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PHYSIOLOGICAL RESPONSE AND NUTRIENT RECOVERY OF COOL-SEASON TURFGRASSES UNDER VARIOUS ENVIRONMENTAL STRESSES

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ABSTRACT

Potassium (K) is an essential plant nutrient commonly applied to increase creeping bentgrass tolerance to environmental stresses and maintain overall turfgrass stand health. Limited research defining the K requirement of creeping bentgrass under heat and drought stress exists. Furthermore, research investigating K, calcium (Ca), and magnesium (Mg) recovery under abiotic stress has been inconsistent. To build on previous research and investigate the differences between liquid and granular K fertilization, experiments were conducted to evaluate the performance of liquid and granular K carriers in conjunction with liquid calcium and magnesium on their ability to suppress summer bentgrass decline of creeping bentgrass (*Agrostis stolonifera* L.) grown in the transition zone of the United States.

A field experiment was conducted from May 2006 to October 2007 to investigate liquid and granular K fertilization on turfgrass quality, clipping yield, chlorophyll, root weight, volumetric soil water content and leaf and root nutrient concentrations of ‘Crenshaw’ creeping bentgrass. Treatments consisted of two annual potassium rates, 0 and 195 kg K ha^{-1} yr^{-1}, in liquid and granular forms, with either liquid calcium (49 kg ha^{-1} yr^{-1}), liquid magnesium (49 kg ha^{-1} yr^{-1}), or both. Liquid K applications significantly reduced visual quality of bentgrass during 2006. Turfgrass quality in 2007 was unacceptable (<7) for the months of June, August, and September, while only plots receiving Ca without K produced acceptable turf. Clipping yield was also significantly decreased under liquid K in August and November 2006, while calcium produced the greatest yield in July and August 2006 and September and October 2007. ‘Crenshaw’

creeping bentgrass treated with liquid K produced 8 and 16% greater clipping K concentration in August and November 2006 and 11 and 21% greater tissue K content by June and October 2007 compared to untreated.

Another two year field study was conducted from May 2006 to October 2007 to determine the performance of two K carriers (liquid and granular) under rates of 0, 98 and 195 kg ha^{-1} annually and a wetting agent (WA) at 19.09 L WA ha^{-1} monthly. Data concerning visual turf quality, clipping yield, root weight, soil moisture, soil hydrophobicity, and leaf and root tissue nutrient concentrations were recorded. Turf quality was improved by the high rate of granular K; however, quality significantly declined for turf receiving the higher liquid K rate throughout 2006 from phototoxic effects of foliar K fertilizers. Wetting agent decreased turf quality in 2006 partially due to excess soil water retention but creeping bentgrass quality was improved under drought conditions in 2007 with the addition of WA. In August and November 2006 and June and October 2007, liquid K at 195.29 kg ha^{-1} produced greater leaf tissue K concentrations compared to untreated. Liquid K at the 195.29 kg ha^{-1} rate adversely affected root weight in August 2006 and October 2007 by 36% and 20%, respectively, while yearly declines in root weight of all treatments were noted. Soil hydrophobicity decreased by 19.92 and 7.16 units at 1.5 cm in 2006 and 2007, respectively, and declined by 8.86 and 6.64 units at 3.0 cm in 2006 and 2007, respectively, with the addition of the WA.

A third field study was conducted from November 2006 to February 2008 to examine the interactive effects of nitrogen (N) and iron (Fe) fertilization on rough

bluegrass (*Poa trivialis* L.) overseed stands under reduced light environments. Treatments included three annual N rates of 49, 98, and 147 kg N ha^{-1} yr^{-1} split between 4 applications during the winter months. Fe was supplied simultaneously at 10.8 kg a.i. ha^{-1} per season. Shade treatments included full sunlight and 55% shade and were applied daily. Data collection included turf quality, clipping yield, chlorophyll, and clipping nutrient concentrations. In this experiment, turf quality was improved with increased N rate and shade treatments in year 1; however visual quality declined greatly for turf under reduced light irradiances and higher N rates by year 2. Rough bluegrass clipping yield and chlorophyll content generally increased linearly with increasing N rates; while shade increased clipping yield by 28% in December 2006 and reduced yield by 38 and 33% in December and February 2007, respectively. Leaf tissue N concentrations were greatest under the highest N rates until February of year 2 when the 98 kg K ha^{-1} yr^{-1} rate produced 16% greater tissue N concentration compared to the 147 kg K ha^{-1} yr^{-1} rate. Rough bluegrass treated with foliar applications of Fe generally exhibited minimal and inconsistent effects on leaf N, Fe and chlorophyll content compared to non-Fe treated turf.

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CHAPTER 1

INTRODUCTION

Golf courses play a significant role in the economy of all regions of the United States with an economic impact of $60 billion annually from the turfgrass industry (Shearman, 2006). In 2004, South Carolina's golf course operations and off-course expenditures of resident and visiting golfers generated an estimated $2.3 billion a year (Flowers, 2006). In order to sustain this economic impact, golf course superintendents must incorporate sound agronomic practices in order to uphold the best playing conditions, turfgrass health, low environmental impacts and aesthetics as possible. Fertilization has long been a tool used by turfgrass managers to achieve optimal turf color, density, playability, and health. With ever-increasing expectations for golf course playing conditions, the need for optimal fertility also rises. Potassium (K) is an essential plant element that constitutes 1.5 to 3% of dry leaf tissue (McCarty, 2005; Carrow et al., 2001; Marschner, 1995). It is a nutrient considered to be second only to nitrogen in quantity required by turfgrasses. Potassium is not known to greatly influence turf color or growth but has strong influences on abiotic stresses such as drought, heat, cold, salinity and wear (Carrow et al., 2001). Because of potassium's ability to elevate turfgrasses natural ability to withstand environmental stress, it has become a nutrient of great concern with turfgrass managers seeking to increase and sustain density and health of turf.

Excessive fertilization with K has shown apparent disadvantages by reducing the amount of other soil and plant extractable cations. Previous studies have shown increasing potassium fertilization resulted in decreases of plant tissue and soil calcium (Ca) and magnesium (Mg) concentrations, often leading to nutrient deficiencies (Woods et al., 2005; Miller, 1999; Sartain 1993).

Localized dry spots (LDS) have been documented as an advanced stage of summer bentgrass decline (Karnok and Tucker, 2001a). Localized dry spots are characterized by irregular patches of turfgrass that show typical signs of severe drought stress. Limited research as to the source of LDS has been performed, but possible causes include humic (Roberts and Carbon, 1972) and fulvic acid (Miller and Wilkinson, 1979) coatings on soil particles, leading to the development of soil hydrophobicity. Currently, the most effective control method against LDS is through timely applications of wetting agents (Karnok and Tucker, 2001a; Karnok and Tucker, 2001b; Leinauer et al., 2001). Wetting agents are applied to reduce the surface tension of water on hydrophobic sand particles, thus increasing soil water retention. Maintaining adequate soil moisture, especially deep within the soil profile will allow turf to develop relatively deeper root systems to explore and exploit additional water resources. However, the combinative effects of K and application of wetting agents during summer months on creeping bentgrass have not been investigated.

It is estimated that some 20 to 25% of maintained turfgrass is grown under some degree of shade (Beard, 1973). Due to the light saturation point of C_3 grasses, shade can be advantageous to cool-season grasses in some situations. Extreme levels of reduced irradiance however, can lead to pronounced upright growth habits, thinner and longer leaves, reduced density, shallow rooting, decreased chlorophyll content, reduced tillering, and heightened disease susceptibility (Dudeck and Peacock, 1992; Beard, 1973). The most common recommendation to sustain acceptable growth under light-stressed conditions is reducing fertility inputs, particularly nitrogen (N). Fertilization of N promotes aggressive shoot growth, and under shaded conditions this results in drastic reductions in turf density and stored carbohydrates **(**Baldwin, 2008; Long, 2006; Bunnell, 2005a; Bunnell et al., 2005b; Trenholm et al., 1998). Foliar applications of iron (Fe) have suggested in order to compensate for lower N fertilization by maintaining desired turfgrass color, however the impact of N and Fe on a winter overseeded, cool-season turfgrass under shade has not been fully investigated.

The objectives of this thesis research were:

1. To investigate the ability of liquid and granular potassium fertilization to reduce summer decline associated with creeping bentgrass.
2. To investigate the interaction of potassium, calcium, and magnesium on nutrient recovery and allocation in roots and shoots of creeping bentgrass.
3. To evaluate the ability of a wetting agent to reduce drought stress and soil hydrophobicity during the summer months.
4. To assess the effects of nitrogen and iron fertilization on overseeded bermudagrass under a reduced light environment.

CHAPTER 2

LITERATURE REVIEW

Creeping Bentgrass

Creeping bentgrass is the most widely used cool-season turfgrass on golf course putting greens today (McCarty, 2005; Turgeon, 2005; Beard, 2001). Creeping bentgrass generally occurs at cooler, moist climates throughout the USA, but are commonly planted as golf greens in the warm, humid regions of the southeastern USA. Creeping bentgrass is known for its fine texture, year-round green color, and tolerance of low mowing heights. Creeping bentgrass possesses excellent cold tolerance and a stoloniferous growth habit, producing very dense turf stand (Fry and Huang, 2004). Because creeping bentgrass produces high amounts of organic matter, an extensive cultivation regime must be present. Slow to recuperate from environmental stresses and damage, creeping bentgrass exhibits minimal wear tolerance (McCarty, 2005).

While creeping bentgrass is used extensively on golf courses in the United States for its exceptional playability, it is prone to decline of turf quality during the summer months, thus must be managed intensely to insure acceptable stand health and playing conditions.

Creeping bentgrass is native to Eurasia, where temperatures ranged from 60 to 75^{o}F (15 to 24^{o}C) (Ward, 1969). Optimal temperatures for cool-season grasses range from 15 to 24 ^{o}C for shoot growth and 10 to 18 ^{o}C for root growth (Beard, 1973). Annual temperatures in the summer months of the southeastern US can reach and exceed 30 to 35

^{o}C. Because roots of creeping bentgrass exhibit a lower optimal growth range, they are the first and most affected by high temperature stress. High soil temperatures have been shown to be more detrimental than high air temperatures to creeping bentgrass turf quality, canopy photosynthetic rate, leaf photochemical efficiency, and root growth (Xu and Huang, 2000). Huang and Liu (2003) found highest rooting depths of creeping bentgrass occurred in May, followed by a decline in rooting depth from July to September and recovery beginning in October. Additionally, very few new roots were produced during the summer months, and production of those roots was only following small decreases in soil temperature. Root mass and length also differ on the cultivar level. A heat tolerant creeping bentgrass cultivar, 'L-93', has shown increased root fresh length and weight compared to the more heat sensitive cultivar, 'Penncross' (Xu and Huang, 2001). Such a root system will facilitate an increased surface area in contact with soil and water, thus, increasing the plant's ability for transpirational cooling and nutrient uptake.

Additional methods of reducing creeping bentgrass surface temperature in the summer months are by syringing and/or use of surface fans. Syringing, or misting, is a common practice on cool-season golf greens where a very fine spray of water is applied to the turf surface in order to provide an evaporative cooling effect. Surface fans are large (0.5 to 1.0 m in diameter) units placed on the outer edge of putting greens, creating air movement across the green surface. These machines are especially useful of greens where surrounding terrain and vegetation restrict air movement. Rodriguez et. al. (2005) reported that surface fans in association with misting reduced turf canopy, soil surface, and soil temperatures by as much as 9, 7, and 6^{o}C, respectively. Duff and Beard (1966) noted air movement reduced soil temperatures at a 5 cm depth on average 7^{o}C. A separate study in the same experiment showed that the application of 6mm of syringe water dropped soil temperature on average 4 ^{o}C. Marginal success was found when using syringing or fans alone (Guertal, 2005). However, when both fan and syringing were used, time that soil remained at temperatures at or above injurious levels was significantly reduced. DiPaola (1984) determined that the effects of syringing, no matter the timing or water volume, could not be detected 1 hour after syringing and after 0.5 hours a reduction in soil temperature of 0.7 ^{o}C was reported.

Relative humidity (RH) is defined as the amount of moisture in the air as a percentage of the amount of moisture in the air to the amount of moisture that air can hold at saturation, given a specific temperature. In low RH climates, such as deserts, daytime temperatures typically peak at over 38^{o}F, with very cool night time temperatures. When moisture is present in air, however, a buffer to temperature changes is created. RH in the southeastern US is reasonably high. Higher amounts of RH produce higher nighttime temperatures due to heat held in atmospheric moisture. This becomes especially concerning when managers try to survive bentgrass summer stress. During periods of high RH, nighttime soil and canopy temperatures remain high and creeping bentgrass does not have the ability to recover from extreme daytime temperatures.

Adding to the dilemma, high RH also poses problems for transpiration. Plants naturally cool themselves in times of heat stress by evaporative cooling, which will be discussed in more detail later. When atmospheric moisture is high, the gradient of water potential used for evaporate cooling is lost. Thus, plants retain water, and uptake of water by roots stops. As a secondary affect, discontinuing water uptake also affects nutrient uptake which simultaneously enter plants with water.

Potassium

Potassium (K) is a primary, essential nutrient for the growth and development of turfgrass. K is only second to nitrogen as the most required plant nutrient with an average plant tissue concentration of 1.5-3.0% by dry leaf tissue weight (McCarty, 2005; Carrow et al., 2001; Marschner, 1995). Of the total K content of the soil, only 1-10% is readily available to plants in nonexchangeable forms (Carrow et al., 2001; Marschner, 1995). Additionally, on turfgrass grown soil media consisting of mostly sand-based materials with low cation exchange capacities (CEC), leaching potential of K salts increases significantly and lowers K availability accordingly (McCarty, 2005; Turgeon, 2005; Carrow et al., 2001). Potassium deficiency is not especially prominent, except when turfgrass is under additional stresses. Turfgrass plants most often exhibit weak and spindly individual plant growth under heat and drought conditions. Plants suffering from K deficiency often exhibit a loss of turgor, and when under water stress they easily become flaccid (Mengel and Kirkby, 2001; Marschner, 1995). Although deficiencies are not often seen in turfgrasses, under severe deficiency, interveinal chlorosis of older leaves appears first, leading to total yellowing of the entire leaf then leaf rolling or burning occurs. In crops, K deficient crops are susceptible to lodging. Due to its mobility, potassium can be translocated from the older, mature leaves to the younger, meristematic tissues of the plant (McCarty, 2005; Carrow et al., 2001; Marschner, 1995). Plant roots absorb K as the K^+ cation, which is highly mobile and regulated by K-channels throughout the plant (Mengel and Kirkby, 2001; Marschner, 1995)

Potassium, unlike many elements, has no strong influence on shoot color, turf density or growth. However, potassium has been shown to allow plants to be better suited to overcome negative effects of high nitrogen fertility by increasing cold hardiness, heat tolerance, disease and pest resistance, drought and high traffic. Turfgrass mangers often apply K at equal or half of N fertility levels. Miller (1999) reported that soil extractible levels of K were increased linearly with increasing K fertilization up to 400 kg ha^{-1} $month^{-1}$. However, maximum tissue K concentration for 'Tifdwarf' hybrid bermudagrass was reached at a rate of 74 kg K ha^{-1} $month^{-1}$. Commonly, K is applied by turfgrass managers at much higher rates than are recommended (Snyder and Cisar, 2000; Miller, 1999).

Previous studies indicate the beneficial effects potassium has during extreme heat stress. Supplemental applications of K during periods of heat stress have been shown to decrease the amount of injury on creeping bentgrass during summer months (Fu and Huang, 2003; Turner and Hummel, 1992; Waddington et al., 1978). In plants, K acts as an osmotic solute, actively regulating the opening and closing of stomatal apertures. Under sufficient leaf tissue K, plants are able to control the opening and closing of these stomata, and thus, regulate the amount of water lost through transpirational cooling. Under K deficiencies, however, the stomatal control mechanism becomes less efficient, evapotranspiration (ET) is increased, and leaf internal temperatures are amplified. The role of K in plant water relations will be discussed later. Fu and Huang (2003) found that foliar applications of K slowed leaf senescence and allowed turfgrass to maintain photosynthetic abilities under supraoptimal temperatures, thus increasing creeping bentgrass heat tolerance.

Under drought situations, plants containing sufficient K are able to expand cell walls, decrease tissue water content and close openings in stomata. Stomatal closure is brought about by an influx of K into the guard cells surrounding the opening, thus decreasing the amount of water lost via transpiration (McCarty, 2005; Taiz and Zeiger, 2005; Marschner, 1995).

As the concentration of K increases in plants, cell walls expand, tissue water decreases, and turfgrass plants are more turgid due to a closer regulation of water loss through stomatal openings. By potassium providing the necessary force to uptake water, drought resistance is greatly increased (McCarty, 2005; Taiz and Zeiger, 2005; Marschner, 1995). Much research has been performed showing the beneficial effects of K on drought stress and recovery from drought stress. For example, Schmidt and Breuninger (1981) reported increasingly higher K fertilization had a direct, positive correlation with drought stress recovery on Kentucky bluegrass.

Turfgrass injuries from cold temperatures are a result of chilling and/or freezing stresses. The extent to which freezing stress injury occurs is a function of the plant species, physiological state of the plant, environmental conditions, and the mechanism of injury (Beard, 1973). Negative correlations have been reported between winter hardiness and crown moisture (Tompkins et. al., 2000). Turf managers apply most nitrogen (N) during the spring and fall of each year for cool season turfgrasses (Beard, 1973). Late fall applications of N have been shown to amplify the extent of winter injury of Kentucky bluegrass by increasing the amount of crown hydration (Carroll and Welton, 1939). Contrastingly, K has been reported to lower crown hydration, and therefore, winter hardiness. Markland and Roberts (1967) found that tissue moisture levels decreased with increasing higher amounts of K, decreasing winter injury. Webster and Ebdon (2005) evaluated perennial ryegrass (*Lolium perenne* L.) low temperature tolerance in response to N and K rates. Results indicated maximum cold hardiness was achieved when low to moderate N (49 to 147 kg ha^{-1} yr^{-1}) levels were applied with medium to high levels of K (245 to 441 kg ha^{-1} yr^{-1}). In other words, the ability of K to increase winter cold tolerance is highly dependent on fall N application levels.

A majority of turfgrass research has investigated disease instance and severity in association to N fertilization levels and timing. Recently, K applications and plant K concentrations have been looked into for their role in suppression of disease outbreaks. Low levels of plant K often result in favorable conditions for disease occurrence, particularly Spring dead spot (*Ophiosphaerella korrae*), Dollar spot (*Ruststroemia floccosum*), Take-all patch (*Gaeumannomyces graminis* var. *avenae*), among others (Carrow et al., 2001). Goss and Gould (1967) noticed a five-fold increase in the occurrence of the *Ophiobolus* patch, or Take-all patch, disease in untreated K plots compared to treated plots. Studies have reported reductions in Dollar spot incidence and severity under adequate K fertilization (Juska and Murray, 1974; Markland, 1969). Still, other studies have shown no differences or remarkable increases in disease occurrence with late fall applications of K (Tredway, 2001; McCarty et al., 1992).

Many turfgrass managers apply excessive nitrogen on extensively worn turf as an attempt to increase turf density and shoot growth. This causes a thinning of cell walls (Beard, 1973) that inversely decreases wear tolerance. K has been shown to enhance wear tolerance by maintaining turgor pressure within cells and reducing tissue succulence (Beard, 1973). Toronto creeping bentgrass had significantly improved wear tolerance under 270 and 360 kg K ha^{-1} (Shearman and Beard, 1975). This study also reported increased tissue K concentration, mat accumulation, load-bearing capacity, and leaf tensile strengths under the higher K rates. Trenholm et al. (2000) demonstrated enhanced wear tolerance on seashore paspalum (*Paspalum vaginatum* Swartz.) and hybrid bermudagrasses (*Cynodon dactylon* L. x *C. transvaalensis* Burtt-Davy) receiving 41 kg K ha^{-1} annually due to greater shoot density, leaf tissue K concentration, and leaf moisture. However, Trenholm et al. (2001) later reported no beneficial response of Seashore paspalum wear tolerance under either 92 or 392 kg ha^{-1} K annually. Studies on creeping bentgrass and Kentucky bluegrass showed no beneficial effects of K application on wear tolerance or recovery under rates of 0 to 192 kg K ha^{-1} annually (Hawes and Decker, 1977; Carroll and Petrovic, 1991).

Although many studies conclude that increasing K fertilization shows a positive, liner relationship with turfgrass quality and health, research reporting conflicting results have also been found. Previous studies have shown K applications provided no beneficial effects on creeping bentgrass. Possible explanations for differential results between studies could possibly be due to existing soil K concentrations (Fitzpatrick and Guillard, 2004; Hawes and Decker, 1977), K requirements between species and cultivars (Gray et. al., 1953), measurement procedures (Woods et. al., 2005), application of plant stress methodology (Carroll and Petrovic, 1991), etc.

Calcium

Calcium (Ca) and magnesium (Mg) are needed in larger amounts than most all other micronutrients. Calcium is absorbed by plants as the Ca^{+2} ion and supplied to plants roots by mass flow and root interception. Ca is highly immobile within the plant with little movement through phloem constituting approximately 0.50 to 1.25% by tissue dry weight of plants (Carrow et al., 2001). Ca is extremely immobile within soils and plants alike, however deficiencies in turfgrass are rare in field situations due to Ca immobility and fibrous monocot rooting characteristics (Carrow et al., 2001).

Perhaps the most important role of Ca in plants is the stabilization of cell walls, preventing breakdown of cell membranes and loss of cellular compounds, particularly under elevated temperatures (Marschner, 1995). Ca^{+2} applications have been shown to decrease the severity of lipid peroxidation of drought stressed tall fescue and Kentucky bluegrass plants (Jiang and Huang, 2001). Fu and Huang (2003) noted that levels of malondialdehyde (MDA), a by-product of lipid peroxidation, were lower following foliar applications of Ca. Calcium also takes part in the promotion of cell division, protein synthesis, and support of carbohydrate movement within the plant.

While beneficial effects of Ca have long been explored, recent research indicates that additional Ca fertilization effects may not be necessary. St. John et. al. (2003) concluded additional Ca treatments had no positive effects on clipping yield, turf quality, or Ca concentration of leaf tissue in creeping bentgrass. Furthermore, the study showed detrimental effects on other leaf tissue nutrient contents are possible due to competition of cation exchange sites.

Magnesium

Plant uptake of the magnesium (Mg) ion is as the Mg^{+2} ion and enters plant roots via mass flow and diffusion. Mg is highly mobile within the plant, with the ion readily translocated within upward (xylem) and downward (phloem). Leaf tissue content of Mg is usually between 0.15 to 0.50% (dry weight). Mg deficiencies in turf have been shown to reduce leaf length, shoot length, and shoot weight (Kamon, 1974). Mg is located in the center of the chlorophyll molecule and 6 to 25% of a plant's total Mg content can be used for this purpose (Carrow et al., 2001). A molecule of chlorophyll contains approximately 7% magnesium (McCarty, 2001). Magnesium is required activation of two enzymes in the synthesis of chlorophyll, as well as being involved as a structural component in ribosomes.

Rehm and Sorensen (1985) reported a linear increase of plant tissue Mg concentrations with increasing rates of Mg fertilization on corn grown on sandy soil (Zea mays L.). This finding correlates well with the findings of other studies performed on warm-season turfgrass species (Cripps, 1989; Sartain, 1985; Landua, 1973). Sartian

(1993) revealed applications of $MgSO_4$ increased visual quality and clipping yields of hybrid bermudagrass and perennial ryegrass.

Conversely, Mg fertilization has been shown to have very little effect on the Mg concentration of tall fescue (West and Reynolds, 1984). Sartain (1993) reported that applications of Mg to plots in which clippings were removed increased the amount of thatch. Other research has shown that soil and tissue Mg concentrations are inversely related to K soil and tissue concentrations (Miller, 1999; Belesky and Wilkinson, 1983; Landua et. al., 1973). However, soil exchangeable Mg levels may offer a viable explanation for conflicting results.

K/Ca/Mg Interaction

The soil level and plant uptake interaction between K, Mg, and Ca has been studied for many years. Data suggests that K is needed by plants in greater proportions than Ca and Mg. A recent trend in turfgrass management is the fertilization of N and K at a 2:1 to 1:1 ratio (Turgeon, 2005; Carrow et al., 2001; Beard and Rieke, 1966) to improve stress tolerance, although Synder and Cisar (2000) reported increasing K rates beyond a N-K ratio of 1:0.5 to 1:1 had no effect on bermudagrass appearance, shoot growth, or root weight. Such high levels of K fertilization have been shown to decrease amounts of soil available Ca and Mg (Woods et. al., 2005; Miller, 1999; Sartain, 1993; Cripps et. al., 1989). Additionally, applications of Ca and/or Mg will decrease soil levels and mobility of K. Sartain (1993) reported that soil extractible Ca was reduced with applications of K and reduced to a greater extent with the application of Mg.

Applications of K at 200 kg ha^{-1} increased clipping yield of 'Tifway' bermudagrass while depleting soil extractable Ca levels. When Ca, Mg, and K were applied, soil extractible K was reduced. It is possible that the divalent nature of Ca and Mg would explain the loss of soil K when all were applied. Woods et al. (2005) reported decreases in leaf tissue and extractible soil Ca and Mg levels in response to increasingly higher K applications on 'L-93' creeping bentgrass when 1:5 H_2O and 0.01 *M* $SrCl_2$ extraction methods were used.

Miller (1999) showed that by increasing K fertilization, extractable soil Ca and Mg in loamy sand and a sand-peat mixture decreased. Also, with increasing K applications, leaf tissue Ca and Mg concentrations were reduced in hybrid bermudagrass. Cripps et. al. (1989) also reported similar findings of K fertilization increasing tissue K concentrations while lowering plant Ca and Mg concentrations in Coastal bermudagrass (*Cynodon dactylon* (L.) Pers.). Landua et al. (1973) correlated K and Mg fertilization on Coastal bermudagrass. Increasing applications of K increased K and decreased Mg tissue concentrations. Conversely, applications of Mg increased Mg tissue levels while decreasing K tissue concentrations. West and Reynolds (1984) found that K fertilization increased plant K levels while applications of Mg did not. Soil test (Mehlich I) showed very high extractable soil Mg and Ca at the onset of the study. Research showed no effects on Ca tissue concentrations. In another study, corn was used to determine the fertilization effects of 6 rates of K and Mg. As observed previously discussed studies, Rehm and Sorensen (1985) found Ka and Mg tissue concentrations increased with increasing fertilization of each nutrient, respectively. However, at all Mg fertilization levels, Mg tissue concentrations decreased curvilinearly with increasingly higher K rates.

Plant-Water Relations

The essential components necessary for proper function and survival of plant life are food (in the form of carbohydrates), nutrients, sunlight, and water. Nearly every plant process is somehow directly or indirectly affected by that plant's available water supply. Because the water content of actively growing turfgrasses can reach up to 90% of total mass, a small decrease in the moisture content of a plant can dramatically affect growth and size, even lead to death (Taiz and Zeiger, 2005; Turgeon, 2005). Water plays countless functions within a plant including mineral and solute transport, substrates in processes such as photosynthesis, maintaining turgidity of cells, buffering against internal temperature changes through transpiration. Plant seeds require moisture for seed germination. Young, actively growing plants maintain a high rate of respiration, which is dependent on their internal water content. Mature leaves must maintain turgor pressure within cells in order to avoid wilting, closing of stomates, reduction of photosynthesis, and interference with countless other primary metabolic processes.

Water is supplied to turfgrass via precipitation and/or irrigation. A majority of water enters turfgrass roots through the apical portion of the root and through root hairs. Plants are known to possess two water absorbing mechanisms: active absorption which occurs in slowly transpiring plants where roots act as osmometers and passive absorption which is seen in plants rapidly transpiring where water is pulled in through the roots

(Kramer and Boyer, 1995; Kramer, 1932). Water uptake is driven by the increasingly negative water potential gradient from the soil, to the plant, and eventually to the atmosphere. The negative water potential of the atmosphere can be so great under certain conditions that water uptake by the plant can not sustain evapotranspirational water loss. On hot, sunny days with low humidity, wilting of creeping bentgrass from a loss of cell turgor pressure readily occurs.

Once within the turfgrass plant, water is primarily transported to desired areas by way of xylem tracheids and vessel elements. The importance of water for plant function is seen here when it becomes involved in various plant processes. Transport of essential plant nutrients is critical for the development of organic structures, activation and production of enzymes, and constituents of photosynthetic processes.

At optimal soil moisture, plants are able to maintain full turgor pressure under almost all but the most extreme environmental conditions of evaporative demand. Turgor pressure is fundamental for many physiological processes including cell enlargement, gas exchange within leaves, phloem transport, and transport of ions and solutes across membranes (Taiz and Zeiger, 2005). With a reduction of soil moisture, however, turgor becomes progressively reduced and two things can occur. First, stomatal guard cells close as a drought avoidance mechanism. Secondly, the production of a deeper and more extensive root system is initiated, given soil temperatures are not limiting. This allows the plant to exploit stored soil moisture, lessening the potential degree of water stress at any stage between irrigation or rainfall events, done as a drought avoidance mechanism (Kneebone et al., 1992).

Water becomes especially important for creeping bentgrass in the summer months when transpiration is at its climax. Transpiration is a two step process in which the evaporation of water from cell surfaces into intercellular spaces occurs, followed by the diffusion of water in the gas forms diffuses out of plant tissues through stomata (Kramer and Boyer, 1995). Stomata are openings on leaf surfaces that allow for gas exchange and plant mediated transpirational water loss. Guard cells surround stomatal openings and control the opening or closing of the stomate. K acts as an osmoregulating solute in guard cells, altering the turgor pressure of guard cells to control stomatal openings. Under low plant K concentrations, turgor pressure of guard cells can not be maintained, forcing stomates to remain open and resulting in a significant increase of transpiration.

Soil Hydrophobicity and Wetting Agents

The occurrence of localized dry pots (LDS) has been identified as one of major concerns of golf putting greens, particularly greens containing greater than 80% sand as defined by the USGA (USGA, 1993). Several possible causes for LDS have been examined, such as excessive thatch layer, compacted soil, poor irrigation coverage, soil salinity, disease, and hydrophobic soil (Karnok and Tucker, 2000). At least one causal agent of LDS has been reported as basidiomycete fungi, most likely *Lycoperdon* spp. (Miller and Wilkinson, 1977; Savage et al., 1969). Studies have reported that soil hydrophobicity develops due to an organic coating that covers soil particles (Roy and McGill, 2001; Tucker et al., 1990). Humic (Roberts and Carbon, 1972) and fulvic (Miller and Wilkinson, 1979) acids have been shown to be responsible for the organic coating on sand particles. Water-repellent soil typically forms within the top 5 cm of the soil profile, since the majority of organic matter, root activity, and microorganism populations, all necessary elements for the development of hydrophobic soil (McCarty, 2005; Karnok and Beall, 1995; Tucker et al., 1990). Soil particles covered with these organic acids greatly increase the surface tension of water, causing water to “bead up” and preventing soil to absorb water. Water is dipolar by nature, containing both positive and negative ends due to uneven layout between oxygen and hydrogen atoms in each water molecule. Because of this, water is able to form bonds between it and other polar molecules as hydrogen bonds; however, water and other polar molecules are strongly repelled by nonpolar molecules. Organic acids possess nonpolar tails, causing a strong repulsion of water in the soil profile, even after heavy irrigation or precipitation (Karnok et al, 2004). Following development of LDS, turfgrass shows symptoms typical to that of severe drought stress initially, forming into round to irregularly shaped dry spots, hindering aesthetic appearance and preventing rewetting of soil. Severe cases of LDS can be detrimental to turf, leading to death in some cases under severe summer stress.

Perhaps the best method of combating LDS is through strategically timed applications of wetting agents (WA), or soil surfactants in addition to a sound water management program. Soil surfactants, or wetting agents (WA), can be described as any substance that lowers the surface tension of a liquid by modifying its surface characteristics (Beard, 2005). WA molecule is made up of a hydrophilic (polar) water attracting group and a long, oil-soluble (nonpolar) hydrocarbon chain (Karnok et al., 2004). The nonpolar tail forms a bond with the nonpolar organic substance coating the soil particle. The polar, hydrophilic group is able to attract water, greatly improving the wettability of that soil.

The use of soil surfactants has shown to be most effective for relieving LDS and sustaining adequate soil moisture (Blodgett et al., 1993; Wiecko and Carrow, 1992; Wilkinson and Miller, 1978). Depending on their ionization or charge, WA's are classified into three major groups: anionic, cationic, and nonionic. Anionic surfactants ionize with water, forming a negative charge, while cationic surfactants form positive charges when combined with water. The disadvantage of anionic and cationic surfactants is that they react with other ions in solution, forming insoluble salts with calcium, magnesium, and ferric ions (Karnok et al., 2004). Nonionic surfactants are the most widely used surfactant on turfgrass (McCarty, 2005). Nonionic WAs do not form these salts, reducing phototoxic effects and foaming when mixing.

Wetting agents have been used for some time to increase water-holding capacity of turfgrass soil media primarily by reducing the hydrophobicity of the growth medium (Karnok and Tucker, 2001a). Wilkinson and Miller (1978) determined the severity of LDS caused by hydrophobic soil can be reduced by improving moisture retention and infiltration when under WA treatments. In a study by Blodgett et al. (1993), WA's were shown to promote wettability of a soil medium by lowering the surface tension of water. It appears that the layer of hydrophobic soil caused, at least in some part, by acidic compounds is confined to the uppermost portions of the soil profile. Tucker et al. (1990) determined the hydrophobic condition seen in their study was limited to the upper 50 mm of soil and was correlated with the presence of an organic soil particle coating. Leinauer et al. (2001) reported that Primer WA consistently improved water retention at depths of 150 and 250 mm when compared to Midorich wetting agent. Midorich however, was shown to retain significantly more soil moisture than Primer at the 50 mm depth. On creeping bentgrass, WA treatment increased root length by 27% and improved turf color and quality under a single application (Karnok and Tucker, 2001a). Additionally, molarity of ethanol droplet test (MED) value of the hydrophobic soil was also reduced for up to 12 weeks following application.

WAs have shown promising results of decreasing the time taken for water to infiltrate soils. One such study examined the ability of six commercially available wetting agents to lower irrigation infiltration times on bermudagrass [*Cynodon dactylon* (L.) Pers.] sod (Miyamoto, 1985). Results of that study showed infiltration times were greatly decreased with the addition of all WA, some to a higher degree than others. Morgan et al. (1966), Ruemmele and Amador (1994), and Wiecko and Carrow (1992) all reported similar results. While the positive effects of WA have been well documented, few studies have shown negative results following the application of a WA. Wiecko and Carrow (1992) observed turf discoloration and reduction in deep rooting (30-60 cm) and of ‘Kentucky 31’ tall fescue (*Festuca arundinaecea* Schreb.) by as much as 44 to 58%. Callahan et al. (1998) correlated increased application of Wet-Ag WA with increased thatch buildup of creeping bentgrass. Engel and Alderfer (1967) offer viable explanation for why this occurred, citing WAs reduce surface tension of water, resulting in quicker drying of turf and an interruption in the organic matter decay process.

Reduced Light Environments

Maintaining acceptable turfgrass under shaded conditions is a major challenge for turfgrass managers worldwide. It is estimated that 20 to 25% of existing turfs must be maintained with some degree of reduced light (Beard, 1973). When grown under shaded conditions, light quality and light intensity reaching turfgrass leaves are reduced, resulting in plant morphological and physiological modifications (Baldwin, 2008; Bunnell, 2005a; Bunnell, 2005b; Goss et al., 2002; Bell and Danneberger, 1999; Kephart et al., 1992; Dudeck and Peacock, 1992; Wilkinson et al., 1975; Wilkinson and Beard, 1974). In addition to light quality and intensity factors, several microclimate factors affected by shading such as restricted air movement, reduced soil and air temperatures, prolonged leaf wetness and higher relative humidity; all conditions favorable for disease development (Baldwin, 2008; Koh et al., 2003; Vargas and Beard, 1981; Beard, 1997; Beard, 1973).

Turfgrass plants rely on the light and chemical reactions of photosynthesis sustain their energy supply for adequate growth and development. Photosynthesis is the chemical conversion of light energy, carbon dioxide (CO_2), and water (H_20) into usable plant energy (carbohydrates) and the by product oxygen (O_2). Environments of low light intensities reduce photosynthetic rates and can be detrimental to the growth and development of certain plants. More detrimental than microclimate factors, shading greatly reduces light quality (red:far red ratio, R:FR) and quantity (PPFD) reaching the turfgrass surface (Taiz and Zeiger. 2005). Light saturation points for optimum photosynthesis are less than one-half full sunlight for C_3 grasses. Light saturation beyond one-half full sunlight leads to decreases in photosynthesis efficacy due to photorespiration in cool-season species (McCarty, 2005; Taiz and Zeiger. 2005; Fry and Huang, 2004). Conversely, C_4 turfgrass species exhibit a nonsaturating growth curve for light intensities found in nature, requiring full sunlight for optimum photosynthesis (McCarty, 2005; Taiz and Zeiger. 2005; Fry and Huang, 2004). Morphological and anatomical differences between C_4 and C_3 turfgrass species, and cultivars of the same species, produce varying plant responses to reduced irradiances. For example, zoysiagrass shade tolerance was noted greater than bermudagrass (Bunnell et al., 2005c), while seashore paspalum has been shown more shade tolerant than selected bermudagrass cultivars (Jiang et al., 2004).

Among cool-season turfgrass species, Gardner and Taylor (2002) noted higher overall quality and turf density on shaded tall fescue, followed by fine fescue, Kentucky bluegrass, rough bluegrass, and perennial ryegrass cultivars. On closely mowed creeping bentgrass, Bell and Danneberger (1999) reported ‘Penncross’ was able to maintain acceptable turf quality while under shade 40% of the day, while Goss et al. (2002) documented 60% light reduction had negligible effects on creeping bentgrass mowed at a greens height. Gardner and Wherley (2005) noted unacceptable performance of rough bluegrass under shade, and also found high rates of trinexapac-ethyl (TE) resulted in greater losses in density. Rough bluegrass can tolerate shaded conditions, however the combination of traffic and low mowing heights, such as in golf tee situations, proves detrimental to rough bluegrass performance (Beard, 2002).

Physiological and morphological responses of cool season grasses to reduced light irradiance include more upright growth habits, thinner and longer leaves, reduced density, shallow rooting, and reduced tillering (Dudeck and Peacock, 1992). Many studies show reduced fertilization, particularly nitrogen, as a management practice to sustain turf quality in shaded conditions. Goss et al. (2002) showed foliar N applications of 150-185 kg ha^{-1} yr^{-1} produced greater turf quality than higher N rates. Additionally, golf course superintendents have recently began increasing supplemental iron applications in order to maintain desired turfgrass color and reduce N input. However, effects of foliar N and Fe applications, and the potential interaction under reduced light environments, on overseeded cool-season putting greens during the winter months are unknown.

Nitrogen

Nitrogen is applied in greater amounts to turfgrass than any other nutrient for growth and development, and nutritional requirements of turf. Nitrogen (N) constitutes 2 to 5% of total dry leaf weight, and is highly mobile within the plant and in soils (Liu et al., 2007; Liu and Hull, 2006; Hull and Liu, 2005; McCarty, 2005; Carrow et al., 2001). N is generally taken up by plant roots in nitrate (NO_3^-) or ammonium (NH_4^+) forms, while urea is preferentially taken up with foliar absorption (Carrow et al., 2001; Marschner, 1995). Turfgrass fertility programs of are primarily based on N fertilization. Nitrogen requirement for overseeded bermudagrass golf greens typically involves fertilization with 0.5 lb N/1,000ft^2 monthly (24 kg N ha^{-1} m^{-1}) during the fall and winter months (McCarty, 2005; McCarty and Miller, 2002).

Initial N deficiency symptoms are general chlorosis, or leaf yellowing, beginning in the older leaves, due to the high mobility of N in plants. A major role of N is as a constituent in the chlorophyll molecule, the light harvesting molecule responsible for capturing light energy from the sun through photosynthesis and converting it into usable plant energy (Marschner, 1995). As a constituent of the chlorophyll molecule, N deficiencies often result in decreases in total chlorophyll content, and thus, loss of leaf color. Under prolonged deficiency, vegetative growth rate is reduced, leaf senescence ensues, and a reduction of shoot density is observed in response to loss of leaves and decrease in tillering (Goss et al., 2002; Carrow et al., 2001).

The most common recommendation to reduce shading injury on turf is through reduced levels of N fertility (Stier and Gardner, 2008; Fry and Huang, 2004; Dudeck and Peacock, 1992). Intraspecific competition between turfgrass plants under shaded conditions causes turf to grow upright rapidly in an attempt to outcompete neighboring plants. Agronomically, excessive shoot growth of putting greens is a disadvantage, especially under excessive N and shading conditions, producing thinning of turf and reduced tillering and stolen growth. Because reduced light and excess N promote shoot growth, root systems and underground carbohydrate storage are sacrificed (Baldwin, 2008; Bunnell et al., 2005a; Goss et al., 2002; Trenholm et al., 1998; Mazur and Hughes, 1976).

Iron

Of the micronutrients, iron (Fe) is the most likely to show deficiencies in turf (Turgeon, 2005) and considered to be the most widely applied (Turner and Hummel, 1992). Tissue Fe concentrations vary between species, but typically range from 100 to 500 ppm (Carrow et al., 2001; Marschner, 1995). Because of enhanced dark green color enhancement following Fe applications, many superintendents apply Fe as a partial substitute for annual N fertilization (Munshaw et al., 2006) or to mask phytotoxic effects of plant growth regulators and herbicides (Zhang et al., 2001). Iron is a component of heme proteins, which are involved in the detoxification of hydrogen peroxide (H_2O_2) and cell wall lignin formation (Marschner, 1995). Perhaps Fe's most important role, however is as a constituent for production of chlorophyll. Thylakoid membranes are the site of the light reactions of photosynthesis, and require large amounts of Fe for membrane structural and functional integrity (Marschner, 1995).

Currently, golf course superintendents apply foliar applications of Fe to promote dark green color without affecting shoot growth, regardless tissue or soil Fe concentrations (McCarty, 2005; Carrow et al., 2001; Turner and Hummel, 1992; White and Schmidt, 1990, Schmidt and Snyder, 1984). Glinski et al. (1992) studied Fe fertilization effects on creeping bentgrass putting greens and found Fe enhanced turfgrass color in all seasons and increased shoot growth, depending on the Fe carrier. On centipedegrass (*Eremochloa ophiuroides* (Munro) Hack.), applications of 2.0 kg Fe ha^{-1} applied in combination with 9.8 kg N ha^{-1} increased visual quality, however elevated air temperatures often led to phytotoxicity (Carrow et al., 1988). On bermudagrass, late-season applications of Fe showed no benefit on turfgrass color retention leading into dormancy or enhancement of spring greenup (Munshaw, 2006).

Winter Overseeding

Each fall, as air temperatures consistently fall below 15.5^{o}C, bermudagrass growth ceases and turf browning follows temperature reductions below 10^{o}C (McCarty, 2005; McCarty and Miller, 2002). To sustain acceptable playing conditions, golf course superintendents in the southeastern U.S. annually overseed bermudagrass putting greens with rough bluegrass (*Poa trivialis* L.) or perennial ryegrass (*Lolium perenne* L.). Advantages of overseeding include winter green color, uniform playing surface, less wear injury to dormant turf, and enhanced playing conditions through the winter months. However, winter overseeding does have limitations. The establishment of acceptable overseeded stands typically involves intensive cultural practices up to six weeks prior to overseeding, increased labor, water and fertility inputs, weed control measures, and decline in putting quality during spring transition (Liu et al., 2007; Long; 2006; McCarty, 2005; Turgeon, 2005; Beard, 1973).

Rough bluegrass, commonly referred to by its scientific name, is a cool-season perennial, demonstrating excellent shade and winter tolerance, increasing in popularity as a primary overseeding species (Hurley, 2003). Because of its stoloniferous growth habit, it can tolerate much lower mowing heights than Kentucky bluegrass (Christians, 2004) and does not require radical increases in mowing heights following establishment needed for ryegrass (McCarty, 2005; McCarty and Miller, 2002). Rough bluegrass establishment is less invasive than perennial ryegrass, and due to its susceptibility to heat and drought stress, rough bluegrass spring transition back to bermudagrass is rapid (Hurley, 2003).

Limited scientific research investigating *Poa trivialis* overseeding management exists in literature. As ultradwarf bermudagrass cultivars became commercially available, establishing a quality overseeding in the fall was a major concern. Hollingsworth et al. (2005) reported differences among bermudagrass cultivars on visual quality of rough bluegrass overseeding, with ‘Mobile 9’, ‘Champion’, and ‘MS Supreme’ bermudagrasses resulting in significantly higher ratings. The study also concluded *Poa trivialis* shoot density was largely unaffected by N source. Camberato and Martin (2004) noted salinity of 5.0 dS m^{-1} reduced germination of rough bluegrass seed by as much as 85% compared to 0 dS m^{-1}. Additionally, Liu et al. (2001) reported differences among seed germination at decreasing day/night temperatures, noting significantly less germination as temperatures declined from 21/6.1^{o}C to 16/2.7^{o}C.

CHAPTER 3

MANAGING SUMMER STRESS ASSOCIATED WITH CREEPING BENTGRASS WITH VARIOUS SOURCES OF POTASSIUM, CALCIUM, AND MAGNESIUM

Introduction

Creeping bentgrass (*Agrostis stolonifera* L.) is currently the most widely used cool-season turfgrass on golf course putting greens in northern states and transition zone of the United States (McCarty, 2005; Turgeon, 2005; Beard, 2001). Traditionally, creeping bentgrass has presented golfers the most superior putting conditions with its fine leaf texture, year-round green color, and lack of requirement for winter overseeding, which is often needed for bermudagrass greens. However, as a C_3 plant, creeping bentgrass does have its limitations. Creeping bentgrass is adapted to cool, moist regions, but is commonly used as putting surfaces in the U.S. transition zone, where it declines during the hot summer months due to high temperatures and relative humidity. Economically, annual maintenance costs of creeping bentgrass greens can easily exceed §75,000 compared to bermudagrass greens for an 18-hole golf course due to increased labor, increased water usage, fungicides, etc (McCarty, 2005).

Potassium (K) is a primary, essential nutrient for the growth and development of turfgrass, with an average plant tissue concentration of 1.5-3.0% by dry leaf tissue weight (McCarty, 2005; Carrow et al., 2001; Marschner, 1995). Potassium is the only essential plant nutrient that is not a constituent of any plant compound. However, potassium's most critical role is functioning as an activator of more than 80 enzymes within plants, such as starch synthase, which converts glucose into a starch storable form (Taiz and Zeiger, 2005; Marschner, 1995). Potassium is also actively involved in osmoregulation of water in plant cells, with the overall osmotic potential of plant cells ultimately dependent on K fluctuations within guard cells (Havlin et al., 2005). By allowing plants to accurately control stomatal opening and closing, K has a major impact on turf water usage as it pertains to water uptake, water use efficiency, and evapotranspiration.

Potassium is often referred to as the "health element" for its strong influence on heat, drought, cold, disease, and salinity stresses. Fu and Huang (2003) reported foliar K applications slowed leaf senescence and allowed turfgrass to maintain photosynthetic abilities under supraoptimal temperatures, increasing creeping bentgrass heat tolerance. Turner and Hummel (1992) found K increased disease resistance, drought, heat, and wear tolerance of both warm and cool-season species. Markland and Roberts (1967) noted that with increasingly higher levels of K, tissue moisture levels were decreased, reducing winter injury of creeping bentgrass. While much scientific data support the idea that K plays a significant role in plant water relations and environmental stress tolerance, few studies have investigated the impact liquid vs. granular K carriers may play on summer creeping bentgrass decline associated with other plant nutrients such as calcium (Ca) and magnesium (Mg).

Although researchers have well-documented the beneficial effects of K on environmental stresses on turfgrasses (Carrow et al., 2001), the interaction of K with other nutrients has been rarely determined. Many studies have been performed investigating the influence of K on soil and plant extractable Ca and Mg. Miller et al. (1999) reported increasing K fertilization on bermudagrass resulted in reduced soil extractable Ca and Mg in native and soil-peat media with corresponding decreases in leaf tissue Ca and Mg. Woods et al. (2005) supported these findings on L-93 creeping bentgrass, citing K-imposed decreases in plant and soil Ca and Mg among various popular soil nutrient testing methods. However, the findings of such reports have been highly influenced by factors such as K rates, soil type, weather conditions, nitrogen inputs, etc.

Since previous research offers contrasting results about the influence of potassium on plant extractable calcium and magnesium, and K carrier research on creeping bentgrass is lacking, further research is warranted as it pertains to creeping bentgrass summer decline. The objectives of the study were to test if light, frequent applications of liquid K, applied in conjunction with supplemental Ca and Mg, could relieve summer stress exhibited by creeping bentgrass by maintaining acceptable turf quality and root growth during the summer months and to determine K, Ca, and Mg recovery in clippings and roots during the summer and fall months.

Materials and Methods

A two year field study was conducted at Clemson University in Clemson, SC from May 25, 2006 through October 31, 2007 on an established 'Crenshaw' creeping bentgrass research green built to USGA specifications (Appendix C-1 and C-2). Plot dimensions measured 2 m x 1.5 m arranged in a complete randomized block design with four replications (Appendix B-1).

Potassium was applied to the treatment plots at 195.29 kg K ha^{-1} yr^{-1} in either granular or liquid form. Granular forms of slow-release, polyon-coated potassium sulfate (0-0-50), derived from polymer coated potassium sulfate (Harrell's Fertilizer, Inc., Lakeland, FL), were applied at 65.1 kg K ha^{-1} on dates of core aerifications. Core cultivation of creeping bentgrass plots were performed on May 25, September 12, and October 19 of 2006 and March 6, September 18 and October 17 of 2007. Creeping bentgrass was core cultivated with 1.3 cm inside diameter hollow tines with a length of 10.2 cm at 5.1 cm spacing. Cores were harvested and removed. Granular potassium was mixed with topdressing sand and applied by hand and swept in using push-type brooms. After granular potassium treatments were swept, N and P fertilizations were supplied by granular Milorganite (6-2-0) at 32.71 kg N $ha^{-1}$and a light topdressing to cover the holes left by the hollow tine aerification. Plots were again swept by hand and irrigated for 15 minutes by automated, overhead irrigation. Particle size and physical characteristics of topdressing sand are shown in Appendix C-1 and C-2.

Liquid potassium treatments were applied with a CO_2 spray tank at 16.27 kg K ha^{-1} every 14 days from May 29 to November 10, 2006 and May 30 to October 30, 2007. Liquid potassium rate of 16.27 kg K ha^{-1} was equivalent to 195.29 kg K ha^{-1} split between 12 applications during the course of the year. The liquid K fertilizer was a 0-0-30 (N-P_2O_5-K_2O) derived from potassium carbonate (Harrell's Fertilizer, Inc., Lakeland, FL).

Calcium treatments were applied every four weeks from June 5 to October 25 in 2006 and June 6 to October 23 in 2007 at a rate 48.82 kg Ca ha^{-1} annually in six equal applications. Calcium source used was a liquid 12% Calcium Complex derived from Calcium Glucoheptonate produced by Grigg's Brothers (Albion, ID). Calcium treatments were made using a CO_2 backpack sprayer and watered in immediately using overhead irrigation.

Magnesium treatments were also applied on a monthly basis from June 6 to October 25 in 2006 and from June 7 to October 22 in 2007 at a rate of 48.82 kg Mg ha^{-1} annually in six equal applications. Magnesium source was a 5% Magnesium Chelate derived from Magnesium Glucoheptonate produced by Grigg's Brothers. Treatments were made in the late afternoon for each application and watered in after approximately three hours following application.

Mowing was performed six d wk^{-1} with a walk-behind reel mower at 3.2 mm with clippings removed. Irrigation was applied at the onset of drought stress throughout the study period, to provide an average of 5 cm wk^{-1} in addition to precipitation. Monthly precipitation is shown in Appendix D.

Nitrogen was supplied to the plots in the form of dissolved urea (46-0-0). Nitrogen applications biweekly at 4.88 kg N ha^{-1} every 14 days using a CO_2 spray tank. A total of 14 applications were made in 2006 at 68.35 kg N ha^{-1} from May 29 to December 3. In 2007, a total of 83 kg N ha^{-1} was applied from March 24 to October 29. On nitrogen application dates of April 17 and May 1, 2007, rate was increased to 12.21 kg N ha^{-1}. Granular Milorganite (6-2-0) was also applied over all plots at 32.55 kg N ha^{-1}

on core aerification dates. Total N rates for 2006 and 2007 were 166 and 180.65 kg N ha^{-1} per year, respectively. A single application of iron (Sequestrene 330 Fe) at 2.7 kg a.i. ha^{-1} was made on 17 April 2007 to increase turfgrass color. A preventative fungicide program was established to prevent the occurrence of dollar spot (*Sclerotinia homeocarpa* F.T. Bennett), pythium (*Pythium* spp.), and brown patch (*Rhizoctonia* spp.). To prevent and control insect outbreaks, Spinosad (Conserve SC) and Lambda-cyhalothrin (Scimitar GC) were applied as needed during the two years of the study at the manufacturer's labeled rates.

Data Collection

Visual turf quality ratings were recorded biweekly throughout the study period each year. Turf quality was rated on a 1 to 9 scale with 9 denoting optimal color, density, and health and 1 denoting dead, brown turf. Visual ratings below 7 were considered unacceptable.

Chlorophyll was measured in June, August, and October each year. Fresh clippings were harvested during mowing and chlorophyll was extracted using dimethyl sulfoxide (DMSO) (Hiscox and Israelstram, 1979) (Appendix A). Total shoot chlorophyll concentration (mg g^{-1}) was determined using a spectrophotometer (Genesys™ 20, ThermoSpectronic, Rochester, NY) with absorbance values at 645 and 663 nm used in the equation determined by Arnon (1949).

Fresh clippings were harvested monthly from June to October using a walk-behind reel mower with clipping collector. Fresh samples were placed in an 80^{o}C oven and dried for at least 72 hours to determine clipping dry weight. Dry tissue samples from June, August, and October of each year were analyzed for nutrient contents by the Clemson University Agriculture Service Laboratory for P, K, Ca, Mg, Zn, Cu, Mn, Fe, S, and Na concentrations. Leaf nutrient concentrations were determined using wet ashing procedures with a Digestion Block Magnum Series Block Designer (Ivesdale, IL) and an ICP model TJA-61E autosampler.

Root samples were harvested using a cylindrical core harvester with a diameter of 10.8 cm to a depth of 20 cm. Root samples were harvested in June, August and October each year. Roots were separated from thatch, washed thoroughly and placed in an 80^{o}C oven for at least 72 hours before determining root dry weight. Dried samples were assessed for root dry weight and assessed for nutrient content by the Clemson University Agriculture Service Laboratory using the same procedures described for leaves above.

Volumetric soil moisture content was determined monthly from June to October within the top 10 cm of soil using a time-domain reflectometer (TDR) (ML2, Delta-T Devices Ltd., Cambridge CB5 OEJ, England) soil moisture sensor. A total of 3 readings were recorded from each individual plot and averaged together, giving a mean recording for each plot.

Data Analysis

All statistical computations were conducted using analysis of variance (ANOVA) within the Statistical Analysis System (SAS Institute, 2003). Means were separated using

Fisher's Protected Least Significant Difference (LSD) test. An alpha of 0.05 was used for all data comparisons.

Results and Discussion

Significant treatment by year interactions were detected; therefore, results will be examined separately for each year. A three-factor interaction between K, Ca, and Mg occurred for turfgrass quality (TQ) and will be examined as treatment combinations for each year. No meaningful interactions between K carriers, Ca rates and Mg rates were observed ($P > 0.05$) for the other parameters measured; therefore, main effects of each treatment for 2006 and 2007 were examined separately.

Turf Quality

Significant differences in TQ among K treatments occurred within the first month of the study in Year 1 (Table 3-1). Between plots receiving no K, granular (Grn), or liquid (Liq) potassium, liquid K carrier significantly reduced visual quality by June 2006 and consistently produced the lowest turf quality until September 2006 (Table 3-1). This immediate impact of foliar applied K can be explained by foliar burning of turfgrass under high rates of liquid potassium due to accumulation of fertilizer salts of leaf blades. Similar responses were observed by Johnson et al. (2003) on creeping bentgrass, where high rates of liquid K fertilization resulted in lower turf quality due to foliar burning caused by high concentrations of fertilizer salts. Waddington et al. (1972) also noted heightened leaf burn to Penncross creeping bentgrass receiving foliar potassium chloride (KCl) under high application frequency.

By 2007, acceptable turfgrass quality was only found on plots receiving Ca only in July, and both Ca and Mg only in July and October (Table 3-2). By September and October, the highest visual quality ratings, 6.63 and 7.25 respectively, were demonstrated on plots receiving Ca and Mg only (Table 3-2). The addition of Grn K carriers apparently had no great impact on visual quality in either year of the study. Previous research confirms a lack of visual response to granular K applications in creeping bentgrass (Long, 2006; Woods et al., 2006; Johnson et al., 2003), bermudagrass (Goatley et al., 1994; Snyder and Cisar, 1992; Johnson et al., 1987), Kentucky bluegrass (Fitzpatrick and Guillard, 2004) and seashore paspalum (Trenholm et al., 2001).

As observed in Table 3-1 and 3-2, for one-half of the study duration, plots receiving Ca only provided the highest visual quality of all treatments. Ca treatment consistently demonstrated greater turf quality on June, July, and September of 2006 and July and August 0f 2007 (Table 3-1 and 3-2). Jiang and Huang (2001a, 2001b) confirmed exogenous Ca applications maintained turf quality under severe drought stress by reducing lipid membrane peroxidation and maintaining antioxidant activities. St. John et al. (2003), however, reported no differences among color or quality of Crenshaw creeping bentgrass with the addition of 23 g Ca m^{-1} annually. Foliar applications of Mg did not greatly influence TQ unless used in conjunction with Ca.

Table 3-1. 'Crenshaw' creeping bentgrass visual turf quality in response to two K carriers, two Ca rates and two Mg rates in 2006.

K carrier†	**Ca/Mg carrier**	**June**‡	**July**	**August**	**Sept**	**October**
		--------------------Turfgrass Quality (1-9)§---------------------				
No K	**0**	7.5	7.3	7.6	7.0	7.4
	Ca	7.8	7.8	8.4	7.3	7.5
	Mg	7.4	7.4	7.6	7.1	6.8
	Ca + Mg	7.8	7.7	8.5	7.1	6.9
Granular	**0**	7.5	7.4	7.0	6.9	7.3
	Ca	7.6	7.5	8.0	6.9	7.8
	Mg	7.5	7.5	7.9	7.0	7.0
	Ca + Mg	7.6	7.4	7.3	6.5	7.3
Liquid	**0**	7.4	7.3	6.9	6.8	6.8
	Ca	7.5	7.4	7.9	7.0	7.3
	Mg	7.6	7.5	7.0	6.9	6.5
	Ca + Mg	7.5	7.3	7.9	7.1	6.9
LSD		0.36	0.38	0.96	0.47	0.47

† Abbreviations: Control = no K fertilization, Granular and Liquid indicate granular or liquid K fertilization at 195 kg K ha^{-1} annually. 0 indicates no calcium or magnesium fertilization, Ca = 49 kg calcium ha^{-1} annually, Mg = 49 kg magnesium ha^{-1} annually.

‡ Values in columns followed by the same letter are not significantly different at $p = 0.05$ using Fisher's Protected LSD.

§ Turfgrass quality based on a visual scale of 1 to 9 with 1 = poorest, 9 = best. Visual rating of >7 indicates acceptable turf quality.

Table 3-2. 'Crenshaw' creeping bentgrass visual turf quality in response to two K carriers, two Ca rates and two Mg rates in 2007.

K carrier†	Ca/Mg carrier	June‡	July	August	Sept	October
		---------------------Turfgrass Quality (1-9)§--------------------				
No K	**0**	5.8	6.3	5.6	5.5	6.4
	Ca	6.6	7.7	6.9	6.3	6.8
	Mg	5.5	6.0	5.8	5.6	6.6
	Ca + Mg	6.5	7.5	6.5	6.6	7.3
Granular	**0**	6.8	6.9	6.3	6.0	6.9
	Ca	5.9	6.3	5.5	5.0	5.8
	Mg	5.8	5.8	5.5	5.1	6.0
	Ca + Mg	5.4	5.8	5.3	5.1	6.0
Liquid	**0**	6.6	6.9	6.0	6.3	6.3
	Ca	6.0	6.3	5.4	5.0	5.8
	Mg	6.3	6.4	5.6	5.8	6.8
	Ca + Mg	6.0	6.4	5.8	6.0	6.6
LSD		NS	1.38	1.29	1.56	1.16

† Abbreviations: Control = no K fertilization, Granular and Liquid indicate granular or liquid K fertilization at 195 kg K ha^{-1} annually. 0 indicates no calcium or magnesium fertilization, Ca = 49 kg calcium ha^{-1} annually, Mg = 49 kg magnesium ha^{-1} annually.

‡ Values in columns followed by the same letter are not significantly different at p = 0.05 using Fisher's Protected LSD. NS = not significant at the 0.05 level.

§ Turfgrass quality based on a visual scale of 1 to 9 with 1 = poorest, 9 = best. Visual rating of >7 indicates acceptable turf quality.

Chlorophyll Concentrations

Increased K rates, either liquid or granular, had no meaningful effect on chlorophyll concentrations (Table 3-3). Similar results have been observed with foliar KH_2PO_4 applications on 'Penncross' creeping bentgrass, where no significant effects on leaf chlorophyll content were observed during high heat stress (Fu and Huang, 2003). Also, no differences in chlorophyll content were noted for Ca or Mg treatments for any date in 2006 or 2007 (Table 3-3). Jiang and Huang (2001b, 2001a) offered contrasting results as foliar Ca treatments mediated chlorophyll loss of tall fescue (*Festuca arundinacea* L.) and Kentucky bluegrass (*Poa pratensis* L.) when exposed to high heat and drought conditions in greenhouse conditions. It is unclear why monthly Mg treatments did not result in elevated chlorophyll content, given the role of Mg as the core of the chlorophyll molecule and the dramatic increase in leaf tissue Mg concentrations observed in this study.

Table 3-3. Total shoot chlorophyll concentration of 'Crenshaw' creeping bentgrass in response to two K carriers, two Ca rates and two Mg rates.

K carrier†	June 06‡	Aug 06	Nov 06	June 07	Aug 07	Oct 07
	------------------Total Chlorophyll Concentration (mg g^{-1})§------------------					
No K	3.05	3.37	2.03	3.41	2.54	2.69
Granular	3.08	3.32	1.93	3.41	2.44	2.54
Liquid	3.04	3.23	2.00	3.43	2.56	2.74
LSD	NS	NS	NS	NS	NS	0.17
Ca Rate						
No Ca	3.09	3.26	1.91	3.38	2.47	2.61
Ca	3.02	3.35	2.06	3.46	2.57	2.71
LSD	NS	NS	NS	NS	NS	NS
Mg Rate						
No Mg	3.08	3.32	1.96	3.44	2.53	2.66
Mg	3.03	3.29	2.02	3.40	2.50	2.66
LSD	NS	NS	NS	NS	NS	NS

† Abbreviations: Control = no K fertilization, Granular and Liquid indicate granular or liquid K fertilization at 195 kg K ha^{-1} annually. No Ca indicates no calcium fertilization, Ca = 49 kg calcium ha^{-1} annually. No Mg indicates no magnesium fertilization, Mg = 49 kg magnesium ha^{-1} annually.

‡ Values followed by the same letter in the same column are not significantly different at p = 0.05 using Fisher's Protected LSD. NS = not significant at the 0.05 level.

§ Total chlorophyll concentration based on mg chlorophyll per fresh g clippings.

Clipping Yield

Differences in shoot growth based on K carrier were only detected in August and November of year 1 (Table 3-4). In August and November 2006, total clipping yield was reduced by 20 and 13 %, respectively, by the addition of liquid K compared to untreated (Table 3-4). A viable explanation for why foliar applications of K hindered vegetative growth may be due to foliar burning of liquid K treatments. This lack of growth response was unexpected, considering initial soil test indicate very low levels of soil extractable K at the onset of the experiment (Appendix C-9). Nevertheless, numerous studies have reported a lack of shoot growth response to K applications on both C_3 and C_4 turfgrass species (Woods et al., 2006; Snyder and Cisar, 2005; Fitzpatrick and Guillard, 2004; Waddington et al., 1972). Alternatively, in a later experiment, Waddington et al. (1972) reported under foliar applications of potassium chloride to 'Penncross' creeping bentgrass, significantly higher clipping yields were observed.

Clipping yield was 14% and 23% higher by the addition of calcium in July and August 2006, respectively (Table 3-4). In year two, Ca increased total clipping yield by 26% and 29% by September and October compared to untreated, respectively (Table 3-5). This contradicts previous findings by St. John et al. (2003) where no apparent increase in clipping mass was detected by the addition of 23 g Ca m^{-2} yr^{-1}. No detectable differences in clipping yields were found for the addition of Mg.

Table 3-4. Clipping yield of 'Crenshaw' creeping bentgrass in response to two K carriers, two Ca rates and two Mg in 2006.

K carrier†	June‡	July	August	October	November
	-------------------Total Clipping Yield (g m^{-2})§---------------------				
No K	3.13	3.10	3.64	3.11	4.16
Granular	2.99	3.21	3.57	3.12	4.16
Liquid	2.93	2.77	2.91	2.81	3.65
LSD	NS	NS	0.64	NS	0.48
Ca Rate					
No Ca	2.93	2.80	2.94	2.96	3.84
Ca	3.10	3.26	3.80	3.07	4.14
LSD	NS	0.43	0.52	NS	NS
Mg Rate					
No Mg	3.00	3.06	3.32	3.04	3.82
Mg	3.03	3.00	3.42	2.99	4.16
LSD	NS	NS	NS	NS	NS

† Abbreviations: Control = no K fertilization, Granular and Liquid indicate granular or liquid K fertilization at 195 kg K ha^{-1} annually. No Ca indicates no calcium fertilization, Ca = 49 kg calcium ha^{-1} annually. No Mg indicates no magnesium fertilization, Mg = 49 kg magnesium ha^{-1} annually.

‡ Values followed by the same letter in the same column are not significantly different at p = 0.05 using Fisher's Protected LSD. NS = not significant at the 0.05 level.

§ Total clipping yield based on grams of dried tissue per square meter. Number of days between mowings differed for each clipping harvest. Dependent upon growth rate at time of harvest.

Table 3-5. Clipping yield of 'Crenshaw' creeping bentgrass in response to two K carriers, two Ca rates and two Mg rates in 2007.

K carrier†	**June**‡	**July**	**August**	**September**	**October**
	-------------------Total Clipping Yield (g m^{-2})§---------------------				
No K	0.63	1.46	2.13	1.34	0.48
Granular	0.69	1.36	2.24	1.20	0.49
Liquid	0.75	1.54	2.16	1.31	0.49
LSD	NS	NS	NS	NS	NS
Ca Rate					
No Ca	0.70	1.32	2.04	1.09	0.40
Ca	0.68	1.58	2.31	1.47	0.57
LSD	NS	NS	NS	0.25	0.10
Mg Rate					
No Mg	0.65	1.41	2.14	1.29	0.45
Mg	0.72	1.49	2.21	1.27	0.53
LSD	NS	NS	NS	NS	NS

† Abbreviations: Control = no K fertilization, Granular and Liquid indicate granular or liquid K fertilization at 195 kg K ha^{-1} annually. No Ca indicates no calcium fertilization, Ca = 49 kg calcium ha^{-1} annually. No Mg indicates no magnesium fertilization, Mg = 49 kg magnesium ha^{-1} annually.

‡ Values followed by the same letter in the same column are not significantly different at p = 0.05 using Fisher's Protected LSD. NS = not significant at the 0.05 level.

§ Total clipping yield based on grams of dried leaf tissue per square meter. Number of days between mowings differed for each clipping harvest. Dependent upon growth rate at time of harvest.

Leaf Tissue Nutrient Concentrations

Concerning leaf tissue K concentration, K application, either in liquid or granular form, increased leaf K concentration on one-half of the sampling dates (Figure 3-1). In August and November 2006, liquid K produced 8 and 16% greater clipping K concentration compared to untreated (Figure 3-1). Liquid K also resulted in an 11 and 21% increase in leaf tissue K concentration by June and October 2007 (Figure 3-1). Findings from numerous studies concur that increasing K applications to turfgrass resulted in enhanced tissue K concentrations (Woods et al., 2006; Dest and Guillard, 2001; Miller, 1999; Miller and Dickens, 1996; Belesky and Wilkinson, 1983; Waddington et al., 1972). Additionally, liquid form of K produced significantly higher leaf tissue K concentration than granular from by 5 and 3% in August 2006 and October 2007, respectively. Previous research confirms these findings, noting greater response in leaf K concentration under foliar KCl applications compared to granular fritted potash (Waddington, 1972). Monthly Ca fertilization was not found to affect tissue K concentration, while Mg only reduced tissue K in August 2007 by 5% (data not shown).

Tissue K concentration on plots receiving no K applications were within the sufficiency range (1.5 to 3.0% by dry weight) as identified by McCarty (2005), Carrow et al. (2001), and Marschner (1995), and remained within the sufficient range throughout the study. Interestingly, tissue K concentrations were at the lowest in August 2007, with drastic increases by October 2007 (Figure 3.1). Weather conditions in year 2 were much drier than that of 2006, and this might have resulted in lower uptake of K in year two under these conditions (Appendix D). The benefits of K to turfgrass under heat and drought stress conditions have been well documented (Carrow et al., 2001). The sudden increase of shoot K concentration, especially by foliar treatments, may indicate a bentgrass's ability to influx and utilize K as a heat and/or drought avoidance mechanism under these conditions as suggested by Fu and Huang (2003).

Application of Ca was found to increase the amount of leaf tissue Ca concentrations on one-half of the sampling dates: August 2006, and August and November 2007. The addition of Ca significantly increased tissue Ca concentration on those dates by 9%, 11%, and 8%, respectively (Table 3-6). Reduced leaf Ca concentrations were consistently observed when K was applied, especially in liquid form (Table 3-6). Liquid K carrier reduced leaf tissue Ca concentration by 10 to 28% over the course of the experiment compared to untreated, while granular forms reduced Ca concentrations up to 24% (Table 3-6). Historically, researchers have observed that increasingly higher rates of K inherently reduced the amounts of soil and tissue Ca and Mg content. Miller (1999) noted that that plant extractable Ca and Mg decreased with increasing K fertilization of Tifdwarf and Tifway bermudagrass when grown on sand-peat (9:1 by volume) and loamy sand. This reduction in plant cation uptake due to competition for cation exchange sites caused by fertilization has been well documented by other researchers (Woods et al., 2005; St. John et al., 2003; Miller, 1999; Sartain, 1993; West and Reynolds, 1984; Waddington et al., 1978)

Interestingly, on the exact dates leaf calcium concentrations were found significant, Mg fertilization was also found to decrease tissue Ca. On August 2006, and August and November 2007, Mg applications reduced tissue Ca by as much as 11 to

17%, indicating that Mg might have an influence on the plant uptake of Ca on those dates (Table 3-6). Reductions of leaf extractable Ca under Mg fertilization were expected due to competition between cations for exchange sites of the growth medium.

Tissue concentrations of Mg treated plots were consistently greater than untreated at all sampling dates (Table 3-7). Leaf tissue Mg concentration was 8%, 19%, and 22% greater in 2006 at each sampling date for plots receiving Mg, respectively, and 7%, 21%, and 19% higher for each date in 2007, respectively (Table 3-7). Liquid K carrier was found to decrease tissue Mg concentration on 4 of 6 sampling dates by as much as 19% in November 2006 (Table 3-7). Additionally, granular forms of K reduced leaf Mg concentration on 5 sampling dates by as much as 15% on November 2006 and October 2007 (Table 3-7). Woods et al. (2005) demonstrated the ability of foliar applied K to decrease leaf Ca and Mg concentrations of L-93 creeping bentgrass grown on a calcareous soil. Ca fertilization significantly decreased tissue Mg concentrations by 7% in August of 2006, and June and August 2007, and by 8% in October 2007 (Table 3-7). St. John et al. (2003) reported similar results, noting an 11% decrease in leaf Mg concentration with the addition of $CaSO_4$ on Crenshaw creeping bentgrass.

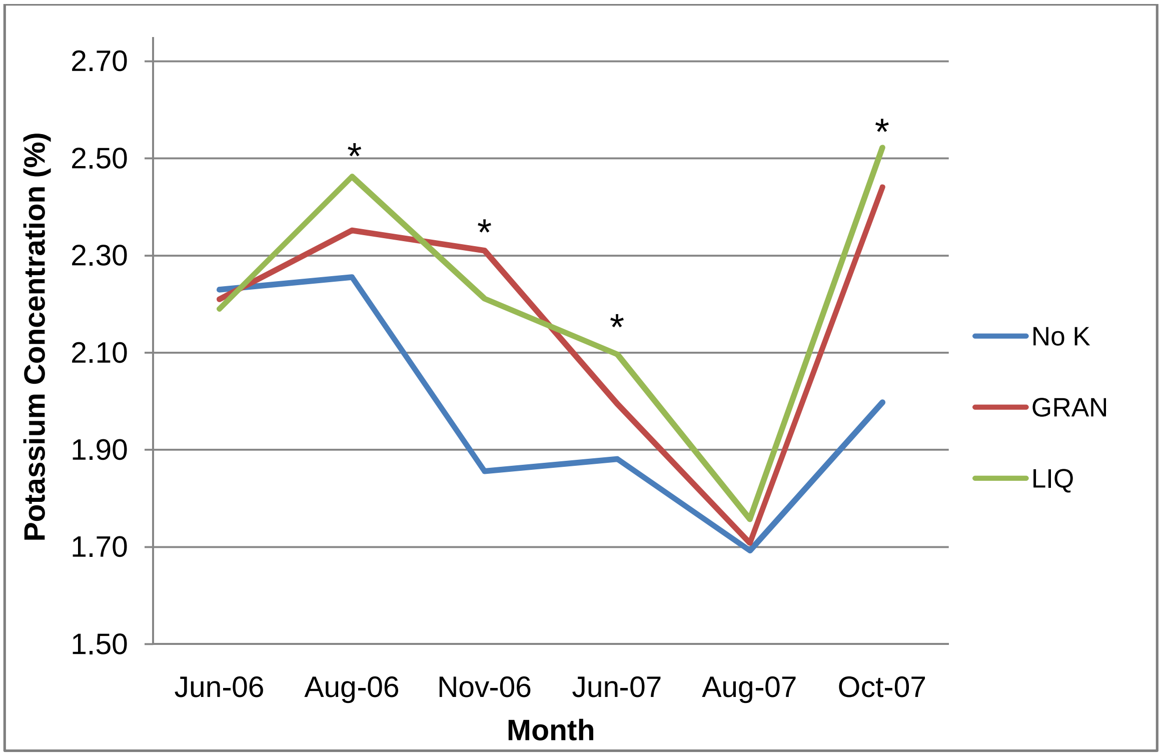


Figure 3-1. Influence of potassium rate and source on leaf tissue potassium of 'Crenshaw' bentgrass concentration from June 2006 to October 2008. *-indicates significant differences at alpha = 0.05.

Table 3-6. 'Crenshaw' creeping bentgrass clipping calcium concentration in response to two K carriers, two Ca rates and two Mg rates.

K carrier†	**June 06**‡	**Aug 06**	**Nov 06**	**June 07**	**Aug 07**	**Oct 07**
	---------------------------Calcium Concentration (%)§---------------------------					
No K	0.30	0.45	0.46	0.46	0.37	0.41
Granular	0.27	0.44	0.35	0.35	0.36	0.33
Liquid	0.27	0.40	0.33	0.33	0.32	0.32
LSD	0.02	0.03	0.05	0.05	0.03	0.02
Ca Rate						
No Ca	0.28	0.41	0.38	0.38	0.33	0.34
Ca	0.28	0.45	0.39	0.39	0.37	0.37
LSD	NS	0.02	NS	NS	0.02	0.02
Mg Rate						
No Mg	0.29	0.47	0.40	0.40	0.37	0.38
Mg	0.27	0.39	0.36	0.36	0.33	0.33
LSD	NS	0.02	NS	NS	0.02	0.02

† Abbreviations: Control = no K fertilization, Granular and Liquid indicate granular or liquid K fertilization at 195 kg K ha^{-1} annually. No Ca indicates no calcium fertilization, Ca = 49 kg calcium ha^{-1} annually. No Mg indicates no magnesium fertilization, Mg = 49 kg magnesium ha^{-1} annually.

‡ Values followed by the same letter in the same column are not significantly different at p = 0.05 using Fisher's Protected LSD. NS=not significant at the 0.05 level.

§ Calcium Concentration based on percent calcium found in dried leaf tissue.

Table 3-7. 'Crenshaw' creeping bentgrass clipping magnesium concentration in response to two K carriers, two Ca rates and two Mg rates.

K carrier†	**June 06**‡	**Aug 06**	**Nov 06**	**June 07**	**Aug 07**	**Oct 07**
	-----------------------Magnesium Concentration (%)§------------------------					
No K	0.24	0.29	0.27	0.29	0.27	0.26
Granular	0.23	0.29	0.23	0.27	0.26	0.22
Liquid	0.23	0.29	0.22	0.27	0.25	0.23
LSD	0.01	NS	0.04	0.02	0.01	0.01
Ca Rate						
No Ca	0.24	0.30	0.25	0.29	0.27	0.25
Ca	0.23	0.28	0.22	0.27	0.25	0.23
LSD	NS	0.01	NS	0.01	0.01	0.01
Mg Rate						
No Mg	0.23	0.26	0.21	0.27	0.23	0.21
Mg	0.25	0.32	0.27	0.29	0.29	0.26
LSD	0.01	0.01	0.03	0.01	0.01	0.01

† Abbreviations: Control = no K fertilization, Granular and Liquid indicate granular or liquid K fertilization at 195 kg K ha^{-1} annually. No Ca indicates no calcium fertilization, Ca = 49 kg calcium ha^{-1} annually. No Mg indicates no magnesium fertilization, Mg = 49 kg magnesium ha^{-1} annually.

‡ Values followed by the same letter in the same column are not significantly different at p = 0.05 using Fisher's Protected LSD. NS=not significant at the 0.05 level.

§ Magnesium Concentration based on percent calcium found in dried leaf tissue.

Root Mass

Applications of K, as either liquid or granular form, Ca, or Mg showed no significant impact on rooting of creeping bentgrass in either year of the study (Appendix C-3). Seasonal declines in overall root weight were observed during both years of the study. However, creeping bentgrass rooting exhibited no beneficial influence from any treatment applied (Appendix C-3).

Root Nutrient Concentrations

Crenshaw creeping bentgrass root tissue K concentration increased with granular K fertilization in 2006 by as much as 17 and 41% in June and November, respectively, while liquid K applications were 29% higher in August compared to untreated (Table 3-8). In 2007, however, liquid K carrier increased root K concentration by 24 and 29% in August and October (Table 3-8). Ca or Mg fertilization had no effect on root tissue K concentrations for either year. To the knowledge of the authors, this study is the first to investigate K, Ca, and Mg fertilization on root tissue nutrient accumulation of creeping bentgrass.

Interestingly, root tissue Ca concentrations of plots receiving 48.82 kg Ca ha^{-1} yr^{-1} were 12, 9 and 10% greater in August of 2006 and 2007 and October 2007, the same dates leaf tissue Ca concentrations were reduced significantly (Table 3-9). Granular and liquid K carrier increased root Ca concentration by 5 and 10%, respectively, in October 2007 (Table 3-9). Mg application significantly reduced root Ca in August and October 2007 by 13 and 10%, respectively (Table 3-9)

Exogenous applications of liquid Mg produced 20 and 9% greater root Mg concentrations in August and November 2006 and 15% higher concentrations in June and August 2007, respectively (Table 3-10). Applications of K or Ca showed no significant impact on root Mg concentrations except in August 2007 where the addition of Ca increased root Mg concentration by 9% (Table 3-10).

Table 3-8. ‘Crenshaw’ creeping bentgrass root potassium concentration in response to two K carriers, two Ca rates and two Mg rates.

K carrier†	**June 06**‡	**Aug 06**	**Nov 06**	**June 07**	**Aug 07**	**Oct 07**
	------------------------Potassium Concentration (%)§--------------------------					
No K	0.040	0.034	0.053	0.053	0.051	0.054
Granular	0.048	0.038	0.090	0.057	0.054	0.060
Liquid	0.046	0.048	0.067	0.057	0.067	0.076
LSD	0.007	0.012	0.019	NS	0.009	0.012
Ca Rate						
No Ca	0.043	0.038	0.065	0.056	0.059	0.071
Ca	0.046	0.043	0.075	0.055	0.055	0.055
LSD	NS	NS	NS	NS	NS	0.010
Mg Rate						
No Mg	0.044	0.043	0.072	0.058	0.060	0.070
Mg	0.045	0.037	0.068	0.054	0.055	0.060
LSD	NS	NS	NS	NS	NS	NS

† Abbreviations: Control = no K fertilization, Granular and Liquid indicate granular or liquid K fertilization at 195 kg K ha^{-1} annually. No Ca indicates no calcium fertilization, Ca = 49 kg calcium ha^{-1} annually. No Mg indicates no magnesium fertilization, Mg = 49 kg magnesium ha^{-1} annually.

‡ Values followed by the same letter in the same column are not significantly different at p = 0.05 using Fisher’s Protected LSD. NS=not significant at the 0.05 level.

§ Potassium concentration based on percent potassium found in dried root tissue.

Table 3-9. 'Crenshaw' creeping bentgrass root calcium concentration in response to two K carriers, two Ca rates and two Mg rates.

Rates (kg K ha^{-1}) †	**June 06**‡	**Aug 06**	**Nov 06**	**June 07**	**Aug 07**	**Oct 07**
	---------------------------Calcium Concentration (%)§------------------------------					
No K	0.24	0.23	0.19	0.22	0.21	0.18
Granular	0.25	0.23	0.20	0.24	0.22	0.19
Liquid	0.25	0.24	0.19	0.25	0.22	0.20
LSD	NS	NS	NS	NS	NS	0.01
Ca Rate						
No Ca	0.24	0.22	0.19	0.23	0.21	0.18
Ca	0.26	0.25	0.19	0.24	0.23	0.20
LSD	NS	0.03	NS	NS	0.02	0.01
Mg Rate						
No Mg	0.26	0.24	0.20	0.24	0.23	0.20
Mg	0.24	0.24	0.19	0.23	0.20	0.18
LSD	NS	NS	NS	NS	0.02	0.01

† Abbreviations: Control = no K fertilization, Granular and Liquid indicate granular or liquid K fertilization at 195 kg K ha^{-1} annually. No Ca indicates no calcium fertilization, Ca = 49 kg calcium ha^{-1} annually. No Mg indicates no magnesium fertilization, Mg = 49 kg magnesium ha^{-1} annually.

‡ Values followed by the same letter in the same column are not significantly different at p = 0.05 using Fisher's Protected LSD. NS=not significant at the 0.05 level.

§ Calcium concentration based on percent calcium found in dried root tissue.

Table 3-10. 'Crenshaw' creeping bentgrass root magnesium concentration in response to two K carriers, two Ca rates and two Mg rates.

K Carrier[†]	June 06[‡]	Aug 06	Nov 06	June 07	Aug 07	Oct 07
	----------------------Magnesium Concentration (%)[§]-------------------------					
No K	0.040	0.053	0.042	0.044	0.044	0.041
Granular	0.042	0.053	0.042	0.044	0.045	0.042
Liquid	0.039	0.054	0.043	0.046	0.045	0.040
LSD	NS	NS	NS	NS	NS	NS
Ca Rate						
No Ca	0.040	0.051	0.044	0.045	0.043	0.040
Ca	0.041	0.055	0.041	0.044	0.047	0.042
LSD	NS	NS	NS	NS	0.004	NS
Mg Rate						
No Mg	0.040	0.047	0.040	0.041	0.041	0.039
Mg	0.040	0.059	0.044	0.048	0.048	0.043
LSD	NS	0.006	0.003	0.003	0.004	NS

† Abbreviations: Control = no K fertilization, Granular and Liquid indicate granular or liquid K fertilization at 195 kg K ha^{-1} annually. No Ca indicates no calcium fertilization, Ca = 49 kg calcium ha^{-1} annually. No Mg indicates no magnesium fertilization, Mg = 49 kg magnesium ha^{-1} annually.

‡ Values followed by the same letter in the same column are not significantly different at p = 0.05 using Fisher's Protected LSD. NS=not significant at the 0.05 level.

§ Magnesium concentration based on percent magnesium found in dried root tissue.

Volumetric Soil Water Content (VSWC)

Granular or foliar K treatments had no significant impact on the retention of soil moisture (Appendix C-4). To the knowledge of the authors, no study has investigated or established the ability of K to sustain soil moisture in field conditions. However, current studies (Chapter 4) suggest rates of 195 kg K ha^{-1} annually can maintain elevated soil moisture under drought conditions. Exogenous applications of Ca and Mg also showed no meaningful differences in volumetric soil moisture (Appendix C-4).

Conclusions

High temperature and drought stress are major limiting factors of creeping bentgrass maintained in the transition zone during the summer months. Severe summer declines in creeping bentgrass growth and visual quality readily occur when air temperatures exceed optimal temperatures for C_3 plants. Additionally, high relative humidity does not facilitate heat transfer, reducing efficacy of transpirational cooling. Proper plant nutrition, mainly that of potassium, has long been perceived as a practical method of managing summer creeping bentgrass decline. However, previous research on the matter has been somewhat inconsistent.

For creeping bentgrass, greatest turfgrass quality was achieved throughout the study on plots receiving no K annually. The addition of Ca, either alone or in conjunction with Mg, was found to enhance visual quality for all K treatments. Foliar applications of K at 195 kg K ha^{-1} yr^{-1} produced turfgrass injury from foliar burning due to high concentrations of fertilizer salts. Johnson et al. (2003) and Fu and Huang (2003) noted similar foliar burning of creeping bentgrass treated with liquid K under high temperature stress, resulting in reduced TQ. Additionally, foliar applications of K greatly reduced clipping yields in August and November 2006, possibly due to the stunting of vegetative growth from the high salt index of liquid fertilizer. Summer applications of liquid K fertilizers to creeping bentgrass should be applied in the very early morning or late afternoon hours to allow air temperatures to subside in an attempt to reduce the amount of phytotoxicity and stunting of shoot growth caused by the high concentrations of fertilizer salts. Interestingly, exogenous applications of Ca greatly increased shoot growth on 40% of the sampling dates. Total shoot chlorophyll content, root mass, and volumetric soil moisture were unaffected by any nutrient treatment.

The primary objective of this research was to investigate foliar and root recovery of liquid and granular K, Ca, and Mg under heat and drought stress conditions. Foliar K applications to creeping bentgrass greatly increased endogenous levels of K in shoot tissue. Leaf K concentration peaked under foliar K treatments in October 2007, 21% higher than untreated. At the advanced stage of summer decline, August 2007, Crenshaw creeping bentgrass exhibited minimal rooting and near-deficient leaf extractible K. By October, leaf K concentration of liquid treated turf increased by 30%, suggesting a plant mediated response to low K levels under heat and drought stress.

While the monthly application of Ca and Mg showed minimal effects on leaf K content, K fertilization consistently reduced the amount of Ca and Mg in shoot tissue. Such a result was expected as Woods et al. (2005) and Miller (1999) documented reduced tissue and soil extractable Ca and Mg in response to increasing K fertilization. Additionally, monthly applications of Ca or Mg were shown to increase their respective tissue concentrations; however fertilization of either Ca or Mg negatively impacted tissue concentrations of the other nutrient.

Root nutrient analyses indicated granular forms of K produced the greatest root tissue K contents by November 2006. The following year, as bentgrass summer decline advanced, creeping bentgrass rooting had greatly decreased, resulting in severely reduced efficacy of root K uptake. Foliar K forms increased root tissue K content by 24 and 29% in August and October 2007, respectively. This finding may indicate the ability of creeping bentgrass to transfer root nutrient uptake responsibilities to foliar absorption in the case of impeded rooting. These results suggest foliar applications are the most efficient method for increasing plant tissue K concentrations before the onset of heat and drought stresses. However, extreme caution should be taken when air and soil temperatures exceed turfgrass optimal ranges.

Based on the two years of data, K summer applications simply cannot remedy creeping bentgrass summer decline due to negative phytotoxic impacts caused by relatively high K concentrations, particularly in liquid form. However, Ca application itself significantly benefited creeping bentgrass during the summer months. In the future, lower K rates should be investigated before the onset of summer decline. A general recommendation based on this research includes pre-stress applications of granular K, in addition to supplemental Ca during periods of supraoptimal temperatures and extended drought to sustain creeping bentgrass growth and quality during the summer months.

CHAPTER 4

MANAGING SUMMER STRESS OF CREEPING BENTGRASS IN THE TRANSITION ZONE UNDER VARIOUS LEVELS OF POTASSIUM AND WETTING AGENTS

Introduction

Creeping bentgrass (*Agrostis stolonifera* L.) is the most widely used cool-season turfgrass for golf greens in the northern states and the transition zone of the United States. Genetically improved creeping bentgrass cultivars, for example 'L-93', have recently become popular putting green surfaces in the transition zone for their improved heat tolerance and resistance to disease pressure (Huang et al., 2001; Landry and Schlossberg, 2001; Settle et al., 2001). These improved cultivars provide excellent putting conditions while tolerating exceptionally low mowing heights and maintaining year-round dark green color. However, at the onset of supraoptimal temperatures and high relative humidity, creeping bentgrass begins to decline. During summer months, golf course superintendents struggle to maintain creeping bentgrass rooting and sustain turf quality and color through periods of extreme heat.

A traditional method of improving creeping bentgrass summer survival by lowering plant stress is through applications of supplemental potassium (K) (Carrow et al, 2001; Snyder and Cisar, 2000). Turner and Hummel (1992) demonstrated in studies of hybrid bermudagrass [*Cynodon dactylon* (L.) Pers. X *C. transvaalenis* Burtt Davy] the ability of K to improve disease resistance, drought, heat, and wear tolerance while Beard

(1973) noted increased rooting as well as improved cold hardiness following K fertilization. Additional research showed that K applications improved turfgrass performance (Christians et al., 1981), wear tolerance (Trenholm, 2000), and drought tolerance (Huang, 2001). Conversely, contrasting research has suggested that increasing the amount of K has no positive effect on clipping yields, root weight, or turf quality (Fitzpatrick and Guillard, 2004). Woods et al. (2006) noted no differences in turf quality and ball rolls speeds on 'L-93' creeping bentgrass from even the highest application rates, however, tissue and soil extractable K contents increased under all treatments, suggesting nonexchangeable forms of K were sufficient for plant growth. Linear increases in soil extractable K have been reported by Miller (1999), however, the same linear trend was not seen in tissue K concentration, suggesting a critical plant K fertilization level.

With turfgrass water resources becoming increasingly limited, water conservation and water use efficiency has become a top priority for turfgrass managers of golf courses, sports fields, recreational parks, and home lawns alike. Additionally, extreme weather conditions such as long periods of high temperatures and drought only magnifies the problem as availability of quality water for irrigation is rapidly declining. In order to sustain turfgrass growth and development in these water-limited environments, mangers must have a strong understanding of the environmental factors which influence turfgrass water use to develop sound irrigation management practices. Research has shown that wetting agents, or soil surfactants, are the most effective tool for managing localized dry spot caused by hydrophobic soils (Karnok and Tucker, 2001a; Karnok and Tucker, 2001b; Leinauer et al., 2001; Blodgett et al., 1993; Wilkinson and Miller, 1978). Karnok and Tucker (2001a) reported increased volumetric water content and decreased soil hydrophobicity of a sand-peat growth medium, as well as improved turfgrass quality and rooting of ‘Penncross’ creeping bentgrass. Another study by Leinauer et al. (2001) investigated the impact of wetting agents on soil hydrophobicity of a USGA sand rootzone mix at increasing depths. Results indicated volumetric soil water content of sand treated with Midorich WA was highest at 50 mm, while Primer WA produced the greatest water retention at 150 and 250 mm. These findings indicate that because of their chemical formulations and mobility, particular wetting agents appear to influence soil water retention differently at various depths. Conversely, similar studies report negative impacts from WA applications such as increased thatch (Callahan et al., 1998), turf discoloration, and reduced rooting (Wiecko and Carrow, 1992) or negligible WA influence on moisture retention or microbial activity of the soil medium (Ruemmele and Amador, 1994).

Because previous research has been unsuccessful at assessing optimal rates and timing of K fertilization, and WA research on creeping bentgrass in combination with K fertilization is lacking, additional research is necessary to examine their ability to mitigate effects of summer creeping bentgrass decline. It is hypothesized that liquid applications of elemental K, in conjunction with monthly WA applications, will significantly reduce summer stress of ‘L-93’ creeping bentgrass by sustaining satisfactory turf quality and stand health throughout the summer months. The objective of this study was to investigate the effects of two potassium carriers, liquid and granular, at three annual rates with monthly applications of WA on summer turf performance of creeping bentgrass in an effort to sustain acceptable turfgrass quality through the summer months while reducing soil hydrophobic conditions.

Materials and Methods

A two-year field study was conducted from 25 May 2006 to 30 October 2007 on an established 'L-93' creeping bentgrass research green built to USGA specifications at Clemson, South Carolina (USGA, 1993). Plot size measured 2.4 x 3.1 m in a randomized split plot design with WA treatments representing the split plot factor, with four replications.

Liquid K solution was applied to the plots biweekly at rates of 8.14 kg K ha^{-1} (low rate) and 16.27 kg K ha^{-1} (high rate). The rates of 8.14 kg K ha^{-1} and 16.27 kg K ha^{-1} are equivalent to 97.65 and 195.29 kg K ha^{-1} annually split over 12 equal applications, respectively. Liquid K was derived from potassium carbonate (StressMax 0-0-30) (Harrell's Fertilizer, Inc., Lakeland, FL 33802), and applied using a CO_2 back-pack type sprayer.

Granular applications of slow-release, polyon-coated K, derived from polymer coated potassium sulfate (Harrell's Fertilizer, Inc., Lakeland, FL 33802), were applied at 32.55 and 65.10 kg K ha^{-1} on dates of core aerification. On May 25, September 25, and October 23 of 2006 and March 21, September 19, and October 17 of 2007, a hollow tine cultivator removed cores from the turf and granular K was mixed with a sand carrier and shaken over the plots, then swept in by hand. Normal topdressing was applied to fill aerification holes. Granular K rates of 32.55 kg K ha^{-1} and 65.10 kg K ha^{-1} are equivalent to 97.66 and 195.29 kg K ha^{-1} per year, respectively.

Wetting agent applications were applied every four weeks from May to October each year at a rate of 19.1 L WA ha^{-1} monthly. The source of wetting agent was Revolution wetting agent produced by the Aquatrols Corporation, Inc. WA treatments were applied using a CO_2 powered sprayer and immediately watered in.

Plots were mowed seven d wk^{-1} with a triplex greens mower at 3.2 mm with clippings removed. Turf was irrigated as needed to prevent plant stress in addition to annual precipitation. Monthly precipitation is shown in Appendix D. Research plots were core cultivated with 1.3 cm inside diameter hollow tines at 5.1 cm spacing and 10.2 cm lengths on 23 March, 25 May, 25 September, and 19 October of 2006 and 21 March, 24 May, 19 September, and 17 October of 2007. Cores were removed and holes filled with topdressing sand (Appendix C-1 and C-2).

In 2006, nitrogen was supplied to the plots at a rate of 4.88 kg N ha^{-1} every 14 d from 29 May to 3 December in the form of Microburst (5-0-0) liquid fertilizer containing 5% N, 2.8% S, 0.5% Mg, 0.02% B, 0.5% Cu, 4.5% Fe, 0.5% Mn, 0.5% Zn, 0.003% Mo. No N was applied on 24 July or 7 August in 2006 to prevent turf burning due to high application rate of iron (Fe) contained in Microburst. In 2007, Microburst was applied at 4.88 kg N ha^{-1} on 24 March and 2 April. For the remainder of 2007, N was supplied as Microburst and dissolved urea (46-0-0) at a rate of 4.88 kg N ha^{-1} every 14 d. Applications of N were not applied from 6 August to 3 September 2007. Granular Milorganite (6-2-0) was also supplied to the plots at 32.55 kg N ha^{-1} on core aerification dates. Preventative fungicides were applied as needed to suppress development of dollar spot (*Sclerotinia homeocarpa*) and pythium (*Pythium* spp.).

Data Collection

Turf quality was rated biweekly on a 1 to 9 scale with 9 being of healthy, dark green turf and 1 being dead, brown turf. Visual quality ratings below 7 were considered unacceptable. Fresh clippings were harvested monthly after approximately 48 hours of uninterrupted growth. Samples were dried for 72 hours in an 80^{o}C oven and then weighed. Samples collected in June, August, and October of each year were analyzed for nutrient contents by the Clemson University Agriculture Service Laboratory.

Root samples were collected using a standard golf course cup cutter with a diameter of 10.8 cm and a depth of 20.3 cm in June, August, and October 2006 and 2007. Samples were thoroughly washed free of sand, dried in an 80^{o}C oven for 72 hours and weighed. Root tissue samples were forwarded to the Clemson University Agriculture Service Laboratory for nutrient concentration analyses. Volumetric soil moisture (m^3/m^3) content was measured monthly in the top 10 cm of soil from June to October of each year using a time-domain reflectometer (TDR) (ML2, Delta-T Devices Ltd., Cambridge CB5 OEJ, England) soil moisture sensor. Three readings were recorded from each plot with the average of the three representing each plot.

Soil hydrophobicity was determined using by a water droplet penetration time (WDPT) method (Wilkinson and Miller, 1978)**.** Two cores were harvested from each plot with a 3 cm diameter to a depth of 10 cm. Cores were allowed to dry at room temperature for four weeks. A single drop of deionized-distilled water was placed at 1.5 and 3.0 cm depths on the core and the time of complete penetration (in seconds) was recorded. Total absorbance was determined when the water droplet had completely soaked into the medium. Absorbance times for the two cores from each plot were averaged among both depths representing soil hydrophobicity values for each depth, respectively.

Data Analysis

All statistical computations were conducted using general liner model (GLM) within the Statistical Analysis System (SAS Institute, 2003). Means were separated by Fisher's Least Significant Difference (LSD) test. An alpha of 0.05 was used for all data comparisons.

Results and Discussion

Significant treatment by year interactions were detected; therefore, results will be examined separately for each year. A K and WA interaction occurred for turfgrass quality (TQ) and will be examined as treatment combinations for each year. No meaningful interactions between K carriers and WA were observed ($P > 0.05$) for the other parameters measured; therefore, main effects of each treatment for 2006 and 2007 were examined and presented separately.

Turf Quality

Significant differences in TQ among K and WA treatments occurred in every month in year 1 (Table 4-1). Granular K fertilization of 195 kg K ha^{-1} yr^{-1} resulted in greatest visual TQ for the majority of 2006. As observed in Table 4-1, liquid K application of 195 kg K ha^{-1}, with or without WA, negatively affected TQ. Furthermore, liquid K at the 195 kg K ha^{-1} rate reduced TQ compared to the 98 kg K ha^{-1} rate by as much as 22 and 20% in August and September 2006, respectively. The sudden negative impact of liquid fertilization, especially at 195 kg K ha^{-1} rate, can be explained by a phototoxicity effect due to high application rate of fertilizer salts. Johnson et al. (2003) reported high rates of foliar K reduced TQ of creeping bentgrass, due to foliar burn of fertilizer salts. In an attempt to reduce the amount of phototoxic effects from liquid K fertilization, liquid K applications were applied at dusk and watered in using overhead, automated irrigation after 1 to 2 hours. Generally, monthly application of WA produced decreased TQ ratings in 2006. In 'Kentucky 31' tall fescue, Wiecko and Carrow (1992) also found no improvement turfgrass quality and reduced deep rooting by all wetting agents examined and minor discoloration by Lesco-Wet following application.

In 2007, plots receiving no K or WA consistently exhibited the poorest visual quality of all treatments (Table 4-2). No obvious trends between K treatments existed in 2007; however, liquid K at 98 kg K ha^{-1} provided significantly higher TQ in September and October compared to untreated. Fu and Huang (2003) reported foliar applications of KH_2PO_4 (10mM) to Penncross creeping bentgrass while exposed to heat stress helped maintain higher turf quality, photochemical efficiency (F_V/F_M), and shoot growth rate than untreated. Interestingly, the WA effect observed in year 1 was not exhibited in year 2, as WA application had a positive impact on TQ regardless of K rate or carrier. Karnok and Tucker (2001a) reported similar findings on Penncross creeping bentgrass in summer field experiments citing significantly improved TQ under one application of WA annually. Except for September, treatments producing the highest visual turf quality were treated with WA; however these differences were not found significant. This result can be partially attributed to weather variations observed between the two years of the study. Weather data for 25 May 2006 through 30 October 2007 can be found in Appendix D. An extreme drought was experienced at the experiment site during the summer of 2007. Apparently, excess moisture from precipitation and irrigation held by WA within the soil profile did not allow for nighttime cooling of soil in 2006. During drought favorable conditions in 2007, WA was able to retain vital soil moisture and sustain creeping bentgrass visual quality.

Table 4-1. Visual turf quality of 'L-93' creeping bentgrass in response to two K carriers, three K rates and a WA in 2006.

Rates (kg K ha^{-1})†		June‡	July	August	Sept	October
		------------------------Turfgrass Quality (1-9)§-------------------------				
0	**0**	7.4	6.9	6.4	7.0	6.8
	WA	7.4	6.4	5.8	7.0	6.8
98 G	**0**	7.9	6.8	6.8	7.3	6.4
	WA	7.5	6.3	6.0	6.8	6.6
98 L	**0**	8.1	6.8	6.8	7.4	7.4
	WA	7.6	6.0	5.6	6.3	6.8
195 G	**0**	7.6	7.1	7.0	7.9	7.1
	WA	7.5	6.3	6.4	7.1	6.6
195 L	**0**	7.3	6.6	5.3	5.9	6.3
	WA	7.9	5.8	5.3	5.6	6.4
LSD		0.71	0.38	0.72	1.02	0.9

† Abbreviations: G = Granular potassium (K) carrier at 98 or 195 kg K ha^{-1} yr^{-1}, L = Liquid K carrier at 98 or 195 kg K ha^{-1} yr^{-1}. WA = Revolution wetting agent at 19.1 L WA ha^{-1} monthly.

‡ Values followed by the same letter in the same column are not significantly different at p = 0.05 using Fisher's LSD. NS=not significant at the 0.05 level.

§ Turfgrass quality based on a visual scale of 1 to 9 with 1 = poorest, 9 = best. Visual rating of $\geq$7 indicates acceptable turf quality.

Table 4-2. Visual turf quality of 'L-93' creeping bentgrass in response to two K carriers, three K rates and a WA in 2007.

Rates (kg K ha^{-1})†		June‡	July	August	Sept	October
		------------------------Turfgrass Quality (1-9)§-------------------------				
0	**0**	4.6	5.3	4.1	4.0	4.3
	WA	6.5	6.4	4.8	4.8	5.3
98 G	**0**	5.3	5.7	4.8	4.8	5.3
	WA	7.4	6.5	4.8	4.8	5.5
98 L	**0**	5.5	5.9	5.5	6.1	6.5
	WA	6.3	6.4	5.6	5.5	6.5
195 G	**0**	6.4	6.6	5.8	5.8	6.1
	WA	6.9	6.6	5.5	5.5	6.5
195 L	**0**	5.9	6.5	5.0	4.6	5.4
	WA	6.8	7.2	5.6	5.6	6.0
LSD		1.39	1.06	NS	2.10	2.18

† Abbreviations: G = Granular potassium (K) carrier at 98 or 195 kg K ha^{-1} yr^{-1}, L = Liquid K carrier at 98 or 195 kg K ha^{-1} yr^{-1}. WA = Revolution wetting agent at 19.1 L WA ha^{-1} monthly.

‡ Values followed by the same letter in the same column are not significantly different at p = 0.05 using Fisher's LSD. NS=not significant at the 0.05 level.

§ Turfgrass quality based on a visual scale of 1 to 9 with 1 = poorest, 9 = best. Visual rating of $\geq$7 indicates acceptable turf quality.

Clipping Yield

Initial application of granular and liquid K at the 195 kg K ha $^{-1}$ rate increased clipping yield by 17 and 18% in June 2006, respectively, compared to the control (Table 4-3). Conversely, one month later, turfgrass growth was reduced by 19 and 22% with the addition of granular K forms at the 98 and 195 kg K ha^{-1} annual rates, respectively (Table 4-3). By September 2007, the greatest vegetative growth response was documented on plots receiving the low rate of liquid K, provided a 36% increase in shoot growth compared to untreated (Table 4-4). Reasons for inconsistent K effects are unknown. It is feasible that foliar K fertilization programs have a higher efficacy of stomatal uptake and utilization to increase turfgrass growth and vigor, especially under stress such as high heat and drought. Previous research has disclosed data revealing foliar K applications produced greater increases in clipping yield at 120 kg K ha^{-1}, as opposed to higher rates of 240 kg K ha^{-1} annually (Waddington et al., 1972). This lack of shoot growth following K application was to some extent expected, as many studies have concluded no increase in clipping yield when K was applied (Snyder and Cisar, 2005; Fitzpatrick and Guillard, 2004; Dest and Guillard, 2001; Waddington et al., 1978). Turf-applied WA only increased clippings on a single sampling date, June 2007, by 18% (Appendix C-5).

Table 4-3. Influence of potassium rate and source on clipping yield of 'L-93' bentgrass from June 2006 to November 2006.

Rates (kg K ha^{-1})†	**June‡**	**July§**	**August**	**October**	**November**
	------------------------Total Dry Clipping Yield (g m^{-2}) ¶-------------------------				
0	1.61	0.78	1.65	3.79	2.58
97.65 G	1.73	0.63	1.70	3.75	2.55
97.65 L	1.84	0.70	1.85	3.79	2.71
195.29 G	1.94	0.66	1.88	4.30	2.61
195.29 L	1.96	0.71	1.84	3.88	2.91
LSD	0.29	0.08	NS	NS	NS

† Values followed by the same letter in the same column are not significantly different at p = 0.05 using Fisher's LSD.

‡ Abbreviations: G = Granular potassium (K) carrier at 98 or 195 kg K ha^{-1} yr^{-1}, L = Liquid K carrier at 98 or 195 kg K ha^{-1} yr^{-1}.

§ Number of days between mowings differed for each clipping harvest. Dependent upon growth rate at time of harvest.

¶ Total dry clipping yield based grams of dried tissue per square meter.

Table 4-4. Influence of potassium rate and source on clipping yield of 'L-93' bentgrass from June 2007 to October 2007.

Rates (kg K ha^{-1})†	**June**‡	**July**§	**August**	**September**	**October**
	------------------------Total Dry Clipping Yield (g m^{-2}) ¶------------------------				
0	3.08	3.23	3.10	1.64	1.50
98 G	3.14	3.15	2.90	1.58	1.64
98 L	3.28	3.75	3.69	2.56	2.04
195 G	3.21	3.80	3.61	2.24	1.83
195 L	3.33	3.69	2.80	1.91	1.69
LSD	NS	NS	NS	0.86	NS

† Values followed by the same letter in the same column are not significantly different at $p = 0.05$ using Fisher's LSD.

‡ Abbreviations: G = Granular potassium (K) carrier at 98 or 195 kg K ha^{-1} yr^{-1}, L = Liquid K carrier at 98 or 195 kg K ha^{-1} yr^{-1}.

§ Number of days between mowings differed for each clipping harvest. Dependent upon growth rate at time of harvest.

¶ Total dry clipping yield based grams of dried tissue per square meter.

Percent Total K in Clippings

Generally, as K rate increased, K concentration within the leaf tissue increased on 5 of 6 sampling dates (Table 4-5). In June 2006, all K treatments produced significant increases in leaf K, with granular carriers at the 98 and 195 kg K ha^{-1} rate both yielding a 4% increase compared to control (Table 4-5). Granular and liquid sources of K at 195 kg K ha^{-1} produced 8 and 11% greater leaf K content in August 2006, respectively, and a 20% greater concentration for both sources by November 2006 compared to untreated (Table 4-5). In June 2007, 195 kg K ha^{-1} in liquid form resulted in a 10% greater clipping K compared to untreated. All K treatments were significantly higher than control by October 2007, with 195.29 kg K ha^{-1} rates producing 15% greater leaf K concentrations (Table 4-5). Sufficient potassium levels range between 1.5 and 3% total dry weight (McCarty, 2005; Carrow et al., 2001). As shown in Table 4-5, all K treatments resulted in sufficient leaf potassium concentrations.

Miller et al. (1999) performed a plateau analysis to indicate maximum K concentrations of 'Tifdwarf' and 'Tifway' hybrid bermudagrass grown in sand-peat and receiving up to 390 kg K ha^{-1} per month. Results indicated no active uptake of the two bermudagrasses when application rates exceeded 74 and 84 kg ha^{-1} monthly, respectively. Our findings generally showed increases in leaf tissue potassium at rates well below what Miller concluded to be the maximum application rate for greatest tissue K concentration. This finding may imply application rates of K fertilization above the level used in this study may benefit potassium tissue concentrations. Additionally, data indicated wetting agent treatments had no significant impact on leaf tissue K concentrations for the duration of the study period (results not shown).

Table 4-5. Potassium rate and source influence on leaf tissue potassium concentration of ‘L-93’ bentgrass from June 2006 to October 2007.

Rates (kg K ha^{-1})[†]	**June 06**[‡]	**Aug 06**	**Nov 06**	**June 07**	**Aug 07**	**Oct 07**
	-------------------------Potassium Concentration (%)[§]-------------------------					
0	2.81	2.58	1.73	2.16	1.69	2.11
98 G	2.93	2.76	1.94	2.19	1.89	2.41
98 L	2.90	2.76	2.01	2.30	2.01	2.38
195 G	2.92	2.79	2.16	3.32	2.05	2.49
195 L	2.87	2.91	2.16	2.40	1.97	2.48
LSD	0.09	0.14	0.11	0.08	NS	0.15

† Values followed by the same letter in the same column are not significantly different at p = 0.05 using Fisher’s LSD.

‡ Abbreviations: G = Granular potassium (K) carrier at 98 or 195 kg K ha^{-1} yr^{-1}, L = Liquid K carrier at 98 or 195 kg K ha^{-1} yr^{-1}.

§ Potassium Concentration based on percent potassium found in dried leaf tissue.

Root Dry Weight

Significant findings were detected among K treatments; however, application of WA yielded no significant differences (data not shown). Root dry weight was 33% greater at the highest granular K rate compared to the low rate and control in June 2006, respectively (Table 4-6). By August 2006, high rate of liquid potassium reduced root dry weight by 36% compared to control and by 42% compared to granular form of the same rate. Additionally, both carriers at the highest K rate provided 20% reductions by study's end in October 2007 (Table 4-6). The negative influence of potassium on root growth was unexpected, considering much literature reports a positive correlation between K applications and root growth (McCarty, 2005; Sartain, 2002; Dest and Guillard, 2001; Belesky and Wilkinson, 1983; Beard, 1973; Juska et al., 1965). It is unclear why applications of K, particularly in liquid form, decreased creeping bentgrass root mass, however it is possible that a build-up of fertilizer salts and phytotoxic effects from liquid K applications severely declined creeping bentgrass rooting. No beneficial impact on root weight was recorded following monthly applications of WA (data not shown).

Table 4-6. Influence of potassium rate and source on root dry weight of 'L-93' bentgrass from June 2006 to October 2007.

Rates (kg K ha^{-1})†	**June 06**‡	**Aug 06**	**Nov 06**	**June 07**	**Aug 07**	**Oct 07**
	------------------------------Root Dry Weight (g m^{-2})§------------------------------					
0	149.1	76.9	58.2	65.7	60.1	38.3
98 G	149.2	85.0	61.0	78.0	46.4	36.1
98 L	156.1	76.8	59.3	77.4	48.7	36.5
195 G	220.4	83.8	65.2	74.2	48.5	30.2
195 L	175.6	49.4	48.1	66.1	47.9	30.2
LSD	69.4	15.2	NS	NS	NS	7.8

† Values followed by the same letter in the same column are not significantly different at $p = 0.05$ using Fisher's LSD.

‡ Abbreviations: G = Granular potassium (K) carrier at 98 or 195 kg K ha^{-1} yr^{-1}, L = Liquid K carrier at 98 or 195 kg K ha^{-1} yr^{-1}.

§ Total dry root weight based grams of dried tissue per square meter.

Root Nutrient Concentrations

In contrast to leaf tissue K concentration, increases in K rate did not generally result in higher root tissue K content (Table 4-7). ‘L-93’ creeping bentgrass treated with 98 kg K ha^{-1} liquid K demonstrated increased K concentrations by 46% and 34% compared to control in November 2006 and August 2007, respectively (Table 4-7). Creeping bentgrass receiving 195 kg K ha^{-1} liquid K exhibited 29% increased root K concentrations in August 2007, compared to the 98 kg K ha^{-1} rate. Observing significantly elevated levels of K in root tissue on plots only receiving foliar K fertilization was to a degree, unexpected. Based on seasonal decline of creeping bentgrass roots observed for all treatments, it is possible that the turf was relying on foliar absorption of K and translocating it into root tissue. Additionally, root K concentrations of WA treated creeping bentgrass were reduced by 38% by the end of year 1 (Table 4-7).

Table 4-7. Influence of potassium rate and source on root tissue potassium of ‘L-93’ creeping bentgrass concentration from June 2006 to October 2007.

Rates (kg K ha^{-1})†	**June 06**‡	**Aug 06**	**Nov 06**	**June 07**	**Aug 07**	**Oct 07**
	-------------------------Potassium Concentration (%)§-------------------------					
0	0.049	0.044	0.043	0.043	0.060	0.053
98 G	0.044	0.066	0.049	0.046	0.071	0.076
98 L	0.045	0.043	0.079	0.051	0.074	0.080
195 G	0.045	0.060	0.058	0.064	0.063	0.069
195 L	0.038	0.046	0.053	0.059	0.085	0.074
LSD	NS	NS	0.031	0.011	0.024	0.018
WA Rate						
Control	0.042	0.049	0.069	0.055	0.076	0.069
WA	0.046	0.055	0.043	0.051	0.065	0.072
LSD	NS	NS	0.018	NS	NS	NS

† Values followed by the same letter in the same column are not significantly different at p = 0.05 using Fisher’s LSD.

‡ Abbreviations: G = Granular potassium (K) carrier at 98 or 195 kg K ha^{-1} yr^{-1}, L = Liquid K carrier at 98 or 195 kg K ha^{-1} yr^{-1}. WA = Revolution wetting agent at 19.1 L WA ha^{-1} monthly.

§ Potassium Concentration based on percent potassium found in dried root tissue.

Soil Moisture

The monthly application of WA had no effect on volumetric water content in either year of the study (Table 4-8). This finding contradicts reports of prior research noting improved soil volumetric water content following WA application (Karnok and Tucker, 2001; Leinauer et al., 2001; Ruemmele and Amador, 1998; Blodgett et al., 1993). Still, literature documenting negligible effects of WAs on improving moisture retention of sand mediums also exists (Ruemmele and Amador, 1994; Wiecko and Carrow, 1992).

Interestingly, volumetric soil water content was significantly higher for plots receiving the higher rate of potassium compared to the control in year 1 of the study (Table 4-8). In June, plots receiving liquid K at 198 kg K ha^{-1} annually averaged 22% higher volumetric soil moisture than control plots. In September and November of the same year, granular forms of K at the same rate raised soil moisture by 23 and 19%, respectively. A closer investigation of increasing K rates and soil water potential is warranted and may reveal insight to increasing volumetric soil water content.

Table 4-8. Volumetric soil water content of 'L-93' creeping bentgrass as influenced by potassium rate and source and monthly applications of WA.

K Carrier†	June 06‡	July 06	Aug 06	Sept 06	Nov 06	June 07	July 07	Aug 07	Sept 07	Oct 07
	--Volumetric Water Content (m^3/m^3)--									
0	0.21	0.24	0.19	0.19	0.28	0.28	0.27	0.18	0.22	0.23
98 G	0.26	0.25	0.21	0.22	0.31	0.31	0.29	0.19	0.22	0.22
98 L	0.25	0.26	0.22	0.21	0.32	0.29	0.31	0.24	0.25	0.24
195 G	0.26	0.26	0.22	0.25	0.35	0.30	0.31	0.23	0.24	0.24
195 L	0.27	0.25	0.21	0.20	0.30	0.31	0.29	0.22	0.23	0.23
LSD	0.035	NS	NS	0.031	0.078	NS	NS	NS	NS	NS
WA Rate										
No WA	0.25	0.26	0.23	0.22	0.32	0.30	0.31	0.22	0.23	0.22
WA	0.25	0.24	0.19	0.21	0.30	0.30	0.28	0.21	0.23	0.25
LSD	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

† Abbreviations: G = Granular potassium (K) carrier at 98 or 195 kg K ha^{-1} yr^{-1}, L = Liquid K carrier at 98 or 195 kg K ha^{-1} yr^{-1}. WA = Revolution wetting agent at 19.1 L WA ha^{-1} monthly.

‡ Values followed by the same letter in the same column are not significantly different at p = 0.05 using Fisher's LSD. NS=not significant at the 0.05 level.

Soil Hydrophobicity

Soil hydrophobicity was affected by WA and K for both years of the study. Wetting agent untreated plots, as expected, always provided significantly higher water droplet absorbance times compared to WA-treated plots which provided much faster times of absorption (Figure 4-1). WA application produced a 19.9 and 8.9 fold reduction of soil hydrophobicity at 1.5 and 3.0 cm depths, respectively in 2006 based on absorption times (Figure 4-1). In 2007, similar trends revealed a 7.2 and 6.6 fold reduction of hydrophobicity at 1.5 and 3.0 cm, respectively, with the addition of the soil surfactant. Previous studies have also reported reductions in soil hydrophobicity following WA application. Karnok and Tucker (2001a) reported a decline in hydrophobicity of sand-peat soil up to 12 weeks following a single WA application. A study by Wilkinson and Miller (1978) showed WAs beneficial in reducing the severity of localized dry spot injury on Penncross creeping bentgrass grown on a sand growth medium. Table 4-9 reveals L-93 creeping bentgrass receiving liquid K at 97.65 kg K ha^{-1} yr^{-1} exhibited the least soil hydrophobicity at 3.0 cm in 2006, while untreated plots exhibited fastest absorption times in 2007 at the 1.5 cm depth. Our data supports the findings of previous researchers who examined wetting agent’s ability to lower surface tension of water, rendering hydrophobic soils rewettable.

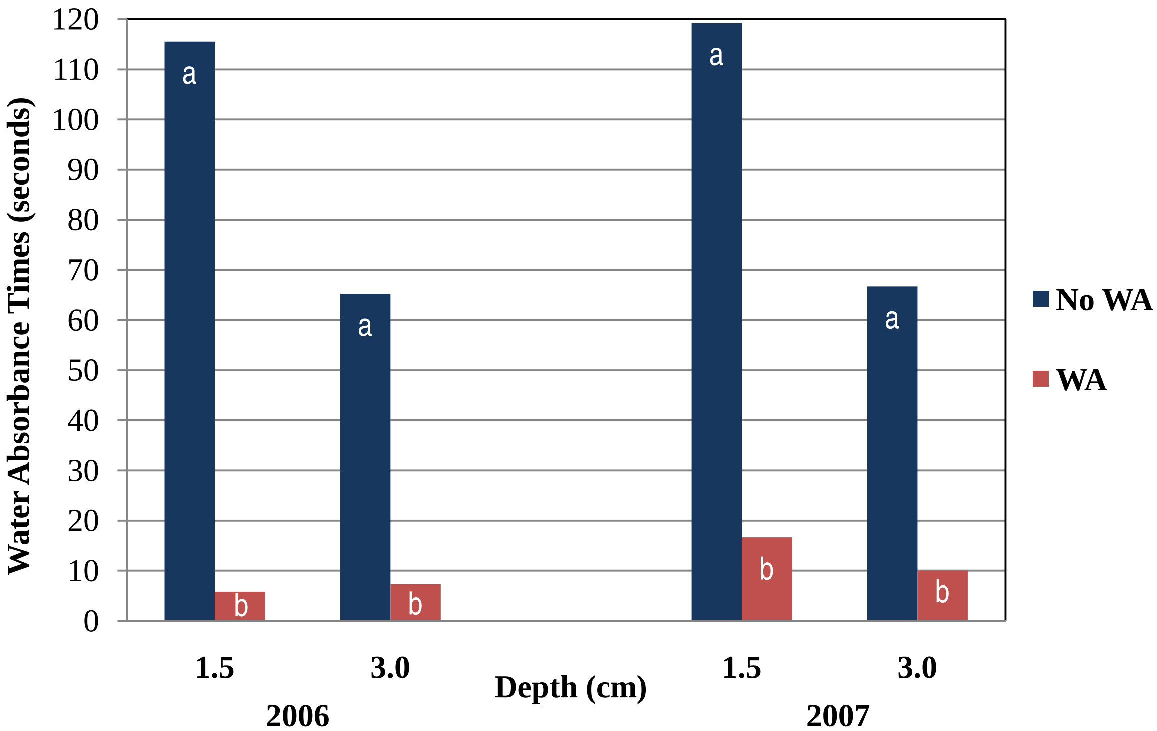


Figure 4-1. Wetting agent (WA) effect on soil hydrophobicity at 1.5 and 3.0 cm depths of an 85:15 sand-peat growth medium in 2006 and 2007. Different letters indicate a significant difference at p=0.05 according to Fisher's LSD.

Table 4-9. Soil hydrophobicity as affected by K at 1.5 and 3.0 cm depths for 'L-93' creeping bentgrass treated with various K rates and carriers.

	Year			
Rates	**2006**		**2007**	
(kg K ha^{-1}) †	**1.5**‡	**3.0**	**1.5**	**3.0**
	--------------Soil Hydrophobicity (sec)§-----------------			
0	64.36	57.56	53.56	39.55
98 G	49.07	28.62	72.52	40.71
98 L	56.50	18.17	63.96	22.02
195 G	64.78	25.01	73.23	42.23
195 L	68.70	52.12	76.37	47.33
LSD	NS	36.56	20.17	NS

† Values followed by the same letter in the same column are not significantly different at p = 0.05 using Fisher's LSD.

‡ Abbreviations: G = Granular potassium (K) carrier at 98 or 195 kg K ha^{-1} yr^{-1}, L = Liquid K carrier at 98 or 195 kg K ha^{-1} yr^{-1}.

§ Soil hydrophobicity based on rate of water droplet absorption time in seconds.

Conclusions

Creeping bentgrass grown in the transitional zone is presented with a gauntlet of inhospitable environmental conditions in the summer months that often lead to the condition referred to as summer creeping bentgrass decline. Year 1 of this study revealed greatest creeping bentgrass visual TQ occurred with plots receiving 195 kg granular K ha^{-1} yr^{-1}, providing the best turfgrass health and playing conditions. Year 2, however, revealed the lower rate of liquid K applied every 14 days increased visual quality above other treatments in the latter portion of the summer. Upon closer examination, it can be concluded that higher rates of foliar applied K impeded visual TQ compared to the liquid 98 kg K ha^{-1} yr^{-1} rate. While Fu and Huang (2003) noted the ability of foliar K applications to increase creeping bentgrass heat tolerance, Johnson et al. (2003) noted high rates of foliar applied potassium reduced TQ, due to foliar burning.

Additionally, monthly WA application reduced TQ in 2006 and showed no beneficial effects on volumetric soil moisture, inconsistent with findings by a majority of previous research. When grown under extreme heat and drought stress in field conditions of 2007, however, monthly applications of WA increased TQ for nearly all treatments. This finding indicates supplemental WA applications, while proven to reduce localized dry spot by reducing soil hydrophobicity, may not be needed during growing seasons of years providing adequate irrigation and precipitation. Further research is needed concerning application of WA timing and rates and weather to confirm this hypothesis.

Clipping yield is a method for golf course superintendents to monitor turfgrass growth and health through the growing season. Although no notable trends of K rate or carrier were observed for clipping yield, liquid K forms were found to increase yield on two sampling dates. Seasonal declines in dry root weight over both years of the study were not mediated by the addition of any of the potassium treatments, and at times, were reduced by as much as 36% by higher K rates used in this study. Wetting agent was applied at 19.1 L WA ha^{-1} monthly and produced a profound reduction in the level of soil hydrophobicity exhibited by treated plots each year.

A primary objective of this study was to investigate K rates and carriers and their influence on tissue K concentrations in roots and shoots. As expected, increasing K rate to 195 kg K ha^{-1} yr^{-1} resulted in consistently higher leaf tissue K, with the greatest concentrations following liquid K fertility. Surprisingly, liquid forms of K improved root tissue K concentrations, at either rate, more so than granular forms. It was observed that root mass decreased linearly each year, possibly indicating why root tissue K levels were highest for foliar K treatments. A lack of rooting available for soil K interception and absorption would obviously impede root K uptake. Due to the mobility of K within the plant, foliar applications of K would greatly increase leaf and root tissue K concentrations, even while rooting is at a minimum.

CHAPTER 5

EVALUATING POA TRIVIALIS UNDER REDUCED LIGHT ENVIRONMENTS WITH VARIOUS RATES OF LIQUID NITROGEN AND IRON

Introduction

Annual winter overseeding of warm-season turfgrass putting greens is a common practice on golf courses in the southeastern United States. Although during winter months, shade conditions are improved due to fell leaves of deciduous trees, lower solar radiation angles and evergreen trees still pose cause serious shade problems for some greens. An estimated 20-25% of the turf grown today is exposed to some degree of low light conditions (Dudeck and Peacock, 1992; Beard, 1973). Unlike warm-season grasses, which require full sunlight to reach maximum photosynthetic capacity, cool-season grasses reach light saturation at approximately ½ full sunlight (McCarty, 2005; Fry and Huang, 2004). Physiological and morphological responses of cool season grasses to reduced light irradiance include increased upright growth habits, increased chlorophyll content, depleted carbohydrate reserves, thinner and longer leaves, reduced density, shallow rooting, and reduced tillering (Dudeck and Peacock, 1992; Beard, 1973).

Reduced N fertilization has long been a recommended practice to suppress vertical growth and carbohydrate depletion of shaded turfgrass (Wilson, 1997). Goss et al. (2002) reported higher quality of ‘Penncross’ creeping bentgrass under shade receiving 150-185 kg N ha^{-1} than higher rates of 212-235 kg N ha^{-1}. However, nitrogen is an essential component of any turfgrass management program, regardless of light level. Additionally, leaf chlorophyll content is increased under shade, however under extremely low light, chlorophyll is significantly reduced (Beard, 1973). Foliar applications of Fe have been used to darken turfgrass color under shade (Glinski et al., 1992) by enhancing granal development in chloroplasts of Kentucky bluegrass (Lee et al., 1996). The effect of increasing N rates and foliar Fe applications on growth and performance of overseeded turf under shade is however, unknown.

Therefore, the objective of this study was to determine the effect of winter shading on turf quality, clipping yield, chlorophyll concentration and nutrient recovery of an overseeded bermudagrass putting green exposed to increasing levels of N fertilization and foliar Fe application.

Materials and Methods

The study was conducted during the winter months of 2006-07 and 2007-08 at the Clemson University Turfgrass Research Center, in Clemson, SC on a Champion bermudagrass field research plot overseeded with 'Sabre' roughstalk bluegrass (*Poa trivialis* L.). Experimental plot was established by sprigs in July 2003 with soil profile constructed to approximate United States Golf Association (USGA) recommendations (USGA, 1993). Plots measured 2.7 x 1.8 m arranged as a randomized split block design with shade treatments representing the split block, with three replications (Appendix B-3).

Treatments consisted of three annual nitrogen rates of 49, 98, and 147 kg N ha^{-1} per season split between 4 equal applications. Nitrogen was supplied as urea (46-0-0) using a CO_2 powered backpack sprayer. Iron was supplied monthly as chelated iron (Sequestrene 330 Fe) tank mixed with nitrogen at a rate of 10.8 kg a.i. ha^{-1} per season. Foliar applications of N and Fe were applied on 8 November, 28 November, 11 January, and 1 February of year 1 and 13 November, 29 November, 10 January, and 2 February of year 2. Shade treatments consisted of control (no shade) and 55% shade using a neutral density, polyfiber black shade cloth (Glenn Harp and Sons, Inc., Tucker, GA) supported by polyvinyl chloride (PVC) frame 183 cm long and 152 cm wide with 2.54 cm diameter PVC pipes. Shade structures were 15 cm above the rough bluegrass surface to reduce sunlight intrusion by the low solar angle of the sun during the winter months, yet allow adequate wind movement. All tents were removed nightly. Shade treatment duration was 16 November to 16 February 2006 and 15 November to 15 February 2007.

Plots were overseeded on 6 October 2006 and 5 October 2007, 41 days prior to the initiation of shade treatments each year. Prior to overseeding, plots were vertically mowed in 2 perpendicular directions with approximately 2 mm wide blade at 2 cm spacing to a depth of 2.5 cm using a SISIS vertical mower (Cheshire SK10 2LZ, England) with debris removed. Plots were mowed a second time at 3.2 mm and rough bluegrass was seeded at 390 kg ha^{-1} pure live seed, using a push drop spreader. Plots were seeded in two directions to ensure uniform seed distribution. Seed were brushed in by hand using push-type brooms and lightly topdressed with the same material as the original root zone mix (Appendix C-1 and C-2). Seedbed moisture was maintained by an overhead, automated irrigation system 4 times daily for 10 days following overseeding. Mowing was resumed at an initial height of 4.8 mm and gradually reduced to 3.2 mm over 21 days. Chlorothalonil (Daconil) was applied to plots as needed to control outbreak of dollar spot on roughstalk bluegrass.

Data collection

Data collected included visual turf quality (TQ), clipping yield, shoot chlorophyll concentration, leaf tissue nutrient concentrations, and microenvironment conditions. Turf quality was rated visually every 14 d based on turf color, density, and overall stand health. Turf quality was rated on a 1 to 9 scale with 1 = dead turf, 9 = dark green, healthy turf, and 7 $\geq$ signifying acceptable turf quality.

Clippings were harvested in December, January, and February using a walk-behind greensmower with a clipping collector (Greenmaster® 800, The Toro Company, Bloomington, MN). Fresh clippings were analyzed for leaf chlorophyll content in January and February of both years. Chlorophyll was extracted using the dimethyl sulfoxide (DMSO) extraction method (Hiscox and Israelstram, 1979) (Appendix A). Total chlorophyll content (mg g^{-1}) was determined using a spectrophotometer (Genesys™ 20, ThermoSpectronic, Rochester, NY) with absorbance values at 645 and 663 nm in the following equation determined by Arnon (1949):

$$(20.2 * D_{645} + 8.02 * D_{663}) * 0.1 = \text{mg chlorophyll g}^{-1} \text{ tissue}$$

Clippings harvested in December, January, and February were oven-dried at 80^{o}C for 72 hr to determine clipping dry weight. Dry samples were analyzed for leaf tissue nutrient concentrations in December and February of each season by the Clemson University Agricultural Service Laboratory. Tissue N concentrations were determined using a LECO FP528 Nitrogen Combustion analyzer (Warrendale, PA). Other plant nutrients were determined using wet ashing procedures with a Digestion Block Magnum Series Block Digester (Ivesdale, IL) and an ICP model TJA-61E autosampler (Madison, WI).

Microenvironment parameters such as surface and soil temperature (Appendix C-6 and C-7) and light quantity (Appendix C-8) were measured weekly from November through February each year. Surface and soil temperature and light intensity (PPFD) ($\mu mol\ m^{-2}\ s^{-1}$) were recorded 3 times daily on clear, cloudless days at approximately sunrise, solar noon, and one hour before sunset using an indoor/outdoor thermometer (model #1455 and model #9840, Taylor, Oakbrook, IL) and quantum radiometer (Model LI-250, LiCor, Lincoln, NE), respectively.

Data Analysis

All statistical computations were conducted using analysis of variance (ANOVA) within the Statistical Analysis System (SAS Institute, 2003). Means were separated by Fisher's Protected Least Significant Difference (LSD) test. An alpha of 0.05 was used for all data comparisons.

Results and Discussion

Treatment interactions occurred N, Fe, and shade for turfgrass quality (TQ) and were examined as treatment combinations for each year. No meaningful interactions between N, Fe, and shading effects were observed ($P > 0.05$) for the parameters measured; therefore, main effects of each treatment for 2006 and 2007 were examined separately.

Turf Quality

Turf quality is the practical means by which to turfgrass managers are able to measure turfgrass performance. Visual turfgrass quality did not reach the minimally acceptable threshold in either year of the study. In year 1, rough bluegrass performed exceptionally well under reduced light conditions compared to full sunlight, with the highest visual ratings produced on plots under shade receiving 147 kg N ha^{-1} annually from November to January (Table 5-1). In February of year 1, a rate of 98 kg N ha^{-1} annually under shade and Fe applications produced 47% higher TQ compared to control (Table 5-1). Previous literature has documented that high rates of N under shade lead to significantly reduced TQ. This was not the case in year 1, as rough bluegrass performed much better under shaded conditions. It is unclear why rough bluegrass performed better under shade in year 1, however a viable explanation may be due to the reduction of soil and surface temperatures produced by shading during the mild winter of year 1 (Appendix C-6 and C-7). Heat tolerance of rough bluegrass is particularly low (Hurley, 2003), therefore shade treatments may prove beneficial to reducing high heat exposure of full-sunlight on sunny winter days. A noteworthy observation from year 1 was that the addition of shade increased TQ of all N and Fe treatment combinations for every sampling date aside from plots receiving 98 kg N ha^{-1} and no Fe in January 2007. Goss et al. (2002) noted a 60% shade reduction caused no loss of turfgrass cover or coloration.

Time played a significant role in this study as differential responses of shading effects were observed in the second year of the study. In year 2, the highest TQ ratings were consistently recorded on plots receiving the highest rate of N and Fe under no light restrictions (Table 5-2). In February, while the 147 kg N ha^{-1} with Fe rate produced the highest visual quality, it was observed that restricting sunlight by 55% resulted in a 50% reduction in turf quality (Table 5-2). Similar research has shown that reduced sunlight irradiance reaching turfgrass often results in reduced turfgrass quality and density (Bunnell et al., 2005a; Bunnell et al., 2005b; Tegg and Lane, 2004; Steinke and Stier, 2003; Qian, 1998; Trenholm et al., 1998; Beard, 1973).

It is unclear why conflicting data was found between years, but may be explained by thatch accumulation and thickness of the plots over time, particularly on plots receiving the highest N rate and/or shade. Long (2006) and Baldwin (2008) performed two year studies investigating N rates and their effect on thatch accumulation of 'Champion' bermudagrass at this site. Both researchers reported minimal, however significant yearly increases of thatch production with increasing N rates. Baldwin (2008) noted 40% a greater thatch mass on plots under 55% light reductions, as well as increases in thatch thickness. Excessive thatch levels may have negatively influenced overseeding establishment each October of this study, particularly for plots receiving higher rates of N and shade treatments. This effect may have become more prominent over time, possibly delaying or prohibiting rough bluegrass germination by year 2. As observed in the first year of the study, minimal differences were detected in TQ following applications of Fe in year 2 (Table 5-2).

Table 5-1. Visual turfgrass quality of rough bluegrass in response to three nitrogen rates, supplemental iron, and two light environments for year 1.

N	Fe	Shade	Nov 2006†	Dec 2006	Jan 2007	Feb 2007
kg ha^{-1} yr^{-1}	**kg ha^{-1} yr^{-1}**	%	----------------------------Turfgrass Quality(1-9)‡---------------------------			
49	**0**	**0**	3.5	3.9	3.7	3.4
	0	**55**	4.6	4.9	4.8	4.9
	10.8	**0**	3.7	3.8	3.8	3.4
	10.8	**55**	4.8	5.4	4.9	5.2
98	**0**	**0**	3.9	4.3	6.0	4.2
	0	**55**	5.4	5.7	4.8	5.7
	10.8	**0**	3.5	4.4	4.8	4.6
	10.8	**55**	5.5	6.0	6.1	6.4
147	**0**	**0**	3.6	4.3	4.7	4.0
	0	**55**	5.9	6.1	6.1	5.8
	10.8	**0**	3.8	4.3	4.8	3.8
	10.8	**55**	5.9	6.2	6.3	5.5
LSD			0.56	0.32	0.61	0.74

† Values followed by the same letter in the same column are not significantly different at $p = 0.05$ using Fisher's LSD.

‡ Turfgrass quality based on a visual scale of 1 to 9 with 1 = poorest, 9 = best. Visual rating of >7 indicates acceptable turf quality.

Table 5-2. Visual turfgrass quality of rough bluegrass in response to three nitrogen rates, supplemental iron, and two light environments for year 2.

N	Fe	Shade	Nov 2007†	Dec 2007	Jan 2008	Feb 2008
kg ha^{-1} yr^{-1}	**kg ha^{-1} yr^{-1}**		----------------------------Turfgrass Quality(1-9)‡---------------------------			
49	**0**	**0**	4.8	4.5	4.3	4.9
	0	**55**	5.0	5.3	4.7	4.3
	10.8	**0**	4.8	4.8	4.1	4.7
	10.8	**55**	4.9	5.2	4.7	4.0
98	**0**	**0**	5.3	5.2	5.3	5.8
	0	**55**	5.3	5.4	4.5	3.6
	10.8	**0**	5.4	5.3	5.3	5.7
	10.8	**55**	5.3	5.3	4.7	4.5
147	**0**	**0**	5.5	5.3	5.3	5.6
	0	**55**	5.6	4.4	3.5	3.1
	10.8	**0**	5.7	5.7	6.0	6.0
	10.8	**55**	5.6	4.4	3.7	3.0
LSD			0.47	0.65	0.64	0.74

† Values followed by the same letter in the same column are not significantly different at p = 0.05 using Fisher's LSD.

‡ Turfgrass quality based on a visual scale of 1 to 9 with 1 = poorest, 9 = best. Visual rating of >7 indicates acceptable turf quality.

Chlorophyll

Differences in total chlorophyll content were observed among N and shade treatments. In 2006, data indicates an increase in shoot chlorophyll content under medium and high N rates in January and February (Table 5-3). By February 2007, however, 98 and 147 kg N ha^{-1} annual rates significantly increased shoot chlorophyll content by 13 and 29%, respectively (Table 5-3). Previous research confirms the findings that C_3 turfgrasses increase light-harvesting pigments, especially chlorophyll, under increasing N fertility (Steinke and Stier, 2003; Van Huylenbroeck and Van Bockstaele, 2001). Bell et al. (2004) concluded that increasing N fertilization of bermudagrass to 293 kg N ha^{-1} and of creeping bentgrass up to 67 kg N ha^{-1} resulted in linear increases of chlorophyll content for both species.

Surprisingly, foliar application of supplemental iron yielded no response in total chlorophyll content of either year (Table 5-3). Such a lack of response has been reported on supina bluegrass (*Poa supina* Schrad.) and Kentucky bluegrass (*Poa pratensis* L.) chlorophyll content under reduced light conditions (Stier and Rogers, 2001). It is possible that foliar applications of Fe were not foliarly absorbed or Fe was taken up and removed from plant tissue following subsequent mowing.

Shading increased chlorophyll content in February of year 1 from 2.36 to 2.57 mg g^{-1} as shading increased from full sunlight to 55% light reduction (Table 5-3). Alternatively, shoot chlorophyll was decreased in December and February of year 2 by 16 and 14% under reduced light conditions, respectively. Bunnell et al. (2005a) confirmed these findings, noting decreased chlorophyll of TifEagle bermudagrass with increasing sunlight restrictions. A typical physiological response of turfgrass under low-light conditions is elevated chlorophyll content (Beard, 1973), however a viable explanation for the conflicting results between years may have been due to weather patterns observed between the summer months of 2006 and 2007 (Appendix D). During the summer of 2007, a severe drought reduced turf density of Champion bermudagrass and subsequently resulted in a dense *Poa trivialis* overseeded stand. Competition between plants may have magnified the shading effects applied in the study, resulting in reduced turf density.

Table 5-3. Total shoot chlorophyll concentration (mg g^{-1}) of rough bluegrass in response to three nitrogen rates, supplemental iron, and two light environments.

Nitrogen kg ha^{-1} yr^{-1}	**Jan 2007**[†]	**Feb 2007**	**Jan 2008**	**Feb 2008**
	------------------Total Chlorophyll Concentration (mg g^{-1})[‡]----------------			
49	2.43	2.31	2.03	1.80
98	2.80	2.56	2.06	2.05
147	3.07	2.53	2.06	2.52
LSD	0.12	0.19	NS	0.17
No Fe	2.78	2.47	2.02	2.07
Fe	2.74	2.46	2.09	2.18
LSD	NS	NS	NS	NS
Full Sun	2.77	2.36	2.23	2.28
Shade	2.75	2.57	1.87	1.96
LSD	NS	0.16	0.12	0.14

† Values followed by the same letter in the same column are not significantly different at $p = 0.05$ using Fisher's LSD.

‡ Total chlorophyll concentration based on mg chlorophyll per fresh gram clippings.

Clipping Yield

Shoot growth was affected by N rate at every sampling date. High rate of N produced significantly higher clipping yields than the low rate at every harvest date by as much as 57% in January 2007 (Table 5-4). Clipping harvests in year 2 revealed similar results, however the extent to which the high rate of N affected shoot growth was less pronounced (Table 5-4). Bowman et al. (2005) confirmed these findings, noting flushes of growth on six warm-season grasses following increased N rates. Supplemental applications of chelated iron produced inconsistent and minimal impact on clipping yield, increasing yield on only one occasion.

Shading conditions increased clipping yield by 19% in December of year 1 (Table 5-4). Similar findings exist in previous literature documenting a positive response of clipping yield with increasing shade levels (Baldwin, 2008; Tegg and Lane, 2004; Qian et al., 1998; Trenholm, 1998; Beard, 1973). Conversely, by year 2 clipping harvest was decreased by 38 and 33% in December and February, respectively (Table 5-4). In the second year of the study, because of plant competition for sunlight and extenuating weather conditions, shoot density of shaded plots was severely reduced, leading to vast decreases in clipping yield.

Table 5-4. Clipping yield of rough bluegrass in response to three nitrogen rates, supplemental iron, and two light environments.

Nitrogen kg ha^{-1} yr^{-1}	**Dec 2006**[†]	**Jan 2007**[‡]	**Feb 2007**	**Dec 2007**	**Jan 2008**	**Feb 2008**
	---------------------Clipping Dry Weight (g m^{-1})[§]--------------------					
49	1.50	5.68	5.38	1.66	4.50	3.99
98	1.90	10.86	8.89	2.12	6.22	4.60
147	2.13	13.31	9.01	2.07	6.21	5.44
LSD	0.30	1.42	0.84	0.25	0.72	0.49
No Fe	1.82	10.13	7.69	1.95	5.32	4.38
Fe	1.86	9.77	7.83	1.95	5.97	4.97
LSD	NS	NS	NS	NS	0.59	0.40
Full Sun	1.65	9.86	7.68	2.41	5.67	5.60
Shade	2.04	10.04	7.83	1.49	5.62	3.75
LSD	0.24	NS	NS	0.21	NS	0.4

† Values followed by the same letter in the same column are not significantly different at p = 0.05 using Fisher's LSD.

‡ Number of days between mowings differed for each clipping harvest. Dependent upon growth rate at time of harvest.

§ Clipping dry weight based on weight of dry leaf tissue harvested per square meter.

Leaf Nutrient Concentrations

Concerning leaf tissue N concentration in year 1, as rate of N increased, leaf concentration of N increased as well (Table 5-5). As observed in Table 5-4, throughout the first year of the study, 147 kg N ha^{-1} annually produced the highest leaf N concentrations of all N rates. By February 2008 however, application of 147 kg N ha^{-1} annually produced decreased leaf N concentrations by16% compared to 98 kg N ha^{-1} annual rate, most likely due to decreased turfgrass density of plots receiving 147 kg N ha^{-1} under shade. Beard (1973) reported that tissue N concentration increases at low light intensities. This explains why shade treatments increased leaf N concentration by 13% in February 2007 (Table 5-5). Exogenous applications of foliar Fe exhibited no impact on the recovery of N in leaf tissue (Table 5-5).

The addition of Fe showed minimal impacts on leaf tissue Fe concentrations. Only once did the application of chelated Fe increase tissue Fe by 7% in January 2007 (Table 5-6). Nitrogen rates higher than 49 kg N ha^{-1} resulted in significantly lower tissue Fe in year 1, however by year 2, the 147 kg N ha^{-1} rate provided 13% higher tissue Fe concentrations (Table 5-6). As expected, shading treatments increased leaf tissue Fe concentration by 20 and 22% by February of each year, respectively, however, no obvious trend can be inferred for Fe fertilization effects (Table 5-6). Adequate iron levels within leaf tissue range from 100 to 500 ppm (Carrow et al., 2001). As observed in Table 5-6, all Fe treatments resulted in adequate iron tissue concentrations.

Table 5-5. Leaf tissue nitrogen concentration of rough bluegrass under three nitrogen rates, supplemental iron, and two light environments.

Nitrogen kg ha^{-1} yr^{-1}	**Dec 2006**†	**Feb 2007**	**Dec 2007**	**Feb 2008**
	--------------------Leaf Nitrogen Concentration (%)‡--------------------			
49	3.51	2.94	3.86	3.88
98	3.88	3.47	4.50	4.17
147	4.05	3.71	4.75	3.52
LSD	0.12	0.13	0.13	0.13
No Fe	3.84	3.39	4.35	3.85
Fe	3.78	3.36	4.38	3.86
LSD	NS	NS	NS	NS
Full Sun	3.80	3.15	4.39	3.82
Shade	3.82	3.59	4.35	3.89
LSD	NS	0.10	NS	NS

† Values followed by the same letter in the same column are not significantly different at p = 0.05 using Fisher's LSD. NS=not significant at the 0.05 level.

‡ Nitrogen concentration based on percent nitrogen found in dried leaf tissue.

Table 5-6. Leaf tissue iron concentration (ppm) of rough bluegrass under three nitrogen rates, supplemental iron, and two light environments.

Nitrogen kg ha^{-1} yr^{-1}	**Dec 2006**†	**Feb 2007**	**Dec 2007**	**Feb 2008**
	----------------------Leaf Iron Concentration (ppm)‡----------------------			
49	242.71	202.29	184.54	138.42
98	215.42	183.71	179.58	144.13
147	216.92	187.83	180.96	158.38
LSD	16.06	15.78	NS	19.45
No Fe	216.53	191.78	183.08	139.78
Fe	233.50	190.78	180.31	154.17
LSD	13.12	NS	NS	NS
Full Sun	233.69	170.36	181.64	128.67
Shade	216.33	212.19	181.75	165.28
LSD	13.12	12.89	NS	15.88

† Values followed by the same letter in the same column are not significantly different at p = 0.05 using Fisher's LSD. NS=not significant at the 0.05 level.

‡ Iron concentration based on ppm iron found in dried leaf tissue.

Conclusion

The ability of a turfgrass species to perform well under shaded conditions often relies on its ability to maintain acceptable turfgrass quality and sustain low shoot growth under reduced light conditions. Rough bluegrass was shown to perform excellently under shading conditions in year 1; however as bermudagrass density suffered from overseeding practices, and unfavorable weather conditions, the ability of rough bluegrass to survive under shade was compromised. Also, greater thatch mass accumulation over time may have negatively affected rough bluegrass establishment by year 2. As noted by previous studies, by the second year of the study excessive nitrogen rates significantly reduced turfgrass quality under shade.

When comparing suitable annual N rates for overseeded turf, increasing N input by 49 kg K ha^{-1} resulted in linear increases in chlorophyll concentration. However, data from this experiment suggests over-fertilization of nitrogen is extremely detrimental to growth and coverage on winter overseeding turfgrasses. Foliar applications of water-soluble urea provided the highest quality rating of 6 in February 2008, however a 55% reduction of sunlight resulted in a 50% decrease in visual turfgrass quality.

Results from this study suggest a nitrogen rate of 98 kg N ha^{-1} annually for overseeded bermudagrass putting greens exposed to reduced light environments. A medium rate of annual N will provide adequate chlorophyll and tissue N concentrations, while maintaining moderate shoot growth. The addition of Fe provided minimal impact on turfgrass quality, clipping yield, chlorophyll or tissue nutrient concentrations. Finally, further research should investigate various N sources and their impact on vegetative growth under shade.

CHAPTER 6

CONCLUSIONS

High temperature and drought stress are quite possibly the two most growth limiting factors to cool-season turfgrass cultured in the transition zone. Nutritional supplements, particularly foliar K, have been suggested to promote optimal plant health during periods of biotic and abiotic stresses. Although the effects of K fertilization on turfgrass responses to environmental stresses have been well documented, there have been conflicting reports as to the proper K fertilization program. Furthermore, research investigating the interaction of K, Ca, and Mg recovery for creeping bentgrass greens under summer stress has been inconsistent.

Studies were conducted in 2006 and 2007 to evaluate liquid and granular K fertilization, in conjunction with foliar applications of Ca and Mg on turfgrass quality, clipping yield, root mass, and leaf and root nutrient concentrations of ‘Crenshaw’ creeping bentgrass. Both K carriers failed to provide acceptable turf quality in year 2 of the study. Furthermore, it was observed that foliar applications of K resulted in significant foliar burning from the high concentration of fertilizer salts. Creeping bentgrass visual quality significantly benefited from monthly applications of Ca alone.

Leaf tissue K concentrations were significantly greater under applications of liquid K, especially following advanced stages of bentgrass summer decline where liquid K treated turf exhibited 30% higher tissue K compared to untreated. Conversely, granular K provided the greatest root K concentrations in 2006, however as creeping bentgrass rooting subsided by 2007, liquid forms significantly improved root K concentrations. Calcium and magnesium fertilization showed little impact on turf endogenous K concentrations, however it was documented that K, in either form, consistently reduced both leaf and root tissue Ca and Mg levels.

In another two-year field experiment, two K carriers, liquid and granular, at three annual rates with monthly applications of WA were applied to 'L-93' creeping bentgrass to investigate summer performance and sustain acceptable turfgrass quality through the summer months while reducing soil hydrophobicity. As observed in the first study, foliar applications of K at 195 kg K ha^{-1} yr^{-1} (16.3 kg K ha^{-1} per application) resulted in significantly reduced visual turf quality due to foliar burning of creeping bentgrass. A notable observation was the contrasting impacts following WA applications of both years. In 2006, under average summer precipitation, WA severely reduced visual quality, while in 2007 under extreme drought conditions, WA apparently sustained adequate soil moisture compared to untreated, thus increasing bentgrass summer performance. Confirming results of the first study, it was noted that biweekly foliar K applications produced significantly greater leaf and root tissue K concentrations. While monthly applications of wetting agents showed no significant impact on volumetric soil moisture, it was found that WA significantly reduced soil hydrophobicity, possibly preventing the formation of Localized dry spots on creeping bentgrass.

A winter study was conducted to determine the effect of winter shading on turf quality, clipping yield, chlorophyll concentration and nutrient recovery of an overseeded bermudagrass putting green exposed to increasing levels of N fertilization and foliar Fe application. Turf quality never reached the acceptable turf quality rating of 7 on the 1-9 scale. In year 1, the greatest turfgrass quality was produced under shade following N fertilization at 147 kg N ha^{-1} annually with supplemental Fe. By year 2 however, visual quality was significantly reduced with the addition of shade treatments. It is unclear as to the reason for these conflicting results, however a possible reasoning includes increasing thatch accumulation, poor establishment and/or fluctuating weather conditions between years. Nevertheless, results from this experiment indicate increasingly higher N application rates resulted linear increases of both leaf chlorophyll concentrations and endogenous N concentrations. It was further observed that applying N in excess of 98 kg N ha^{-1} under reduced light environments resulted in significantly reduced visual turf quality and density over time.

Additional research is needed in order to determine optimal timing and application rates of K to pre-condition creeping bentgrass to high heat injury and maintain adequate summer performance of creeping bentgrass in the transition zone. Research is also warranted on optimal timings and rates of WA applications in order improve creeping bentgrass growth and performance to mediate the effects of summer bentgrass decline. Lastly, future experiments are needed to determine N source effects on overseeded cool-season turfgrass species maintained under reduced light environments.

APPENDICES

Appendix A

Procedures for Chlorophyll Analyses

Appendix A

Chlorophyll Extraction with DMSO

1. Weigh 0.1 g fresh tissue into Erlenmeyer flasks.
2. Add 10 mL of Dimethyl Sulfoxide to each flask. Cover with rubber stopper.
3. Incubate in 65^o C water shake bath for 1.5 hour.
4. Transfer extract into spectrophotometer using pipette.
5. Measure and record absorbance values at 645 nm and 663 nm wavelengths.
6. Chlorophyll content is determined by following formula (Arnon, 1949):

$$(20.2 \times D_{645} + 8.02 \times D_{663}) \times 0.1 = \text{mg chlorophyll g}^{-1} \text{ tissue}$$

$D_{663 \text{ and } 645}$ = absorbance values at given light wavelengths.

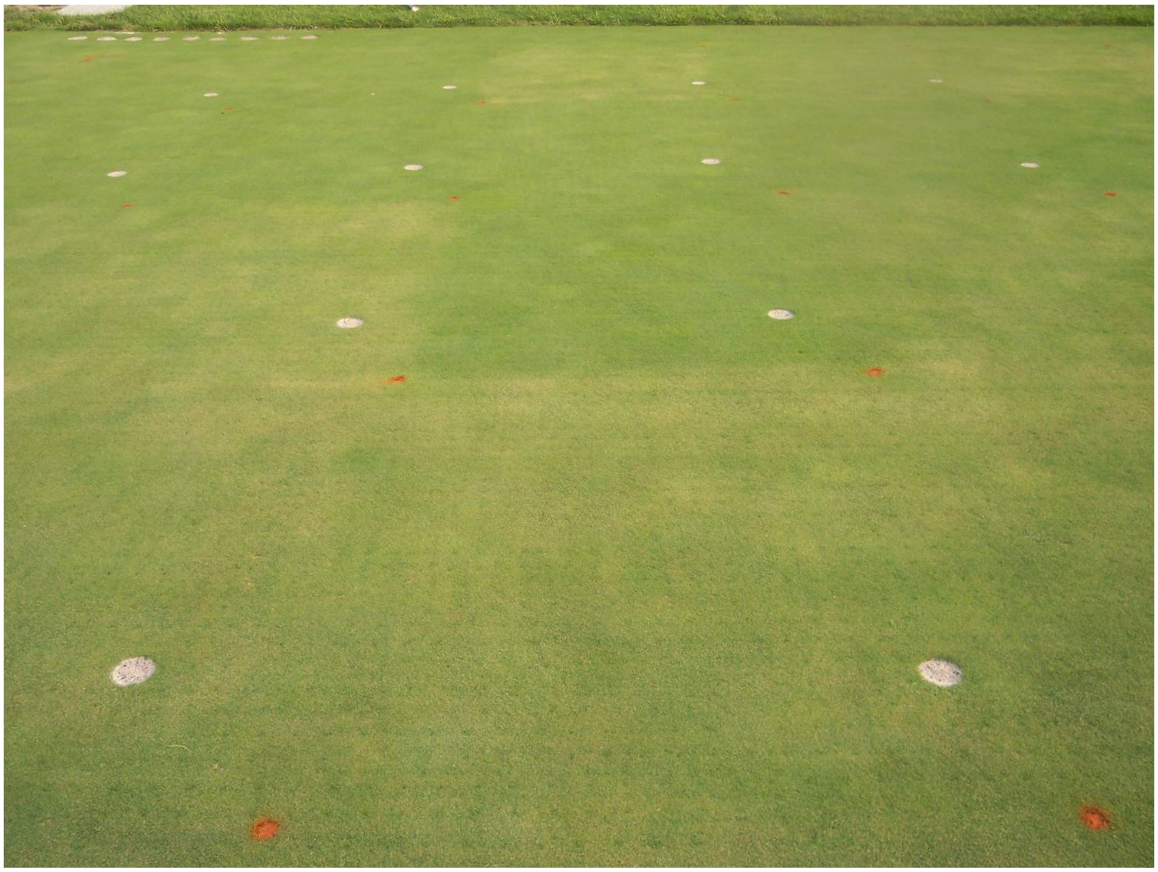
Appendix B

Illustrations

B-1. Randomized complete block experimental design for 'Crenshaw' creeping bentgrass field study. Where 0 K = No K, Gran K = granular K, and Liq K= liquid K indicate potassium carrier receiving potassium fertilization at either 0 or 195 kg K $ha^{-1}yr^{-1}$, No Ca = no calcium, Ca = calcium at 49 kg ha^{-1} yr^{-1}, No Mg = no magnesium, Mg = magnesium at 49 kg ha^{-1} yr^{-1}.

Block 1		Block 2		Block 3		Block 4	
Gran K No Ca No Mg	No K Ca No Mg	Liq K Ca Mg	Liq K No Ca No Mg	0 K Ca Mg	Liq K No Ca Mg	Liq K Ca Mg	Gran K No Ca No Mg
Liq K No Ca No Mg	Liq K Ca No Mg	Gran K No Ca No Mg	Gran K Ca No Mg	No K Ca No Mg	Liq K No Ca No Mg	Liq K No Ca Mg	No K No Ca No Mg
0 K Ca Mg	Liq K No Ca Mg	No K Ca No Mg	0 K Ca Mg	Gran K No Ca Mg	Gran K Ca No Mg	Liq K No Ca No Mg	Gran K Ca Mg
No K No Ca No Mg	0 K No Ca Mg	Liq K No Ca Mg	Gran K No Ca Mg	Gran K No Ca No Mg	Liq K Ca No Mg	Gran K No Ca Mg	Gran K Ca No Mg
Gran K Ca No Mg	Liq K Ca Mg	Gran K No Ca Mg	Gran K Ca Mg	No K No Ca No Mg	Gran K Ca Mg	Gran K No Ca Mg	0 K Ca Mg
Gran K Ca Mg	Gran K No Ca Mg	Liq K Ca No Mg	No K No Ca No Mg	Liq K Ca Mg	Gran K No Ca Mg	Liq K Ca No Mg	No K Ca No Mg

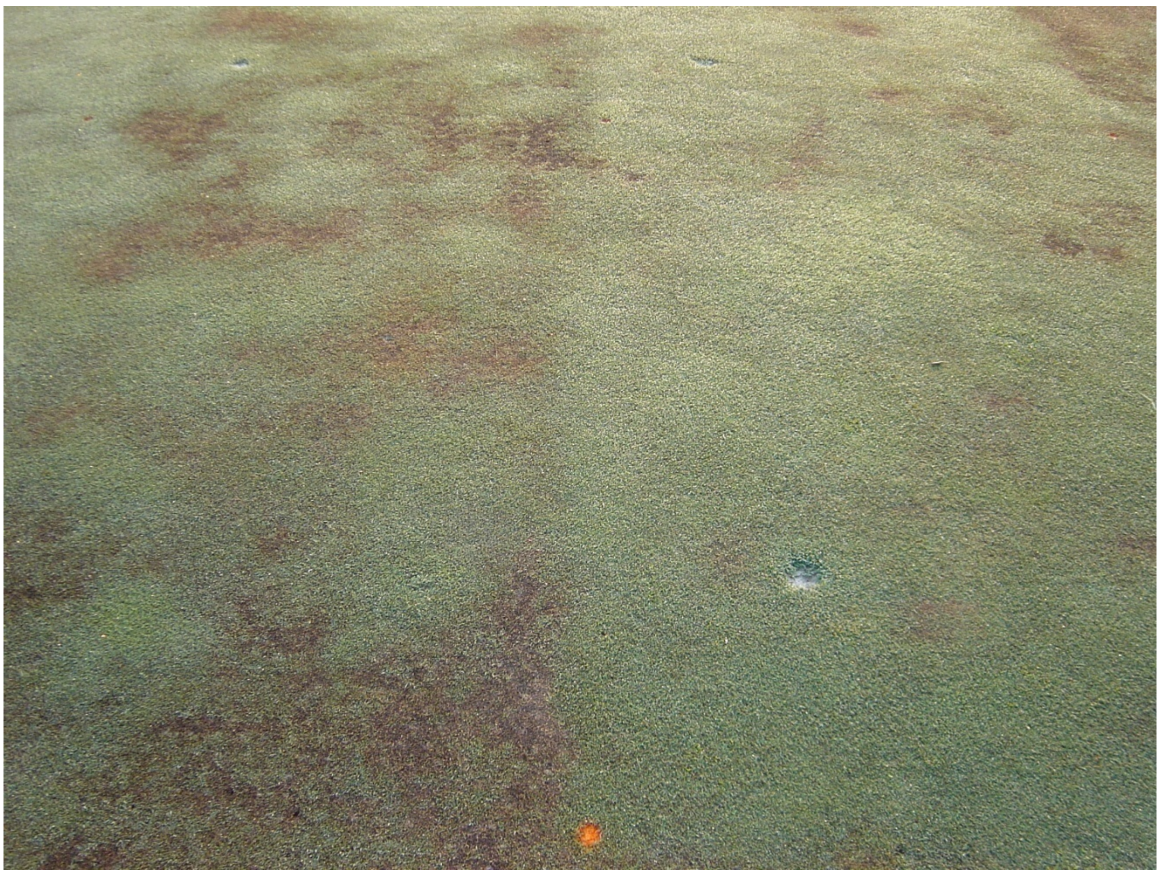
B-2. Digital photograph illustrating foliar phototoxicity of ‘Crenshaw’ creeping bentgrass receiving 0 (foreground) and 195 (background) kg liquid K ha^{-1} annually.



B-3. Randomized split block design for ‘L-93’ creeping bentgrass summer stress study where 0, 98, and 195 indicate kg K ha^{-1} yr^{-1}, No WA = no wetting agent, WA = wetting agent at 19.1 L WA ha^{-1} monthly.

0 No WA	**98 Liq No WA**	**98 Grn No WA**	**195 Liq No WA**	**195 Grn No WA**	Block 1
WA	**WA**	**WA**	**WA**	**WA**	
195 Liq No WA	**195 Grn No WA**	**0 No WA**	**98 Liq No WA**	**98 Grn No WA**	Block 2
WA	**WA**	**WA**	**WA**	**WA**	
98 Liq No WA	**195 Grn No WA**	**195 Liq No WA**	**0 No WA**	**98 Grn No WA**	Block 3
WA	**WA**	**WA**	**WA**	**WA**	
98 Grn No WA	**98 Liq No WA**	**195 Grn No WA**	**195 Liq No WA**	**0 No WA**	Block 4
WA	**WA**	**WA**	**WA**	**WA**	

B-4. Digital photograph illustrating ‘L-93’ creeping bentgrass treated with Revolution wetting agent at 0 (left) and 19.1 right) L WA ha^{-1} monthly from May to October in 2006 and 2007.



B-5. Digital photograph illustrating hydrophobic soil characteristic of USGA putting green sand media not treated with Revolution wetting agent in ‘L-93’ creeping bentgrass field study.

B-6. Randomized split block experimental design and treatment assignment for rough bluegrass shade study where 49, 98, and 147 indicate kg N ha^{-1} per season, Fe = 10.8 kg a.i. ha^{-1} per season. Blocks were randomly assigned N and Fe treatments, with shade representing the split plot factor (dashed line).

Block 1

49	**98**	**49**	**98 Fe**	**49 Fe**	**49 Fe**	
						Shade
147 Fe	**147**	**147 Fe**	**98**	**98 Fe**	**147**	Shade

Block 2

98 Fe	**98 Fe**	**49**	**49**	**98**	**49 Fe**	
						Shade
147	**98**	**49 Fe**	**147 Fe**	**147 Fe**	**147**	Shade

Block 3

98	**98 Fe**	**147**	**147**	**147 Fe**	**49 Fe**	
						Shade
49 Fe	**49**	**147 Fe**	**98 Fe**	**98 Fe**	**49**	Shade

B-7. *Poa trivialis* field study where nitrogen was applied at 49, 98, and 147 kg ha^{-1} yr^{-1}, with or without liquid iron, and with or without a 55% sunlight reduction (Photograph is taken from opposite direction of plot map).

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B-8. Digital photograph demonstrating effects of full sunlight (left and right) and 55% light reduction (center) on Poa trivialis overseed from November to February.

Appendix C

Tables and Figures Not Shown in Text

C-1. Particle size analysis of USGA greens mix used in all studies at Clemson University.

	Soil Separation %			Sieve Size/Sand Fraction Sand Particle Diameter % Retained					
Sample	Sand	Silt	Clay	No. 10 Gravel 2mm	No. 18 V. coarse 1mm	No. 35 Coarse 0.5mm	No. 60 Medium 0.25mm	No. 100 Fine 0.15mm	No. 270 V. fine 0.05mm
Clemson Mix	98.0	1.0	1.0	0.1	3.2	27.9	51.7	12.0	3.1
USGA Value	≥92%	≤3%	≤3%	≤3% gravel ≤10% combined		≥60%		20%	≤5%

C-2. Soil physical properties of USGA greens mix used in all studies at Clemson University.

Sample	Particle Density (g cm^{-3})	Bulk Density (g cm^{-3})	Infiltration Rate (cm h^{-1})	Total Porosity %	Aeration Porosity %	Capillary Porosity %	Organic Matter %
Clemson Mix	2.64	1.41	17	46.8	23.4	23.3	1.4
USGA Value		1.3-1.6	15-60	33-58	15-30	15-25	0.7-3.0

Table C-3. 'Crenshaw' creeping bentgrass root dry weight in response to two K carriers, two Ca rates and two Mg rates.

K carrier†	**June 06**‡	**Aug 06**	**Nov 06**	**June 07**	**Aug 07**	**Oct 07**
	-------------------------Root Dry Weight (g m^{-2})§					--------------------------
Control	91.67	56.05	29.5	52.56	16.09	17.79
Granular	98.8	52.21	30.39	60.46	20.06	19.46
Liquid	81.45	44.71	30.44	48	16.37	19.63
LSD	NS	NS	NS	NS	NS	NS
Ca Rate						
No Ca	96.22	54.30	31.95	55.57	17.98	20.04
Ca	85.06	47.67	28.27	51.78	17.03	17.88
LSD	NS	NS	NS	NS	NS	NS
Mg Rate						
No Mg	93.05	50.90	29.11	55.18	19.67	17.76
Mg	88.23	51.08	31.12	52.16	15.35	20.16
LSD	NS	NS	NS	NS	NS	NS

† Abbreviations: Control = no K fertilization, Granular and Liquid indicate granular or liquid K fertilization at 195 kg K ha^{-1} annually. No Ca indicates no calcium fertilization, Ca = 49 kg calcium ha^{-1} annually. No Mg indicates no magnesium fertilization, Mg = 49 kg magnesium ha^{-1} annually.

‡ Values followed by the same letter in the same column are not significantly different at p = 0.05 using Fisher's Protected LSD. NS=not significant at the 0.05 level.

§ Total dry root weight based grams of dried tissue per square meter.

Table C-4. Volumetric water content of 'Crenshaw' creeping bentgrass in response to two K carriers, two Ca rates and two Mg rates.

K Carrier	**June 06**[†]	**July 06**	**Aug 06**	**Sept 06**	**Nov 06**	**June 07**	**July 07**	**Aug 07**	**Sept 07**	**Oct 07**
	--------------------Volumetric Water Content (m^3/m^3)--------------------									
Control	0.21	0.19	0.28	0.26	0.32	0.27	0.24	0.18	0.26	0.27
Gran	0.21	0.19	0.28	0.26	0.33	0.26	0.23	0.16	0.26	0.25
Liq	0.22	0.20	0.28	0.26	0.33	0.27	0.22	0.17	0.23	0.25
LSD	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Ca Rate										
No Ca	0.20	0.19	0.28	0.25	0.32	0.27	0.23	0.16	0.25	0.25
Ca	0.22	0.19	0.29	0.27	0.33	0.26	0.23	0.18	0.25	0.26
LSD	NS	NS	NS	0.02	NS	NS	NS	NS	NS	NS
Mg Rate										
No Mg	0.21	0.19	0.28	0.26	0.33	0.27	0.23	0.17	0.25	0.25
Mg	0.21	0.19	0.28	0.26	0.33	0.26	0.22	0.17	0.25	0.26
LSD	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

† Values followed by the same letter in the same column are not significantly different at p = 0.05 using Fisher's Protected LSD. NS=not significant at the 0.05 level.

Table C-5. Influence of Revolution wetting agent on clipping yield of 'L-93' creeping bentgrass from June 2006 to October 2007.

Treatment	June 06†	July 06	Aug 06	Sept 06	Nov 06	June 07	July 07	Aug 07	Sept 07	Oct 07
	----------------------------------Total Dry Clipping Yield (g m^{-2}) ‡----------------------------------									
No WA	1.75	0.71	2.01	4.00	2.76	2.88	3.68	2.94	2.02	1.71
WA	1.89	0.68	1.56	3.80	2.59	3.53	3.37	3.50	1.96	1.77
LSD (0.05)	NS	NS	NS	NS	NS	0.46	NS	NS	NS	NS

† Values followed by the same letter in the same column are not significantly different at p = 0.05 using Fisher's LSD. NS=not significant at the 0.05 level.

‡ Total dry clipping yield based grams of dried tissue per square meter. Number of days between mowings differed for each clipping harvest. Dependent upon growth rate at time of harvest.

Table C-6. Turf canopy temperature recorded weekly on a rough bluegrass overseeded putting green exposed to full sunlight and 55% light reduction from November 2006 to February 2008.

Date	Morning		Solar Noon		Afternoon	
	Shade	Full Sun	Shade	Full Sun	Shade	Full Sun
	----------------------------Canopy Temperature (^oC)------------------------					
11/20/2006	13.3	7.8	19.1	20.6	15.6	17.1
11/28/2006	10.7	9.9	18.7	19.8	20.1	20.0
12/5/2006	7.8	9.6	17.1	19.2	12.6	13.8
12/14/2006	2.3	1.9	19.1	22.5	13.0	14.4
12/23/2006	17.0	20.7	20.9	24.6	17.6	19.7
12/29/2006	11.1	12.1	18.3	16.8	12.0	13.7
1/3/2007	9.1	10.0	12.4	16.1	7.6	9.3
1/9/2007	1.7	6.9	14.0	19.4	6.6	4.8
1/17/2007	2.2	3.1	10.1	13.2	3.6	3.2
1/26/2007	2.8	5.5	13.9	21.8	9.3	11.8
1/31/2007	-1.9	3.2	10.9	16.3	6.2	13.0
2/7/2007	6.8	10.2	21.5	26.2	15.8	21.3
2/14/2007	0.6	2.5	13.1	20.4	12.4	16.8
11/19/2007	3.1	3.8	21.1	23.9	16.3	18.9
11/26/2007	1.3	0.4	21.3	26.0	14.7	18.2
12/3/2007	9.2	9.4	20.3	27.5	13.0	17.2
12/11/2007	11.4	12.6	27.4	31.0	18.6	19.2
12/20/2007	5.1	5.3	11.6	13.4	7.1	7.2
12/23/2007	3.8	4.4	13.6	14.6	6.6	7.3
1/1/2008	1.8	4.0	13.3	13.6	7.2	7.9
1/7/2008	4.0	5.5	22.9	26.8	12.3	13.1
1/15/2008	-1.8	-2.3	13.4	17.1	6.7	14.4
1/24/2008	2.4	4.5	14.4	19.2	7.5	12.9
1/29/2008	2.8	4.3	16.9	24.0	12.7	17.5
2/7/2008	0.6	-0.2	21.8	26.7	15.8	20.3
2/14/2008	0.1	-1.4	14.7	21.0	16.0	18.9

Table C-7. Turf soil temperature recorded weekly on a rough bluegrass overseeded putting green exposed to full sunlight and 55% light reduction from November 2006 to February 2008.

Date	Morning		Solar Noon		Afternoon	
	Shade	Full Sun	Shade	Full Sun	Shade	Full Sun
	---------------------------Canopy Temperature (^{o}C)------------------------					
11/20/2006	9.3	10.4	10.9	11.9	12.2	12.9
11/28/2006	11.5	11.8	14.4	15.1	16.3	16.3
12/5/2006	5.2	6.5	7.4	9.1	8.3	10.4
12/14/2006	6.1	7.6	8.8	11.1	10.7	12.8
12/23/2006	15.1	17.4	17.3	20.7	14.6	17.4
12/29/2006	6.6	6.7	7.6	9.8	6.7	7.9
1/3/2007	5.9	6.1	7.3	7.9	7.1	8.3
1/9/2007	5.4	5.7	6.8	7.4	8.3	9.6
1/17/2007	7.2	6.7	7.3	8.3	7.9	9.1
1/26/2007	2.6	3.3	2.9	5.2	7.1	8.6
1/31/2007	1.5	3.2	1.9	5.4	2.9	6.1
2/7/2007	2.8	1.4	4.7	6.2	6.7	8.2
2/14/2007	3.4	3.9	3.9	6.2	6.6	9.1
11/19/2007	6.9	8.2	9.7	10.6	11.1	12.2
11/26/2007	6.2	7.3	9.0	9.6	11.0	12.6
12/3/2007	8.9	10.4	10.7	11.7	11.3	12.6
12/11/2007	10.6	11.2	13.7	14.2	15.3	15.4
12/20/2007	5.5	6.3	7.6	7.9	7.7	8.1
12/23/2007	7.6	8.3	9.9	11.3	10.6	12.6
1/1/2008	5.4	5.7	7.1	7.8	7.6	8.6
1/7/2008	4.4	5.3	7.1	8.1	9.8	10.9
1/15/2008	2.9	4.2	3.6	5.0	6.0	7.8
1/24/2008	3.6	4.4	4.2	5.1	5.1	6.7
1/29/2008	1.6	2.7	3.1	4.6	7.7	8.9
2/7/2008	5.3	5.9	7.8	8.8	9.7	11.1
2/14/2008	3.3	3.9	4.2	5.4	7.9	8.9

Table C-8. Light intensity (PPFD) recorded weekly on a rough bluegrass overseeded putting green exposed to full sunlight and 55% light reduction from November 2006 to February 2008.

Date	Morning		Solar Noon		Afternoon	
	55% Shade	Full Sun	55% Shade	Full Sun	55% Shade	Full Sun
	Light Intensity (μmol m^{-2} s^{-1})					
11/20/2006	8.7	22.2	235.4	387.5	70.7	115.4
11/28/2006	69.5	109.8	345.9	748.2	64.4	116.9
12/5/2006	114.6	41.2	394.1	1009.1	117.3	198.4
12/14/2006	40.7	119.6	147.8	388.2	106.7	180.3
12/23/2006	70.5	126.7	154.6	379.2	69.5	112.6
12/29/2006	108.4	169.5	174.5	440.3	47.4	96.4
1/3/2007	76.9	104.5	228.7	564.3	37.5	83.3
1/9/2007	37.7	43.8	298.4	725.1	11.0	31.5
1/17/2007	57.6	180.2	290.1	708.5	17.5	40.5
1/26/2007	184.8	340.3	375.5	795.2	61.1	199.5
1/31/2007	93.9	104.5	310.8	766.7	67.1	144.4
2/7/2007	37.6	206.2	348.9	930.7	114.8	292.6
2/14/2007	83.1	321.2	351.7	881.5	172.7	462.6
11/19/2007	46.3	98.5	289.5	791.2	43.8	89.7
11/26/2007	24.0	149.8	340.8	796.3	86.1	267.0
12/3/2007	31.9	65.2	302.2	716.3	22.2	175.6
12/11/2007	43.8	84.0	269.5	767.7	21.9	58.4
12/20/2007	13.9	42.2	57.9	154.5	1.5	3.7
12/23/2007	31.3	72.2	339.6	728.8	37.9	148.3
1/1/2008	10.2	30.9	311.5	731.8	38.7	157.3
1/7/2008	29.7	58.4	332.5	733.5	`15.06	40.3
1/15/2008	20.7	50.1	374.1	756.6	65.3	180.7
1/24/2008	43.4	88.2	313.7	811.3	27.9	230.5
1/29/2008	91.0	267.3	287.4	782.0	66.9	291.2
2/7/2008	14.2	31.6	420.1	882.5	101.8	283.6
2/14/2008	38.2	224.1	322.8	853.9	93.1	273.6

Table C-9. Initial soil nutrient analysis for the ‘Crenshaw’ creeping bentgrass study site used in Chapter 3.

Soil pH			5.1		
Cation Exchange Capacity (CEC)			2.6 meq/100g		
Nutrient			ppm		
Phosphorus (P)			5.5		
Potassium (K)			12		
Calcium			145		
Magnesium (Mg)			24		
Zinc (Zn)			2.8		
Manganese (Mn)			8.5		
Copper (Cu)			1.1		
Boron (B)			0		
Sodium (Na)			7		
Base Saturation	Ca: 28%	Mg: 8%	K: 1%	Na: 1%	Total: 38%

Appendix D

Clemson, SC Weather Data

Appendix D. Clemson, SC 2006 through 2008 weather data.

Date	Temp (°C) Max	Min	Rain (cm)
5/1/06	24.4	11.7	0.0
5/2/06	22.8	6.7	0.0
5/3/06	25.6	16.7	0.0
5/4/06	29.4	10.6	0.0
5/5/06	28.3	16.1	0.0
5/6/06	27.2	13.9	0.9
5/7/06	27.8	16.7	0.0
5/8/06	17.8	11.1	0.5
5/9/06	18.9	11.7	0.0
5/10/06	20.0	11.7	0.0
5/11/06	23.3	15.0	0.0
5/12/06	23.9	8.9	0.1
5/13/06	21.1	7.2	0.0
5/14/06	23.9	13.9	0.0
5/15/06	24.4	8.9	0.0
5/16/06	22.2	8.9	0.0
5/17/06	22.8	8.3	0.0
5/18/06	24.4	11.7	0.0
5/19/06	26.1	8.9	0.0
5/20/06	26.1	13.9	0.2
5/21/06	27.8	17.2	3.3
5/22/06	27.2	18.3	0.1
5/23/06	27.8	14.4	0.0
5/24/06	28.3	12.2	0.0
5/25/06	30.0	13.3	0.0
5/26/06	32.2	15.0	1.3
5/27/06	30.0	19.4	4.4
5/28/06	31.7	18.9	0.0
5/29/06	31.1	17.8	0.0
5/30/06	32.2	17.8	0.0
5/31/06	33.3	18.3	0.0
6/1/06	32.2	18.3	0.0
6/2/06	31.7	20.0	0.1
6/3/06	30.6	19.4	4.5
6/4/06	28.3	13.3	0.0

Appendix D. Clemson, SC 2006 through 2008 weather data.

Date	Temp (°C) Max	Min	Rain (cm)
6/5/06	28.3	12.2	0.6
6/6/06	26.1	11.1	0.0
6/7/06	28.9	12.2	0.0
6/8/06	30.0	16.1	0.0
6/9/06	31.1	14.4	0.0
6/10/06	31.7	17.2	0.0
6/11/06	35.0	20.0	0.0
6/12/06	34.4	20.0	0.0
6/13/06	32.8	17.8	1.0
6/14/06	23.3	17.2	0.6
6/15/06	31.7	15.6	0.0
6/16/06	30.6	15.6	0.0
6/17/06	31.1	15.0	0.0
6/18/06	31.1	15.6	0.0
6/19/06	30.6	16.1	0.0
6/20/06	32.2	18.3	0.0
6/21/06	35.6	18.3	0.0
6/22/06	35.6	19.4	0.0
6/23/06	37.2	20.6	0.0
6/24/06	35.0	20.0	4.2
6/25/06	31.7	20.6	0.0
6/26/06	30.0	20.6	4.8
6/27/06	25.6	19.4	9.1
6/28/06	31.7	18.3	0.0
6/29/06	31.1	17.8	0.0
6/30/06	32.2	16.7	0.0
7/1/06	32.2	18.3	0.0
7/2/06	33.3	18.9	0.4
7/3/06	34.4	19.4	0.0
7/4/06	35.0	20.0	0.0
7/5/06	35.0	21.7	0.5
7/6/06	29.4	20.6	0.6
7/7/06	28.9	18.3	0.0
7/8/06	26.7	16.1	0.0
7/9/06	28.3	16.1	0.0

Appendix D. Clemson, SC 2006 through 2008 weather data.

Date	Temp (^oC)		Rain (cm)
	Max	Min	
7/10/06	30.0	20.0	0.0
7/11/06	32.8	19.4	0.0
7/12/06	33.3	20.6	0.0
7/13/06	34.4	22.2	0.0
7/14/06	34.4	20.6	0.1
7/15/06	33.9	22.2	0.0
7/16/06	35.6	21.7	0.0
7/17/06	33.9	18.9	0.0
7/18/06	34.4	19.4	0.0
7/19/06	35.0	20.0	0.0
7/20/06	36.7	21.7	0.0
7/21/06	35.0	21.1	0.0
7/22/06	35.0	21.1	0.2
7/23/06	32.8	21.1	0.8
7/24/06	30.6	20.0	0.0
7/25/06	30.6	21.1	3.0
7/26/06	32.2	20.0	0.0
7/27/06	34.4	21.7	0.0
7/28/06	35.0	21.1	0.0
7/29/06	36.1	22.8	0.0
7/30/06	31.1	20.6	0.1
7/31/06	33.9	21.1	0.0
8/1/06	36.1	22.2	0.0
8/2/06	37.8	23.3	0.0
8/3/06	37.8	23.9	0.3
8/4/06	36.1	22.2	0.9
8/5/06	37.2	22.2	0.0
8/6/06	32.8	23.3	0.0
8/7/06	33.3	22.2	0.0
8/8/06	36.7	22.8	0.0
8/9/06	36.7	21.1	0.0
8/10/06	36.1	22.2	0.0
8/11/06	36.1	21.7	0.0
8/12/06	31.7	19.4	1.2
8/13/06	23.9	18.3	0.0

Appendix D. Clemson, SC 2006 through 2008 weather data.

Date	Temp (°C)		Rain (cm)
	Max	Min	
8/14/06	29.4	18.9	0.0
8/15/06	32.2	20.6	0.0
8/16/06	33.9	21.1	1.8
8/17/06	31.7	22.2	0.0
8/18/06	30.6	18.3	0.0
8/19/06	31.7	18.3	0.0
8/20/06	33.3	21.1	0.0
8/21/06	33.9	20.0	0.0
8/22/06	33.3	21.1	0.0
8/23/06	32.8	20.0	2.4
8/24/06	30.6	21.7	0.0
8/25/06	31.1	18.9	0.0
8/26/06	31.7	17.2	0.0
8/27/06	32.2	17.8	0.0
8/28/06	32.8	17.8	0.0
8/29/06	33.9	23.3	0.0
8/30/06	35.0	22.2	0.0
8/31/06	35.0	21.7	0.1
9/1/06	30.0	20.0	0.0
9/2/06	28.9	19.4	2.8
9/3/06	28.3	21.1	0.0
9/4/06	29.4	21.1	0.0
9/5/06	30.6	21.1	0.0
9/6/06	27.2	18.3	3.1
9/7/06	29.4	18.3	0.0
9/8/06	25.6	17.2	0.0
9/9/06	28.9	16.7	0.0
9/10/06	28.3	16.7	0.0
9/11/06	30.6	17.2	0.0
9/12/06	27.8	16.7	0.0
9/13/06	24.4	16.1	1.9
9/14/06	18.3	15.6	2.4
9/15/06	26.7	14.4	0.0
9/16/06	27.2	13.9	0.0
9/17/06	28.9	15.6	0.0

Appendix D. Clemson, SC 2006 through 2008 weather data.

Date	Temp (°C)		Rain (cm)
	Max	Min	
9/18/06	28.9	15.6	0.0
9/19/06	29.4	20.0	1.1
9/20/06	28.3	11.1	0.0
9/21/06	25.6	9.4	0.0
9/22/06	22.8	15.0	0.0
9/23/06	26.1	19.4	0.5
9/24/06	30.6	18.9	0.8
9/25/06	27.2	15.6	0.2
9/26/06	26.1	13.3	0.0
9/27/06	24.4	13.9	0.0
9/28/06	26.1	12.2	0.0
9/29/06	26.7	7.2	0.0
9/30/06	21.7	7.2	0.0
10/1/06	23.9	12.2	0.0
10/2/06	28.9	11.1	0.0
10/3/06	27.8	12.8	0.0
10/4/06	29.4	14.4	0.0
10/5/06	30.0	14.4	0.0
10/6/06	29.4	17.2	0.0
10/7/06	28.3	7.2	0.0
10/8/06	21.1	12.2	0.0
10/9/06	20.0	12.2	0.0
10/10/06	26.7	11.1	0.0
10/11/06	27.8	13.9	0.0
10/12/06	26.7	14.4	0.0
10/13/06	22.2	10.0	0.0
10/14/06	19.4	0.6	0.0
10/15/06	21.7	0.0	0.0
10/16/06	21.1	7.2	0.0
10/17/06	18.3	8.3	2.3
10/18/06	17.2	12.8	4.0
10/19/06	26.1	16.7	0.0
10/20/06	23.3	17.2	0.5
10/21/06	23.3	5.0	0.0
10/22/06	19.4	8.3	0.0

Appendix D. Clemson, SC 2006 through 2008 weather data.

Date	Temp (°C)		Rain (cm)
	Max	Min	
10/23/06	20.6	4.4	0.3
10/24/06	15.0	0.0	0.0
10/25/06	13.9	-1.7	0.0
10/26/06	13.3	2.2	0.0
10/27/06	17.8	8.9	0.0
10/28/06	15.0	9.4	4.3
10/29/06	19.4	5.6	0.0
10/30/06	22.8	5.6	0.0
10/31/06	24.4	7.2	0.0
11/1/06	18.3	8.9	0.0
11/2/06	25.0	12.8	0.0
11/3/06	21.7	-1.7	0.0
11/4/06	12.2	-1.1	0.0
11/5/06	11.7	-1.1	0.0
11/6/06	13.3	2.2	0.0
11/7/06	13.9	7.2	0.6
11/8/06	12.8	11.1	2.1
11/9/06	20.0	6.1	0.0
11/10/06	25.0	6.1	0.0
11/11/06	26.1	8.9	0.0
11/12/06	21.1	5.0	0.3
11/13/06	17.8	-0.6	0.0
11/14/06	21.7	1.7	0.0
11/15/06	22.2	10.0	0.0
11/16/06	20.0	10.0	3.8
11/17/06	12.8	3.9	0.0
11/18/06	15.0	0.6	0.0
11/19/06	15.0	-1.1	0.0
11/20/06	13.9	3.9	0.0
11/21/06	8.3	-1.1	0.0
11/22/06	12.8	3.9	0.2
11/23/06	20.0	4.4	0.0
11/24/06	20.0	1.7	0.0
11/25/06	22.2	0.6	0.0
11/26/06	20.6	-0.6	0.0

Appendix D. Clemson, SC 2006 through 2008 weather data.

Date	Temp (^oC)		Rain (cm)
	Max	Min	
11/27/06	21.7	0.0	0.0
11/28/06	21.1	5.6	0.0
11/29/06	21.7	11.1	0.0
11/30/06	21.1	15.6	0.3
12/1/06	20.6	18.9	0.6
12/2/06	21.7	-0.6	0.1
12/3/06	17.2	5.0	0.0
12/4/06	15.0	3.3	0.0
12/5/06	12.8	-2.8	0.0
12/6/06	14.4	-1.7	0.0
12/7/06	15.0	5.6	0.0
12/8/06	13.9	-8.3	0.0
12/9/06	5.6	-8.9	0.0
12/10/06	10.6	-5.0	0.0
12/11/06	13.9	-1.1	0.0
12/12/06	19.4	0.0	0.0
12/13/06	18.3	9.4	0.0
12/14/06	20.0	0.6	0.0
12/15/06	18.9	0.6	0.0
12/16/06	21.1	2.2	0.0
12/17/06	22.8	0.6	0.0
12/18/06	20.6	1.1	0.0
12/19/06	23.9	3.9	0.0
12/20/06	23.3	9.4	0.0
12/21/06	11.1	8.3	0.0
12/22/06	12.8	8.9	2.7
12/23/06	17.2	14.4	2.1
12/24/06	21.1	0.6	0.0
12/25/06	16.7	6.1	2.4
12/26/06	9.4	5.0	1.9
12/27/06	10.0	-1.1	0.0
12/28/06	11.1	-3.3	0.0
12/29/06	13.9	0.0	0.0
12/30/06	16.7	6.1	0.0
12/31/06	12.2	10.6	1.4

Appendix D. Clemson, SC 2006 through 2008 weather data.

Date	Temp (°C)		Rain (cm)
	Max	Min	
1/1/07	20.0	10.6	4.7
1/2/07	16.7	-1.7	0.0
1/3/07	13.3	-2.2	0.0
1/4/07	15.0	7.2	0.0
1/5/07	18.3	8.9	0.9
1/6/07	18.9	10.6	1.7
1/7/07	21.1	7.2	0.0
1/8/07	14.4	8.9	4.0
1/9/07	13.3	0.6	0.0
1/10/07	10.0	-1.7	0.0
1/11/07	10.0	-3.9	0.0
1/12/07	10.0	-3.3	0.0
1/13/07	15.6	10.0	0.0
1/14/07	20.6	11.1	0.0
1/15/07	21.1	12.8	0.0
1/16/07	21.7	11.1	0.0
1/17/07	12.8	-1.7	0.0
1/18/07	5.0	-1.1	0.0
1/19/07	6.1	2.8	0.4
1/20/07	13.3	0.6	0.0
1/21/07	11.1	3.9	0.0
1/22/07	6.7	2.2	2.9
1/23/07	10.0	0.6	0.0
1/24/07	9.4	-1.7	0.0
1/25/07	10.0	0.0	0.0
1/26/07	10.0	-4.4	0.0
1/27/07	12.2	2.2	0.0
1/28/07	15.6	5.0	0.0
1/29/07	10.0	-8.9	0.0
1/30/07	5.6	0.6	0.0
1/31/07	12.2	-5.6	0.0
2/1/07	6.7	-2.8	0.0
2/2/07	2.2	1.7	2.3
2/3/07	9.4	-2.8	0.0
2/4/07	6.1	-3.3	0.0

Appendix D. Clemson, SC 2006 through 2008 weather data.

Date	Temp (°C)		Rain (cm)
	Max	Min	
2/5/07	8.3	-2.2	0.0
2/6/07	8.3	-6.1	0.0
2/7/07	10.0	3.3	0.0
2/8/07	19.4	-1.1	0.0
2/9/07	16.7	-2.8	0.0
2/10/07	7.8	-3.9	0.0
2/11/07	10.0	-5.6	0.0
2/12/07	12.8	-2.8	0.0
2/13/07	18.3	5.0	0.0
2/14/07	15.6	3.9	1.7
2/15/07	14.4	-5.6	0.0
2/16/07	7.2	-3.3	0.0
2/17/07	7.8	-2.8	0.0
2/18/07	5.6	-1.1	0.0
2/19/07	9.4	-3.9	0.0
2/20/07	14.4	4.4	0.0
2/21/07	13.9	9.4	0.2
2/22/07	20.0	8.9	2.7
2/23/07	21.7	1.1	0.0
2/24/07	16.1	-2.2	0.0
2/25/07	16.1	7.8	0.9
2/26/07	11.1	3.9	2.2
2/27/07	18.3	2.8	0.0
2/28/07	20.6	0.0	0.0
3/1/07	20.6	7.2	0.0
3/2/07	18.3	7.2	8.2
3/3/07	16.7	5.6	0.0
3/4/07	16.1	1.1	0.0
3/5/07	10.6	-4.4	0.0
3/6/07	18.3	6.7	0.0
3/7/07	20.0	1.7	0.0
3/8/07	21.1	2.8	0.0
3/9/07	21.7	6.1	0.0
3/10/07	16.1	7.2	0.0
3/11/07	20.6	7.2	0.0

Appendix D. Clemson, SC 2006 through 2008 weather data.

Date	Temp (°C)		Rain (cm)
	Max	Min	
3/12/07	23.9	10.0	0.0
3/13/07	21.1	3.3	0.0
3/14/07	26.7	10.6	0.0
3/15/07	26.1	10.6	0.0
3/16/07	23.9	14.4	0.8
3/17/07	19.4	1.1	0.2
3/18/07	11.7	-2.2	0.0
3/19/07	13.9	1.1	0.0
3/20/07	19.4	10.0	0.0
3/21/07	26.1	12.8	0.0
3/22/07	22.2	10.0	0.0
3/23/07	23.3	8.9	0.0
3/24/07	26.7	9.4	0.0
3/25/07	29.4	11.1	0.0
3/26/07	31.7	14.4	0.0
3/27/07	25.0	12.8	0.0
3/28/07	27.8	11.7	0.0
3/29/07	28.9	16.7	0.0
3/30/07	18.9	8.9	0.0
3/31/07	19.4	10.6	0.0
4/1/07	24.4	16.1	0.0
4/2/07	20.6	15.0	0.8
4/3/07	27.8	13.9	0.0
4/4/07	28.9	13.9	0.7
4/5/07	25.0	6.1	0.0
4/6/07	21.7	-0.6	0.0
4/7/07	15.6	-2.2	0.0
4/8/07	7.8	-2.8	0.0
4/9/07	13.9	0.6	0.0
4/10/07	12.8	-1.7	0.0
4/11/07	15.6	3.9	0.0
4/12/07	10.6	8.3	1.1
4/13/07	22.8	3.9	0.0
4/14/07	23.3	10.0	0.0
4/15/07	22.8	15.6	0.0

Appendix D. Clemson, SC 2006 through 2008 weather data.

Date	Temp (^oC)		Rain (cm)
	Max	Min	
4/16/07	17.2	6.1	0.0
4/17/07	21.1	8.9	0.0
4/18/07	28.3	8.3	0.0
4/19/07	24.4	6.7	0.0
4/20/07	23.9	7.8	0.0
4/21/07	20.6	6.1	0.0
4/22/07	24.4	5.6	0.0
4/23/07	26.7	7.2	0.0
4/24/07	26.7	12.2	0.0
4/25/07	27.8	12.8	0.1
4/26/07	28.3	13.3	0.0
4/27/07	23.9	14.4	0.2
4/28/07	25.6	9.4	0.0
4/29/07	23.9	10.6	0.0
4/30/07	29.4	8.3	0.0
5/1/07	30.6	10.6	0.0
5/2/07	32.2	12.8	0.0
5/3/07	31.7	15.6	0.0
5/4/07	30.0	13.9	0.0
5/5/07	20.0	11.7	2.4
5/6/07	15.0	12.8	1.3
5/7/07	22.2	6.1	0.0
5/8/07	22.8	8.3	0.0
5/9/07	26.7	17.2	0.0
5/10/07	27.2	13.9	0.0
5/11/07	29.4	16.1	0.0
5/12/07	31.1	17.8	0.0
5/13/07	28.3	15.6	0.0
5/14/07	31.1	15.6	0.0
5/15/07	25.0	9.4	0.0
5/16/07	28.3	14.4	0.0
5/17/07	25.6	10.0	0.1
5/18/07	25.0	8.3	0.0
5/19/07	22.8	4.4	0.0
5/20/07	23.9	7.8	0.0

Appendix D. Clemson, SC 2006 through 2008 weather data.

Date	Temp (°C)		Rain (cm)
	Max	Min	
5/21/07	28.9	8.9	0.0
5/22/07	31.1	10.0	0.0
5/23/07	31.1	13.3	0.0
5/24/07	29.4	16.1	0.0
5/25/07	28.3	12.2	0.0
5/26/07	29.4	12.2	0.0
5/27/07	30.6	13.9	0.0
5/28/07	31.7	14.4	0.0
5/29/07	29.4	15.0	0.0
5/30/07	32.2	12.8	0.0
5/31/07	31.7	16.1	0.0
6/1/07	31.7	17.8	0.0
6/2/07	31.1	18.9	0.0
6/3/07	26.1	16.7	0.9
6/4/07	31.1	17.8	0.1
6/5/07	32.2	17.8	0.0
6/6/07	29.4	16.1	0.4
6/7/07	32.8	16.7	0.0
6/8/07	34.4	21.7	0.0
6/9/07	33.9	18.9	0.0
6/10/07	36.7	16.7	0.0
6/11/07	35.0	21.7	0.0
6/12/07	28.3	16.7	1.5
6/13/07	28.3	14.4	1.4
6/14/07	30.0	15.6	0.0
6/15/07	28.9	17.2	0.0
6/16/07	26.1	18.9	0.3
6/17/07	30.0	18.3	0.0
6/18/07	33.3	16.7	0.0
6/19/07	33.9	20.0	0.0
6/20/07	33.3	20.0	0.5
6/21/07	32.2	14.4	0.0
6/22/07	32.8	15.0	0.0
6/23/07	33.9	17.8	0.0
6/24/07	33.9	20.6	0.0

Appendix D. Clemson, SC 2006 through 2008 weather data.

Date	Temp (°C)		Rain (cm)
	Max	Min	
6/25/07	36.1	21.7	0.0
6/26/07	35.0	18.9	2.5
6/27/07	32.8	19.4	0.0
6/28/07	33.9	20.0	0.0
6/29/07	34.4	20.0	0.0
6/30/07	33.3	20.6	1.1
7/1/07	32.8	20.0	1.3
7/2/07	32.2	18.3	0.9
7/3/07	21.7	18.3	0.0
7/4/07	26.7	17.2	0.0
7/5/07	30.0	16.7	0.0
7/6/07	31.7	16.7	0.0
7/7/07	33.3	19.4	0.0
7/8/07	30.0	19.4	0.0
7/9/07	31.1	19.4	0.0
7/10/07	33.3	19.4	0.0
7/11/07	33.3	21.7	0.5
7/12/07	30.6	17.2	0.0
7/13/07	32.2	17.8	0.0
7/14/07	30.0	17.8	0.0
7/15/07	28.3	18.9	0.0
7/16/07	26.7	19.4	1.3
7/17/07	32.2	20.0	0.0
7/18/07	32.2	21.1	2.2
7/19/07	32.2	20.0	0.0
7/20/07	33.9	21.1	0.0
7/21/07	35.0	17.8	0.0
7/22/07	29.4	18.9	0.0
7/23/07	29.4	16.7	0.0
7/24/07	28.9	18.3	0.0
7/25/07	31.1	17.2	0.0
7/26/07	32.2	18.9	0.0
7/27/07	32.8	19.4	0.0
7/28/07	33.3	21.1	0.0
7/29/07	28.9	21.1	0.5

Appendix D. Clemson, SC 2006 through 2008 weather data.

Date	Temp (^oC)		Rain (cm)
	Max	Min	
7/30/07	30.0	21.1	0.0
7/31/07	32.8	19.4	1.1
8/1/07	32.8	20.0	0.0
8/2/07	34.4	21.1	0.0
8/3/07	34.4	20.0	0.0
8/4/07	34.4	19.4	0.0
8/5/07	35.6	21.1	0.0
8/6/07	35.6	21.1	0.3
8/7/07	36.7	22.8	0.0
8/8/07	37.2	23.9	0.0
8/9/07	38.9	23.3	0.0
8/10/07	39.4	22.2	0.0
8/11/07	38.9	23.3	0.0
8/12/07	37.8	23.9	0.0
8/13/07	33.3	22.2	0.0
8/14/07	36.7	19.4	0.0
8/15/07	36.7	19.4	0.0
8/16/07	38.3	21.7	0.0
8/17/07	38.9	25.0	0.0
8/18/07	36.7	21.1	0.0
8/19/07	37.2	21.7	0.0
8/20/07	35.6	21.7	0.0
8/21/07	36.7	22.8	0.0
8/22/07	38.3	23.9	0.0
8/23/07	38.9	22.8	0.0
8/24/07	36.7	21.1	0.9
8/25/07	36.1	20.6	0.0
8/26/07	35.0	21.1	0.0
8/27/07	35.0	20.6	3.0
8/28/07	32.2	21.7	0.0
8/29/07	33.9	22.8	0.0
8/30/07	35.0	23.3	0.0
8/31/07	32.2	21.7	0.1
9/1/07	32.8	20.6	0.1
9/2/07	30.6	19.4	0.0

Appendix D. Clemson, SC 2006 through 2008 weather data.

Date	Temp (^oC)		Rain (cm)
	Max	Min	
9/3/07	30.0	16.7	0.0
9/4/07	32.8	19.4	0.0
9/5/07	33.9	16.1	0.0
9/6/07	33.9	18.3	0.0
9/7/07	33.3	20.0	0.0
9/8/07	32.2	17.2	0.0
9/9/07	33.3	16.7	0.0
9/10/07	35.0	17.8	0.0
9/11/07	35.0	20.0	0.0
9/12/07	35.0	21.1	0.0
9/13/07	32.2	21.7	0.0
9/14/07	27.2	21.7	0.1
9/15/07	26.7	17.8	5.6
9/16/07	30.0	14.4	0.0
9/17/07	25.0	14.4	0.0
9/18/07	26.1	13.9	0.0
9/19/07	25.6	13.3	0.0
9/20/07	28.3	16.1	0.0
9/21/07	26.7	20.0	0.0
9/22/07	26.7	20.0	0.0
9/23/07	31.1	18.3	0.0
9/24/07	32.8	18.3	0.0
9/25/07	33.3	19.4	0.0
9/26/07	31.7	15.6	0.0
9/27/07	32.2	15.6	0.0
9/28/07	31.1	16.1	0.0
9/29/07	29.4	11.1	0.0
9/30/07	26.7	10.6	0.0
10/1/07	26.7	10.0	0.0
10/2/07	27.2	12.2	0.0
10/3/07	28.3	18.9	0.0
10/4/07	26.7	20.0	0.0
10/5/07	26.7	20.6	1.5
10/6/07	27.8	20.0	0.0
10/7/07	28.3	16.7	0.0

Appendix D. Clemson, SC 2006 through 2008 weather data.

Date	Temp (^oC)		Rain (cm)
	Max	Min	
10/8/07	30.0	16.7	0.0
10/9/07	31.1	16.7	0.0
10/10/07	32.2	16.7	0.0
10/11/07	31.7	11.1	0.0
10/12/07	30.0	5.6	0.0
10/13/07	22.2	6.7	0.0
10/14/07	22.8	7.8	0.0
10/15/07	26.7	8.3	0.0
10/16/07	27.2	12.2	0.0
10/17/07	23.9	15.6	0.0
10/18/07	27.8	17.2	0.0
10/19/07	23.9	20.0	0.3
10/20/07	23.9	10.0	0.1
10/21/07	24.4	6.1	0.0
10/22/07	27.2	11.7	0.0
10/23/07	17.8	17.2	0.5
10/24/07	28.9	15.0	1.6
10/25/07	17.8	12.2	0.1
10/26/07	21.1	12.2	0.0
10/27/07	22.8	12.2	0.0
10/28/07	23.3	5.6	0.0
10/29/07	21.1	6.1	0.0
10/30/07	18.3	-0.6	0.0
10/31/07	20.6	1.7	0.0
11/1/07	23.3	8.3	0.0
11/2/07	25.6	11.1	0.0
11/3/07	21.7	2.2	0.0
11/4/07	25.0	0.6	0.0
11/5/07	21.1	2.2	0.0
11/6/07	22.8	8.3	0.0
11/7/07	16.7	-2.2	0.0
11/8/07	13.9	-2.8	0.0
11/9/07	13.9	-0.6	0.0
11/10/07	19.4	5.6	0.0
11/11/07	17.2	-1.1	0.0

Appendix D. Clemson, SC 2006 through 2008 weather data.

Date	Temp (°C)		Rain (cm)
	Max	Min	
11/12/07	15.6	-0.6	0.0
11/13/07	20.6	5.6	0.0
11/14/07	23.9	12.8	0.0
11/15/07	26.7	11.1	0.6
11/16/07	12.8	-1.1	0.0
11/17/07	12.2	-3.3	0.0
11/18/07	16.7	6.1	0.0
11/19/07	22.8	7.2	0.0
11/20/07	24.4	5.0	0.0
11/21/07	23.9	5.6	0.0
11/22/07	22.8	15.6	0.7
11/23/07	21.1	1.7	0.3
11/24/07	12.8	-2.2	0.0
11/25/07	9.4	4.4	0.0
11/26/07	10.0	6.1	0.8
11/27/07	13.3	7.2	0.8
11/28/07	18.3	-1.7	0.0
11/29/07	17.2	0.6	0.0
11/30/07	19.4	1.1	0.0
12/1/07	15.6	-0.6	0.0
12/2/07	18.9	2.8	0.0
12/3/07	15.6	10.6	0.1
12/4/07	16.7	0.0	0.0
12/5/07	14.4	1.7	0.0
12/6/07	16.7	-1.1	0.0
12/7/07	7.8	-1.7	0.0
12/8/07	11.1	5.0	0.0
12/9/07	22.8	10.0	0.0
12/10/07	23.9	11.7	0.0
12/11/07	26.1	10.0	0.0
12/12/07	25.6	11.7	0.0
12/13/07	26.1	12.2	0.0
12/14/07	22.8	5.0	0.1
12/15/07	20.6	4.4	0.0
12/16/07	11.7	1.7	2.3

Appendix D. Clemson, SC 2006 through 2008 weather data.

Date	Temp (^oC) Max	Min	Rain (cm)
12/17/07	1.7	-3.3	0.0
12/18/07	10.0	-6.1	0.0
12/19/07	9.4	-1.7	0.0
12/20/07	11.1	1.7	0.0
12/21/07	11.1	6.7	2.1
12/22/07	8.9	7.2	0.0
12/23/07	11.7	7.8	1.3
12/24/07	16.1	-3.3	1.0
12/25/07	15.0	1.1	0.0
12/26/07	11.7	3.9	1.7
12/27/07	11.1	7.2	0.0
12/28/07	13.9	9.4	0.0
12/29/07	13.3	7.2	2.2
12/30/07	18.3	6.7	0.9
12/31/07	8.9	0.0	2.9
1/1/08	13.9	0.0	0.0
1/2/08	9.4	-5.0	0.0
1/3/08	2.2	-10.6	0.0
1/4/08	3.3	-9.4	0.0
1/5/08	7.8	-3.3	0.0
1/6/08	11.7	1.7	0.0
1/7/08	19.4	2.2	0.0
1/8/08	21.1	6.7	0.0
1/9/08	20.0	13.3	0.0
1/10/08	22.2	8.9	0.4
1/11/08	14.4	9.4	1.4
1/12/08	17.2	-0.6	0.0
1/13/08	13.9	2.8	0.0
1/14/08	12.8	1.1	0.0
1/15/08	11.1	-0.6	0.0
1/16/08	10.6	-5.0	0.0
1/17/08	0.6	0.0	2.1
1/18/08	4.4	2.8	0.0
1/19/08	13.3	3.9	0.1
1/20/08	4.4	-5.6	0.5

Appendix D. Clemson, SC 2006 through 2008 weather data.

Date	Temp (°C)		Rain (cm)
	Max	Min	
1/21/08	2.8	-9.4	0.0
1/22/08	3.9	0.6	0.0
1/23/08	3.3	2.8	0.9
1/24/08	12.8	0.0	0.0
1/25/08	10.6	-8.9	0.0
1/26/08	5.0	0.6	0.0
1/27/08	10.0	-3.3	0.0
1/28/08	16.1	-4.4	0.0
1/29/08	13.9	4.4	0.0
1/30/08	17.8	1.7	0.7
1/31/08	12.2	-1.7	3.7
2/1/08	12.2	1.7	0.2
2/2/08	11.7	-2.8	0.0
2/3/08	15.0	-1.7	0.3
2/4/08	18.3	6.7	0.0
2/5/08	15.0	6.7	0.0
2/6/08	21.1	12.2	0.5
2/7/08	18.3	3.3	0.0
2/8/08	18.3	1.7	0.0
2/9/08	16.1	0.6	0.0
2/10/08	18.3	3.9	0.0
2/11/08	17.2	-1.1	0.0
2/12/08	17.2	2.2	0.0
2/13/08	15.6	3.3	0.8
2/14/08	15.0	-4.4	0.0
2/15/08	11.7	-0.6	0.0
2/16/08	16.7	3.9	0.0
2/17/08	20.6	8.9	0.0
2/18/08	16.7	11.1	2.6
2/19/08	13.9	2.8	0.0
2/20/08	12.2	1.1	0.0
2/21/08	18.3	2.2	0.0
2/22/08	7.2	1.7	2.7

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