrass irrigated with the saline water source during the 2008 experiment.
*, **, and ns = P<0.05, P<0.01 and P>0.001, respectively.

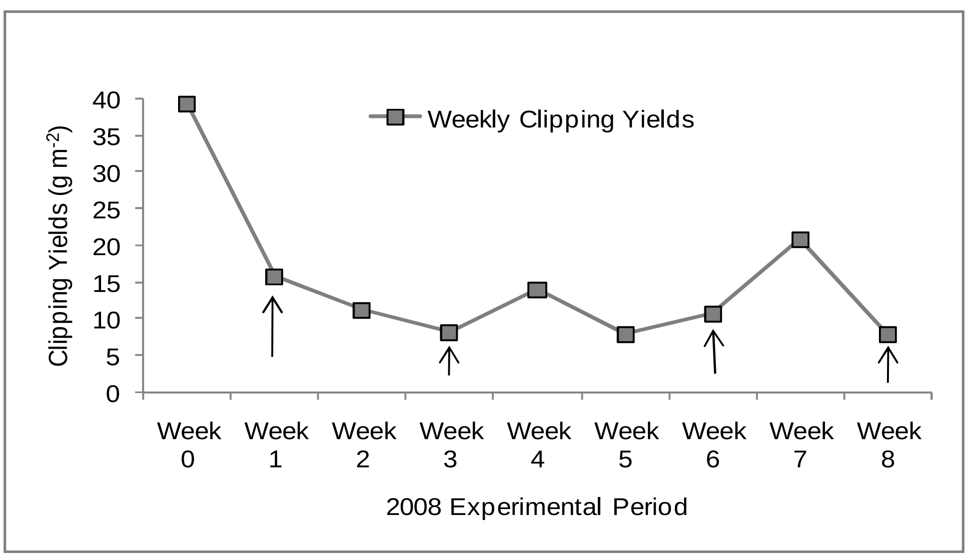


Figure 2.7. Weekly clipping yields were not influenced by biweekly fertilizer applications. Arrows indicate the week in which a fertilization event occurred. Bermudagrass was always fertilized through an injection system with Monday irrigations.

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CHAPTER THREE

Using Spectral Reflectance to Identify Associations with Bermudagrass Quality, Soil Water Content and Soil Electrical Conductivity

Introduction

Spectral reflectance provides a quick and easy way to identify environmental stresses for various crops, including turfgrasses (Jiang and Carrow, 2005). Since turfgrass stress management usually requires extensive sampling of soil and plant tissues (usually over a large area such as a golf course or athletic field) to properly identify and diagnose a problem, spectral reflectance can be implemented to provide a non-destructive and early detection method for stress management of turfgrass (Rodriguez and Miller, 2000). Researchers have reported strong relationships between spectral reflectance and plant leaf pigment (Carter and Spiering, 2002; Stiegler et al., 2005; and Bell et al., 2004), green biomass (Gamon et al., 1995), and water status (Penuelas et al., 1997; Rollin and Milton, 1998) in turfgrass systems. Thus, spectral reflectance has been used to evaluate turfgrass performance under various stress conditions including: drought (Fenstermaker-Shaulis et al., 1997; Huang et al., 1998; Jiang et al., 2004; and Jiang et al., 2005), traffic and compaction (Jiang et al., 2003a; Jiang et al, 2003b; Trenholm et al., 1999 and Guertal and Shaw, 2004), nutrient deficiency (Sembiring et al., 1998; Kruse et al., 2004), disease (Raikes and Burpee, 1998; Rinehart et al., 2001; and Anderson et al., 2004) and insects (Hamilton and Gibb, 2000).

Spectral reflectance is the portion of reflected light from the plant leaf or canopy that is relative to the incident light. Plant leaves reflect, absorb, or transmit light energy and this reflectance is mainly controlled by leaf internal structure, leaf surface properties, and concentration of plant biochemical composition (Penuelas and Filella, 1998). Plants use energy in the visible spectrum with wavelengths between 400-700 nm for photosynthesis and growth, with red wavelengths found between 600-700 nm (Fry and Huang, 2004). The amount of irradiance is low due to strong adsorption from the plant pigments, mainly chlorophyll (Knipling, 1970). Near infrared radiation (NIR) in wavebands of 700-1300 nm becomes highly reflected due to leaf scattering and low light absorption (Knipling, 1970 and Asra et al., 1984) at the air-water interfaces within mesophyll cells (Gupta and Woolley, 1971). The normalized difference vegetation index (NDVI) can be used to measure plant stress with a remote sensor and is calculated by [(near infrared reflectance – red reflectance) / (near infrared reflectance + red reflectance)]. The green normalized difference vegetative index (GNDVI) has been proposed as alternative to the NDVI and is calculated by replacing the red band in the NDVI with a green band (Gitelson et al., 1996). Greenness is associated with nitrogen status of many agronomic crops (Blackmer et al., 1994). Additionally, ratios of reflectance in the NIR and visible (red) wavelengths (NIR/R) may be beneficial to describe crop growth or environmental stresses and overall crop status (Trenholm et al., 1999). Daughtry et al. (1992) found an association between NIR/R and shoot biomass. Turf quality and canopy temperature is also correlated with NIR/R (Jiang et al., 2003a).

Spectral Reflectance Use on Turfgrass

Spectral reflectance has been used on various turfgrass cultivars to investigate environmental stresses such as drought. In one study, researchers found that reduced leaf water content correlated with near-infrared reflectance at 736-874 nm for Kentucky bluegrass (*Poa pratensis* L.), but not for perennial ryegrass (*Lolium perenne* L.) (Suplick-Ploense and Qian, 2002). Other researchers documented that turf quality or leaf firing had high correlations with canopy reflectance from 667 to 693 nm in bermudagrass (*Cynoden dactylon* L. x C. *transvaalensis*) (Jiang and Carrow, 2005).

Researchers have also investigated using spectral reflectance on turfgrass when irrigated with a reduced irrigation rate. One study documented that applying irrigation at 80 and 100% ET on five warm-season turfgrasses did not result in different NDVI and infrared to red (IR/R) measurements; however, difference in reflectance indices were significant when irrigation rates were 40 and 60% ET (Lee et al., 2004b). These researchers concluded that spectral reflectance could be used to aid in irrigation scheduling and better management of the water condition of the plant (Lee et al., 2004b). In another study, researchers detected water stress with spectral reflectance on 'Tifgreen' bermudagrass before it was visually apparent (Park et al., 2007).

Research regarding spectral reflectance use for the detection of salinity stress in turfgrass is limited. In one study, scientists used remote sensing to evaluate salinity effects on seashore paspalum (*Paspalum vaginatum* Swartz) and reported that the tolerant cultivars (SI 93-2 and HI 101) had higher NDVI and IR/R and lower stress indices compared to the least tolerant cultivar (Adalayd) (Lee et al., 2004a). This and other past studies (as discussed previously) used reflectance to examine treatment differences and, or to determine an association between the objective and subjective quality rating methods of the grass. Assessment of turfgrass quality performed by a trained evaluator is subjective; in comparison, the sensor provides a more objective evaluation. However, very little research has been conducted to determine if reflectance is associated with primary factors that influence turfgrass quality and stress such as soil water content and soil salinity.

The goals were to determine the relationship between the subjective and objective analysis methods of turfgrass quality, and determine if spectral reflectance was related to primary stress factors. The objectives of this experiment were to determine if monitoring reflectance can be used to assess turfgrass quality and stress by (a) determining if there is a relationship between the IR/Red index and visual quality, soil water content, and soil salinity, and (b) identifying if reflectance ratios were influenced by factor treatments.

Methods and Materials

The experiment was conducted on the same plots and time as mentioned in Chapter 2. Measurements were collected using an experimental active turfgrass quality sensor (LI-COR Biosciences, Lincoln, Nebraska) which measures two wavelengths, one in the near-infrared (NIR) (715-950 nm) and one in the red (400-700 nm). The LI-COR sensor was mounted face down parallel to the soil surface on a tri-pod 1 m (3 ft) from the ground surface facing an eastward direction. The sensor monitored an area with a diameter of 20.3 cm (8 in) along a 0.8 m (32 in) and 1.4 m (56 in) horizontal transect (for plots with 41 cm (16 in) and 81 cm (32 in) spacings, respectively) every 20.3 cm (8 in). This methodology ensured that readings were recorded over the entire width between drip lines for two subsurface drip lines in each plot, thus four readings for the narrow spaced lines and eight readings for the wide spaced lines. In order to make sure that the sensor was positioned in the same locations with the same orientation for each data collection event, golf tees were placed in the ground to indicate where to place tripod legs. The data were collected every Monday for the eight week experimental periods and measurements were collected at approximately the same time of day (between 9 and 11 am) on Monday of each week. Bermudagrass plots were mowed in the same orientation prior to collecting sensor measurements.

Prior to collecting measurements, the LI-COR was calibrated by collecting seven measurements (red and NIR) with the sensor positioned over a dark green Formica sheet. An average of the red and NIR measurements was obtained and results divided by the reflectance of the dark green Formica sheet (0.725). The resulting values were multiplied by the red and NIR values collected to obtain the corrected reflectance measurements. At the same time reflectance was recorded, visual turfgrass quality was assessed on a scale of 1-9 (9=dark green turf, 1=dead/brown turf, and 6=minimally acceptable turf) and soil water content was measured using a TH_2O Portable Soil Moisture Probe (Dynamax Inc, Houston, Texas).

The same soil cores that were mentioned previously in Chapter 2 were used for this experiment. Soil cores were taken to determine salinity at pre, mid, and post experiment (at 0, 4, and 8 weeks) at soil depths of 0-10 cm (0-4 in), 10-20 cm (4-8 in), and 20-30 cm (8-12 in). The cores were collected directly in front or behind each 20.3 cm diameter circle in which reflectance measurements were recorded. A 1:2 (soil/water) salinity extraction method was used to determine ECe (Rhoads, 1996). Data were examined using correlation and ANOVA (SAS Institute, 2003). Pearson's correlation coefficient was used to investigate the degree of association between NIR/Red and visual quality, soil water content, and soil salinity, while ANOVA examined treatment effects on the NIR/Red index.

Results and Discussion

Reflectance Association with Quality

The NIR/Red was positively correlated with visual quality scores for all weeks in the 2007 experiment, and for seven of the eight weeks in the 2008 experiment (Week 0, 3, 4, 5, 6, 7, & 8 at $P<0.01$, Table 3.1). In general, the positive association between NIR/Red and visual quality was stronger in 2007 than in 2008. The positive relationship is expected since quality considers both color and density. The higher density of chlorophyll per leaf, and the greater density of leaves, would result in a greener grass. Trenholm et al. (1999) also found a high degree of correlation (0.63-0.91) between turfgrass quality ratings and IR/R. Using another growth index (NDVI), Bell et al. (2002) reported more consistency when using the NDVI over time compared to the ratings from trained evaluators ($r^2 = 0.75$ and 0.41 for NDVI related to turf color).

Reflectance Associations with Primary Stress Factors

For both experiments, NIR/Red did not consistently correlate with soil water content (Table 3.1). A negative relationship was determined during the pretreatment week (Week 0 and 1) of the 2007 experiment; however, from mid-experiment onwards, a positive association was observed (0.19-0.56, Table 3.1). In 2008, there was a positive association for each week, although weekly *r* values were generally lower than in 2007.

A positive relationship would be expected since an increase in soil water content would result in a less stressed bermudagrass sward which would utilize water in daily plant production rather than coping with stress. However, the inconsistent correlation during the drought year (2007) suggests that perhaps the rate of change in soil water content was faster than the rate of change in plant response (growth).

In 2007, there were no significant relationships determined between NIR/Red and ECe at any depth or for the average before the experiment began (Week 0, Table 3.2). At Week 4 (mid-experiment), there was a positive relationship between NIR/Red and ECe for Depths C and the average (Table 3.2). At Week 8, positive associations were determined between NIR/Red and ECe at all three depths, and the average (Table 3.2). The positive relationships between NIR/Red and ECe at the lower soil depths (Depth C at Week 4 and Depths B & C at Week 8) may be due to the bermudagrass's response to salinity stress. Bermudagrass elongates its root cortex to compensate for the increased solute concentration (Leonard, 1983). Although root cortex quantity or elongation was not determined in this study, there was an increase in root biomass from the 15-30 cm soil section (see Chapter 2). Thus it is expected that more root cortexes would be present to elongate in the lower depths, where greater osmotic potential influences would occur as the bermudagrass tries to take up soil water. In addition, bermudagrass has salt glands located on leaves to excrete salts. Increasing density will increase salt exclusion, and also results in more chloroplasts to absorb Red wavelengths and reflect NIR, resulting in an increase in NIR/Red. Similar results regarding the relationship between salinity and IR/R were reported by Lee et al. (2004a). IR/R reflectance was used to study the response of nine seashore paspalum (*Paspalum vaginatum* Swartz) ecotypes to variable salinity levels (1.1 - 49.7 dS m^{-1}) under greenhouse conditions. An increase of root growth of 51% (partial R^2) was indicated by an association between salinity stress (ECw=50 dS m^{-1}) and IR/R reflectance (Lee et al., 2004a).

It should be noted that ECe during both experiments were very low (see Chapter 2) and of no concern to be a soil or plant hazard. The fact that NIR/Red was positively correlated with low ECe suggests that the bermudagrass and sensor was sensitive to minor increases in ECe. Except for Depth A at the end of the experiment, NIR/Red was not associated with ECe during the 2008 experiment.

Reflectance Differences Due to Factor Treatments

The only factor that influenced NIR/Red reflectance was time (Week, Table 3.3 and Figure 3.1). This was similar to visual quality ratings and clipping yields as discussed in Chapter 2. Air temperature and rainfall amounts appeared to follow a similar pattern of weekly NIR/Red measurements in 2007, but not for 2008.

Conclusions

Past research has supported using the NIR/Red reflectance index to measure changes in plant responses to both abiotic and biotic factors (Trenholm et al., 1999; Walburg et al., 1981; Howell, 1999; Jiang et al., 2003a; Jiang et al., 2003b; Park et al., 2007; Guertal and Shaw, 2004). Most of the research has primarily compared ratings from a subjective point of view (visual based ratings such as quality, density and texture) and few quantitative characteristics (yields and chlorophyll content). In this experiment, besides visual quality, the primary factors that cause plant stress (soil water content and soil salinity) were measured in conjunction with the NIR/Red to determine if bermudagrass responded to changes from the impact of these stress factors.

The positive correlation between quality assessed visually (subjective assessment) and by monitoring NIR/Red (objective assessment) indicates that the growth index can be used as a means to assess quality changes in the bermudagrass.

The drought that occurred during the 2007 experiment allowed for NIR/Red to be monitored from a broad range of soil water content and ECe. The inconsistent correlations between soil water content and NIR/Red in 2007 may be attributed to the change in soil water content which was relative to the quick change in bermudagrass growth response, when irrigations were applied three times per week but not sufficient to overcome stress due to the drought conditions. Additionally, salt accumulation in the lower levels of the soil profile at the root-zone during the drought probably attributed to salinity stress which was correlated with ECe at mid and post experimental periods. In comparison, the abundance of rainfall during the 2008 experiment resulted in non-stress conditions. This provided an opportunity to evaluate how sensitive the index was to detecting minor changes in soil water content and ECe. There was a positive linear relationship between NIR/Red and ECe in the 2007 experiment and no relationship during the 2008 experiment. Perhaps the lack of correlation in the 2008 experiment can be attributed to the general lower ECe from less saline water applications and abundant rainfall under normal weather conditions. Even in the 2007 experiment although there was a broader ECe range, values were still very low. This suggests that monitoring NIR/Red can determine minimal bermudagrass growth changes.

This experiment indicated that spectral reflectance can be used to assess bermudagrass response to changes in primary stress factors depending on level of stress. The index was less sensitive to short term stresses, such as for soil water content, compared to longer term stresses, such as soil salinity. In addition, NIR/Red allows for an objective, non-biased (quantitative) evaluation of turf quality. Future research should investigate using spectral reflectance to assess turfgrass quality and stresses due to using higher saline water concentration than what was evaluated in this experiment, lower quality water sources, and reduced irrigation volumes.

<u>Tables</u>

Table 3.1. Correlation (r) and significance for Near-infrared/Red reflectance ratio with visual quality and soil water content (SWC) during the 2007 and 2008 experiments.

	Quality†		**SWC**	
Week	2007	2008	2007	2008
	----------------------*r / Significance*		----------------------	
0	0.51 ***	0.38 ***	-0.20 *	0.20 *
1	0.66 ***	0.11 ns	-0.11 ns	0.14 ns
2	0.66 ***	0.18 ns	-0.04 ns	0.22 *
3	0.94 ***	0.33 ***	0.19 ns	0.47 ***
4	0.68 ***	0.60 ***	na∫	0.11 ns
5	0.83 ***	0.62 ***	0.56 ***	0.50 ***
6	0.65 ***	0.70 ***	0.48 ***	0.29 ***
7	0.65 ***	0.54 ***	na	0.28 **
8	0.62 ***	0.35 ***	na	0.35 ***

† Visual quality was rated on a scale from 1 – 9, with 1= dead, brown grass, 6= minimally acceptable, and 9=green, healthy grass.
‡*, **, ***, and ns = P<0.10, P<0.05, P<0.01 and P>0.10, respectively
∫ na = no correlation with SWC available due to equipment failure.

Table 3.2. Correlation (r) and significance for Near-infrared/Red reflectance ratio (index) with pre (Week 0), mid (Week 4), and post (Week 8) trial soil electrical conductivity at three depths (A=0-10 cm, B=10-20 cm, C=20-30 cm) and overall averages for the 2007 and 2008 experiments.

	2007				2008			
Week	Depth A	Depth B	Depth C	Avg	Depth A	Depth B	Depth C	Avg
	--			*r / Significance*	--			
0	-0.07 ns†	0.11 ns	0.05 ns	0.01 ns	0.17 ns	0.17 ns	0.08 ns	0.14 ns
4	0.18 ns	0.21 ns	0.23 *	0.40 ***	-0.17 ns	0.18 ns	0.18 ns	0.18 ns
8	0.26 **	0.38 ***	0.38 ***	0.34 ***	0.22 *	0.05 ns	0.13 ns	0.14 ns

† *, **, ***, and ns = P<0.10, P<0.05, P<0.01 and P>0.10, respectively.

Table 3.3. Degrees of freedom (df) and significance for factor and factor interactions for NIR/Red for the 2007 and 2008 experiments. Significant values (P<0.05) are in bold.

Factor and factor interaction	df	RATIO 2007	RATIO 2008
		-----------*r*-----------	
Source	1	0.1203	0.3476
Spacing	1	0.5652	0.8784
Volume	1	0.1864	0.5113
Week	8	**<0.0001**	**<0.0001**
Source*Spacing	1	0.5561	0.2204
Source*Volume	1	0.7178	0.8547
Source*Week	8	0.5061	0.1323
Volume*Week	8	0.1388	0.5760
Source*Spacing*Volume	1	0.5806	0.2942
Source*Spacing*Week	8	0.7227	0.9314
Source*Volume*Week	8	0.9628	0.9192
Spacing*Volume	1	0.6902	0.6482
Spacing*Week	8	0.7172	0.9957
Spacing*Volume*Week	8	0.9618	0.9849
Spacing*Source*Volume*Week	8	0.2835	0.1986

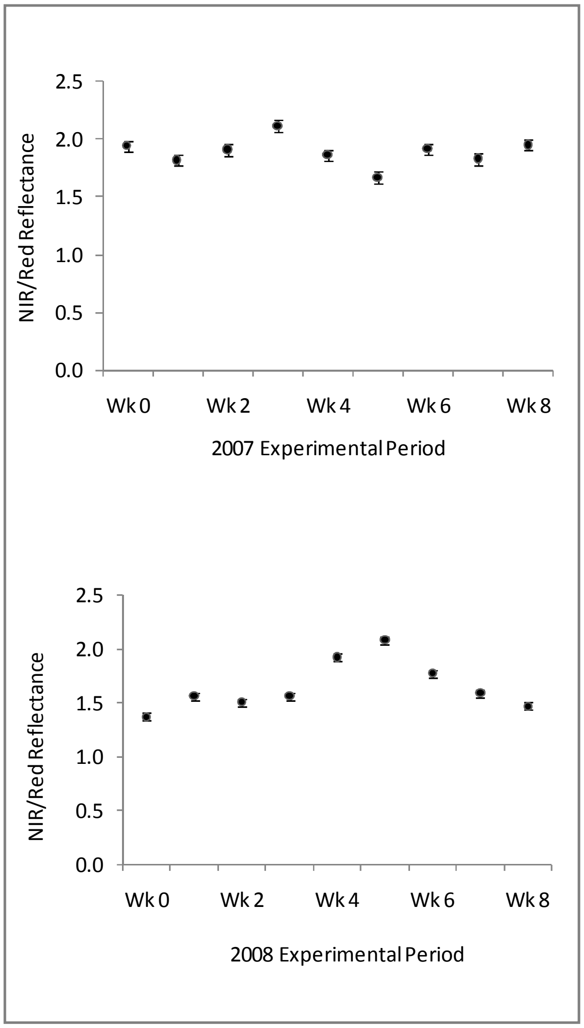

Figure 3-1. Near infrared/Red reflectance measurements were influenced by time for the 2007 and 2008 experiments.

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