CHAPTER 1

THE USE OF DIGITAL IMAGE ANALYSIS AND SPECTRAL REFLECTANCE TO QUANTIFY DROUGHT STRESS IN HYBRID BLUEGRASS AND BERMUDAGRASS

ABSTRACT

Frequent monitoring of stress levels in turfgrass is a key to maintaining healthy turfgrass stands. Current methods used to monitor turfgrass for drought stress can be time consuming and expensive. This study was conducted to determine if data obtained from digital image analysis and spectroradiometry could accurately detect drought stress in turfgrasses and discriminate between degrees of drought stress. Furthermore our objective was to determine if there was a strong correlation between these data and visual ratings, relative water content (RWC) and leaf osmolality. The greenhouse study was conducted in 2006 with hybrid bluegrass [*Poa arachnifera* (Torr.) x *pratensis* (L.)] cv. Reveille and bermudagrass [*Cynodon dactylon* (L.)] cv. Princess 77 at New Mexico State University. Increasing drought levels decreased RWC, increased osmolality, and decreased visual ratings for both species. Percent green cover and hue values obtained from digital image analysis and Normalized Difference Vegetation Index (NDVI) calculated from spectroradiometry readings were moderately to highly correlated with visual ratings, RWC and leaf osmolality. Both methods effectively detected drought stress and may have applications in turfgrass management as rapid and quantitative

methods that could potentially replace traditional qualitative visual measures of drought stress in turf.

Abbreviations: □DC, direct current; ET_O, reference evapotranspiration; FAO, Food and Agriculture Organization of the United Nations; *Kc*, crop factor; IR, irrigation amounts; LAI, leaf area index; NDVI, Normalized Difference Vegetation Index; NIR, near-infrared; PVC, polyvinyl chloride; rpm, revolutions per minute; RWC, relative water content.

INTRODUCTION

Human population growth and urban development in the arid southwestern USA is a source of increasing stress on water supplies, which range, depending on precipitation, from almost adequate to scarce. In addition, urban development has led to the proliferation of recreational areas such as golf courses and athletic fields, and irrigation of landscaped areas (including lawns) account for over 50% of total urban potable water use in the summer in the Southwest (Kjelgren et al., 2000). Despite the recreational, aesthetic, and economic benefits of turfgrass (Beard and Green, 1994), the present day water shortages in the Southwest clearly set limits on expectations and water consumption for turf irrigation. Consequently, irrigation water conservation strategies have been implemented by many municipalities. These strategies include selecting appropriate plants and the installation of irrigation scheduling technologies (Albuquerque Bernalillo County Water Utility Authority [ABCWUA], 2007). Applications of these technologies are aimed at determining minimum irrigation requirements of turfgrasses in order to avoid over-irrigation (Carrow et al., 2002). Water requirements and subsequent irrigation are calculated from the plants' water status after allowing a dry-down cycle. Turf areas that are affected by drought stress show wilt, reduced quality and reduced growth, which in return affects the recuperative potential of the grass plants (Beard, 1973). For a dry-down and subsequent recovery strategy to be effective, thresholds must be established to determine the extent to which plants can be stressed and still recover, and to determine irrigation requirements that are necessary for the recovery of plants subjected to this mild stress. Determining thresholds can be achieved by monitoring soil moisture, visually examining the plants for signs of stress on a regular basis, or by the use of innovative remote sensing technologies. These include digital image analysis and spectroradiometry to assess plant light reflectance in response to stress (Ikemura and Leinauer, 2006). Soil moisture measurements have the disadvantage that they only provide information on the immediate area sampled, and therefore multiple samples must be taken to provide an accurate representation of a larger turf area, which can be time consuming. Daily monitoring using visual assessments can also be time consuming and labor intensive. Scheduling turfgrass irrigation based on remotely sensed plant water status and/or on drought status has long been suggested as a means for determining timing and duration of irrigation cycles (e.g. Throssell et al., 1987: Jalali-Farahani et al., 1993).

Early work in the 1980s and 1990s suggested measuring the plant leaf surface temperature in the 10.5 to 12.5 μm waveband by means of an infrared thermometer to quantify a plant's drought stress level (Idso et al., 1981; Everest, 1984). Hatfield (1990) provided a detailed summary on the subject of infrared thermometry to measure plant stress. Throssell et al. (1987) and Jalali-Farahani et al. (1993) suggested the use of a Crop Water Stress Index calculated from remotely measured leaf surface temperature for irrigation scheduling of cool and warm season turfgrasses, respectively. More recently, multi-spectrum radiometry and calculated reflectance ratios from visible wavelengths (400 to 700 nm) and from the near-infrared (NIR) range (700 to 2500 nm) have been successfully used to determine plant stress responses (Carter, 1993). Spectroradiometry can be used to assess the plant light reflectance in the visible and near-infrared ranges. The reflectance of narrow band wavelengths as well as ratios of those wavelengths are highly correlated with the absorbency of photosynthetically active radiation, leaf area index (LAI), and plant response to stresses (Trenholm et al., 1999a). More recently, spectral reflectance has been used extensively on several turfgrasses to evaluate stand quality (Bell et al., 2002; Trenholm et al., 1999a), tissue Nitrogen content (Bell et al., 2004), moisture stress (Fenstermaker-Shaulis et al., 1997; Fitz-Rodriguez and Choi, 2002; Hutto et al., 2006. Jiang and Carrow, 2005; Park et al., 2005; Ploense, 2002), salinity stress (Ikemura, 2004), disease stress (Rinehart et al., 2001; Green at al., 1998; Raikes and Burpee, 1998), nutrient stress (Kruse et al., 2005), wear stress (Trenholm at al., 1999b) and stress from soil compaction (Guertal and Shaw, 2004).

In addition to spectral radiometry, digital image analysis has also been used to objectively assess turf stand parameters. Richardson et al. (2001) accurately estimated percent ground cover from digital photographs, and Karcher and Richardson (2003) documented the use of digital image analysis to quantify turfgrass color. Ikemura et al.

(2002) used image analysis to predict tissue nitrogen content in cool and warm season grasses. However, limited information is available on the use of digital image analysis as a standardized measurement of turf stress. Everitt et al (1987a, 1987b) used the near-infrared region in digital images to detect drought stress in plants. Carter and Miller (1994) investigated digital photography in conjunction with optical interference filters to detect herbicide chlorosis in soybean. However, no published information is currently available on the use of standard digital imagery and subsequent image analysis to detect and quantify drought stress.

Bermudagrass is the most commonly grown turfgrass in the southern U.S. and in tropical and subtropical regions of the world (Taliaferro, 2004). Turf type bermudagrass cultivars that have been historically used for highly maintained and trafficked turf stands were sterile hybrids and had to be propagated from sprigs or sod (Beard, 1973). New seeded bermudagrass varieties such as Princess 77 and Riviera have been introduced to the turf market and offer turf quality equal to top performing vegetative varieties such as Tifway and Tifgreen (Rodgers, 2003). However, very little information is known on the performance of these new seeded bermudagrass varieties under drought or other environmental stresses. Hybrid bluegrass, a genetic cross between *Poa arachnifera* (Torr.) and Kentucky bluegrass (*Poa pratensis* L.) has been suggested to withstand high temperatures and extended periods of drought due to greater drought resistance mechanisms compared to perennial ryegrass or Kentucky bluegrass (Read et al., 1999; Abraham et al., 2004; Ploense, 2002). Consequently, hybrid bluegrass could become a high-quality, dark-green alternative to bermudagrass in the high altitude, desert Southwest that offers color year round and provides heat tolerance and drought resistance during the summer. To date, no published studies have compared heat tolerant hybrid bluegrasses to bermudagrass.

We conducted a study to determine if digital image analysis and spectroradiometry could be effectively used to detect and quantify drought stress, and to compare stress responses in turfgrasses. The objective of this study was to assess the efficacy of digital image analysis and spectroradiometry in detecting and quantifying drought stress in hybrid bluegrass [*Poa arachnifera* (Torr.) x *pratensis* (L.)] cv. Reveille and bermudagrass [*Cynodon dactylon* (L.)] cv. Princess 77 when subjected to five progressively longer drought periods. To do so, we assessed whether data obtained from digital image analysis and spectroradiometry could be adequately correlated with qualitative visual ratings, relative water content (RWC) and leaf osmolality measurements, three standard methods used to evaluate stress in plants. Hybrid bluegrass and bermudagrass were selected as the test species to assess the abilities of these remote sensing methods to measure drought stress in a warm season grass species (Princess 77) and a drought resistant cool season grass species (Reveille).

MATERIALS AND METHODS

Two greenhouse drought experiments were conducted in 2006 at the New Mexico State University Fabian Garcia Research Center in Las Cruces, NM. For both experiments, Princess 77 bermudagrass and Reveille hybrid bluegrass were established from sod in cone-shaped polyvinyl chloride (PVC) pots 15 cm in diameter and 20 cm in depth during April of 2006. Each container was filled with the same amount of an air-dried rootzone consisting of a Brazito sandy loam (mixed, thermic typic Torripsament). The surface of the rootzone was kept at approximately 1 cm below from the top of the container rim. Washed hybrid bluegrass and bermudagrass sod was placed on top of the rootzone and watered thoroughly immediately after planting. Starter fertilizer (15-15-15 [N-P-K]) in the amount of 5 g Nm^{-2} was applied to each container at planting. No additional fertilizer was applied after planting the sod. In order to provide insulation and minimize heating of the rootzone from outside of the container walls, each pot was placed inside a second container of the same size and shape. During the subsequent establishment phase, grasses were watered with tap water to prevent drought stress and clipped with scissors twice a week to maintain a 4.0 cm stand height. The establishment period of the grasses was considered successful when the plants in each container had produced a dense root system reaching the bottom of the pot. Two drought experiments were conducted during the summer of 2006. Experiment 1 started on May 21, 2006 (50 days after planting the sods) and Experiment 2 on July 2, 2006 (88 days after planting the sods). The air temperature inside the greenhouse was recorded by a temperature data logger (HOBO Temp, Onset Computer Corp., Bourne, MA) and reached a maximum of 30°C during the day and a minimum of 20°C during the night for both experiments.

Drought Treatment

Drought treatments were applied by watering at different irrigation amounts. The Food and Agriculture Organization of the United Nations' (FAO) updated version of the Penman-Monteith evapotranspiration (ET_O) estimation model for crop irrigation (also known as FAO 56) (Allen et al., 1998) was used to calculate evapotranspiration replacements (=irrigation amounts) for each treatment. ET_O (mm) was calculated from climate data that was downloaded from New Mexico State University's climate center web page (http://weather.nmsu.edu). The weather station used to collect the relevant climate data was located approximately 200 m east of the greenhouse used in this study. Calculated ET_O was solely used to estimate an irrigation baseline and does not necessarily reflect actual evapotranspiration values inside the greenhouse. The drought treatments were applied by watering the grasses every other day at different ET_O replacement levels during a 6 day dry-down cycle. An ET_O adjustment factor, also called crop factor (K_C), was used to calculate the irrigation amounts (IR) for the different drought treatments. K_C values of 100% (control) and 20, 40, 60, and 80% were applied. The IR applied for the drought treatments were calculated using the following formula:

$$IR\ (mm) = ET_O\ (mm) * K_C \quad (1)$$

Prior to the onset of drought treatments, the turfgrass pots were irrigated fully until water drained from the containers. The drought experiment started one day after each container had been fully watered and assigned irrigation treatments were applied every other day for 7 days. Measurements were taken seven days after drought treatments started.

Drought Evaluations

Prior to taking visual ratings or collecting spectroradiometry and digital image data, the turf was clipped with scissors and the clippings were collected to determine RWC. A portion of the clippings from each plot were re-hydrated overnight, dried at 85°C for 12 hours, and RWC was calculated using the following formula:

$$RWC\ (\%) = (Fresh\ weight - Dry\ weight) / (Turgid\ weight - Dry\ weight) * 100 \quad (2)$$

The remaining clippings were placed in zip lock bags and immediately frozen for later analysis of osmolality. To determine osmolality, clippings were packed in a forensic spin filter (USA Scientific, Inc., Ocala, FL) and centrifuged (Centrifuges 5415D, Eppendorf, New York, NY) at 13.2 revolutions per minute (rpm) for 5 minutes to extract plant sap. Osmolality was measured using a Vapor Pressure Osmometer (Wescore, Inc., Logan, UT). All plots were visually rated for turf quality on a scale of 1 to 9 with 1 corresponding to brown, dead turf and 6 reflecting the minimum acceptable quality. A rating of 9 indicated an optimal quality.

Digital Image Data Collection

The digital images were collected using a web camera (QuickCam Pro4000, Logitech Inc., Fremont, CA) in an enclosed PVC box to provide a controlled light environment. The images were collected in the JPEG format at an image size of 1280 × 960 pixels. Camera settings included a shutter speed of 1/100 s and white balance of incandescent mode. The dimensions of the PVC pipe were 15.24 cm in diameter and 35.0 cm in height. The inside of the PVC pipe was painted white with latex paint to enhance maximum light reflectance, and a 0.3 cm thick wooden board covered the top of the pipe. A web camera and two clear 5 watt tungsten halogen light bulbs (OS 64405, Osram Sylvania Inc., Danvers, MA) were placed inside the PVC pipe. All images were downloaded to a PC and cropped to exclude non-turf area for digital image analysis. To quantify the turf color and cover in each picture, hue, saturation, and brightness values were determined using the "Turf Analysis" macro written and described by Karcher and Richardson (2005). Hue values were measured for the 8 control treatments and an average hue value was calculated. This average hue value represented normal healthy and unstressed conditions in the grass plant. This value was subtracted from all hue values obtained from drought treated plants and these corrected hue values were used in all subsequent statistical analyses.

Spectroradiometer Data Collection

The spectroradiometry readings of the turf canopy were taken using a LabSpec Pro spectroradiometer (Analytical Spectral Devices Inc., Boulder, CO) under a controlled light environment in an enclosed PVC box similar to the one described above. The top of the PVC pipe was covered with a 0.3 cm thick wooden board which contained a small hole through which a fiber optic sensor was inserted and two larger holes through which two clear 5 watt tungsten halogen light bulbs were inserted to illuminate inside the box. The holes were covered with aluminum foil to prevent any sunlight from entering the box. The fiber optic sensor had a 25° angle of view, so that a 7.98 cm diameter of the turfgrass area was measured. In order to reduce noise from the lights, direct current (DC) was used to supply the light source. The spectral reflectance data collected were used to calculate Normalized Difference Vegetation Index (NDVI) using the following equation (Trenholm et al, 1999b):

$$NDVI = (935\ nm - 661\ nm) / (935\ nm + 661\ nm) \quad (3)$$

Statistical Analysis

The experimental design was completely randomized and treatments were replicated four times. Hues from the drought stressed plants were normalized to Hues in control plants using the following equation:

$$NHue = |\ Hue\ treatment - Mean\ control\ hue\ | \quad (4)$$

To test the effect of drought on the quantitative and qualitative response data collected, percent green cover, NHue, NDVI, RWC, osmolality, and visual ratings were subjected to analysis of variance using SAS Proc Mixed (SAS Institute, Inc., 2002) followed by means separation using Fisher's protected least square difference (LSD) test ($\alpha = 0.05$). Hue, NDVI, and percent green cover were regressed against visual ratings, osmolality, and RWC. Coefficients of determination were examined to determine the degree of association between variables and responses.

RESULTS AND DISCUSSION

Analysis of variance indicated no significant interactions between the first and the second experiments for the measured parameters (Table 1-1). Therefore, treatment means of all parameters were pooled over both experiments. The effects of reduced irrigation on RWC, osmolality, visual rating, percent green cover, NHue, and NDVI for both species are shown in Table 1-2. The six parameters we compared varied in their abilities to detect differences in drought stress between bermudagrass and hybrid bluegrass. For hybrid bluegrass, RWC, visual rating, and percent green cover gradually decreased as drought progressed. Even at the lowest stress level (80% ET_O), RWC, visual rating, percent green cover, and NHue differed significantly from the control treatment. For bermudagrass, RWC, visual ratings, percent green cover, NHue, and NDVI only differed from the control for the 20% ET_O treatment. These results indicate that hybrid bluegrass exhibited drought stress at higher ET_O treatment levels than bermudagrass, which only revealed signs of stress at the 20% ET_O treatment.

Relative leaf water content is considered an indicator of a plant's water status (Sinclair and Ludlow, 1985). Taiz and Zeiger (1998) reported a 50% leaf water content threshold for most plants, at which point physiological malfunctions take place and plant death occurs. In this study turf quality was acceptable (visual ratings of 6 or greater) for hybrid bluegrass until RWC dropped to 70% at the 80% ET_O treatment (data not presented). For bermudagrass acceptable turf quality was observed until RWC dropped to 74% at the 40% ET_O irrigation treatment. This indicates that bermudagrass exhibited a greater ability to maintain leaf water content than hybrid bluegrass at reduced irrigation levels. The change in osmolality with increasing drought was also more pronounced in hybrid bluegrass than in bermudagrass (Table 1-2). When osmolality changes in treated plants were compared to controls, bermudagrass increased osmolality significantly only when irrigation was reduced to 40% or to 20% ET_O. Hybrid bluegrass had less leaf solute concentrations than control at 60% ET_O. Changes in RWC and osmolality indicated greater drought resistance in bermudagrass than in hybrid bluegrass (Table 1-2). Fu et al. (2004) measured leaf water content in 'Midlawn' bermudagrass, 'Meyer' zoysiagrass, and 'Falcon II' tall fescue during dry down periods in a field study and found greater drought tolerance (greater ability to tolerate leaf desiccation) in bermudagrass than in zoysiagrass or tall fescue. Qian and Fry (1997) showed significantly greater osmotic adjustment in

'Midlawn' bermudagrass than in 'Mustang' tall fescue after drought. Our results are similar to those of Fu et al. (2004) who found acceptable turf quality in Kentucky bluegrass and tall fescue until RWC dropped below 76% and 77%, respectively. Abraham et al. (2004) identified drought resistant Kentucky and hybrid bluegrasses that held RWC at 60% after 35 drought days, however quality ratings for these bluegrasses had dropped to 5. For 'Midlawn' bermudagrass the RWC threshold below which turfgrass quality was unacceptable was 65% (Fu et al., 2004), whereas in our study turfgrass quality of Princess 77 was still acceptable (6.3) at 74% RWC. Numerous studies (e.g. Kim and Beard, 1988; Carrow, 1995) have demonstrated that warm season turfgrasses in general exhibit lower water use rates than cool season turfgrasses under non-limiting soil water conditions. During periods of drought or water replacement below evapotranspiration losses (deficit irrigation), Bremer et al. (2006) showed greater turf quality in tall fescue than in hybrid bluegrass, and Fu et al. (2004) showed that bermudagrass sustained acceptable turf quality longer than tall fescue during a drought period. No study has investigated the effect of deficit irrigation on warm and cool season grasses including hybrid bluegrass in a side by side comparison.

NHue and NDVI in bermudagrass only differed from the control for the 20% ET_O treatment and values agree with RWC values, visual ratings, and percent green cover (Table 1-1). Consequently, NDVI and Hue correlated highly with visual ratings

(r^2=0.76 and 0.77, respectively) and also with RWC (r^2=0.81 and 0.76, respectively) (Figure 1-2). Percent green cover also correlated highly with visual ratings (r^2=0.81) and with RWC (r^2=0.88). Osmolality correlated only moderately with Hue (r^2=0.6), NDVI (r^2=0.54), and percent green cover (r^2=0.70). For hybrid bluegrass, NDVI and NHue did not reflect the increase in stress to the same extent as did RWC or visual ratings. NHue and NDVI at the 60% ET_O treatment did not differ from the 80% ET_O treatment or from the control. Only at the 40% and 20% ET_O treatment levels did NHue and NDVI indicate a significant change in spectral reflectance compared to the control (Table 1-2). However, coefficients of determination between Hue and visual ratings and RWC, and between NDVI and visual ratings and RWC were generally higher for hybrid bluegrass than for bermudagrass. Coefficients of determination between hue and osmolality, NDVI and osmolality, and percent green cover and osmolality were lower than the other coefficients, but still higher than in bermudagrass (Figure 1-1 and 1-2). Our findings support those of Fenstermaker-Shaulis et al. (1997), who reported a strong correlation (r^2 = 0.9) between NDVI and tissue moisture content in drought stressed tall fescue. Fitz-Rodriguez and Choi (2002) found a strong correlation (r^2 = 0.72) between NDVI and turfgrass quality in unstressed bermudagrass over 2 growing periods. Jiang and Carrow (2005) demonstrated a high correlation between reflectance at 673 to 693 nm and turf quality for drought stressed bermudagrass. Ploense (2002) also suggested the narrow bands of spectral reflectance (660-672 nm) were most sensitive to and highly correlated with visual quality in drought exposed Kentucky bluegrass, hybrid bluegrass, and perennial ryegrass. Coefficients of determination between NDVI and turf quality or other plant parameters have not been reported for hybrid bluegrass.

NHue values were significantly different between the two species at stress levels of 80%, 40% and 20% ET_O. Similar species separation was expected for NDVI for our drought treatments. However, NDVI values were only different for the 2 species at the 40% ET_O treatment level. This suggests that NDVI may not be suitable for comparing drought stress between species. Jiang and Carrow (2005) reported different narrow-band spectral reflectance responses for warm and cool season turfgrasses under drought stress. Ploense (2002) found differences in canopy spectral reflectance changes in drought stressed hybrid bluegrass, Kentucky bluegrass, and perennial ryegrass not only between species, but also between seasons.

When examining the relationship between hue and visual rating, osmolality, and RWC, the best fit was obtained using a second degree polynomial regression for both species (Figure 1-1 and 1-2). The apex of each of these regressions corresponded to the same hue value (green color), which is the color of healthy turfgrass. During drought stress, hue either decreases from green color to yellow then to brown (left of apex) or increases to darker green then to bluish green color (right of apex). Hybrid bluegrass expressed about 2/3 of its color change from green to darker green (Figure

1-2) and bermudagrass changed its color mostly to yellow and brown (Figure 1-3). Decreasing hue from green to yellow then to brown is mostly caused by leaf firing, and the increasing hue from green to darker green to bluish green is caused by wilting. Further research might be needed to explore changes in hue values for different species under different kinds of stresses.

Our second objective was to determine if digital image analysis and spectroradiometry were effective methods to detect early signs of drought stress, even before they were visible by standard methods such as RWC, osmolality, and visual rating. Of the 6 methods we used to detect drought stress, RWC, visual rating, percent green cover, and NHue were more effective than NDVI at detecting early signs of stress in hybrid bluegrass, as evidenced by values significantly different from controls at the lowest drought treatment we used (Table 1-2). Osmolality value differed significantly from controls at 60% ET_O, whereas 40% ET_O levels were needed before NDVI values differed significantly from control values. Changes in osmolality were more sensitive to drought in bermudagrass than in hybrid bluegrass. To determine if any single method is most effective at detecting early signs of drought stress, further studies would be needed using a greater number of drought treatments, particularly at the lower drought stress levels.

CONCLUSIONS

Our data indicated that digital image analysis and spectral radiometry could be effectively used to detect drought stress in turf and to quantify subjective variables such as visual ratings. These methods have potential to quickly and non-destructively monitor appearance and water status of a turfgrass stand and could be used for irrigation scheduling. Further research is needed to assess drought stress for more turfgrass species under different durations of deficit irrigation and to determine whether or not grasses recover from different levels of drought. In addition, more research is needed to evaluate the ability of spectral radiometry and digital image analysis to distinguish drought stress from other forms of stress, such as salinity stress or heat stress. Based on our findings, bermudagrass exhibits greater drought resistance than hybrid bluegrass.

REFERENCES

Abraham, E. M., B. Huang, S. A Bonos, and W. A. Meyer. 2004. Evaluation of drought resistance for Texas bluegrass, Kentucky bluegrass, and their hybrids. Crop Sci. 44:1746-1753.

Albuquerque Bernalillo County Water Utility Authority (ABCWUA). 2007. Water Conservation – Conserving For Our Future.

Allen, R.G., L.S. Pereira, D. Raes, M. Smith. 1998. Crop evapotranspiration – Guidelines for computing crop water requirements, FAO Irrigation and drainage paper 56.

Beard, J. B., and R. L. Green. 1994. The role of turfgrasses in environmental protection and their benefits to humans. J. Environ. Qual. 23:452-460.

Beard, J.B.1973. Turfgrass: science and culture. Prentice-Hall, Englewood Cliffs, N.J.

Bell, G. E., B. M. Howell, G. V. Johnson, W. R. Raun, J. B. Solie, and M. L. Stone. 2004. Optical sensing of turfgrass chlorophyll content and tissue nitrogen. HortScience. 39:1130-1132.

Bell, G.E., D.L. Martin, S.G. Wiese, D.D Dobson, M.W. Smith, M.L. Stone, and J.B. Solie. 2002. Vehicle-Mounted Optical Sensing: An Objective Means for Evaluating Turfgrass Quality. Crop Sci. 42:197-201.

Bremer, D. J., K. Su, S. J. Keeley, and J. D. Fry. 2006. Performance in the transition zone of two hybrid bluegrasses compared with Kentucky bluegrass and tall fescue. [Online]Appl. Turfgrass Sci. p.1-9.

Carrow, R. N., P. Broomhall, R. R. Duncan, and C. Waltz. 2002. Turfgrass water conservation. Part I. Primary strategies. Golf Course Manage. 70:49-53.

Carrow, R. N. 1995. Drought resistance aspects of turfgrasses in the southeast: evapotranspiration and crop coefficients. Crop Sci. 35:1685-1690.

Carter, G.A. 1993. Responses of Leaf Spectral Reflectance to Plant Stress. Am. J. Bot. 80:239-243.

Carter, G.A. and R.L. Miller. 1994. Early Detection of Plant Stress by Digital Imaging within Narrow Stress-Sensitive Wavebands. Remote Sens Environ. 50:295-302.

Everest, M.M. 1984. Agricultural Research Utilizing Infrared Thermometry. ASAE Paper No. 84-2076, American Society of Agricultural Engineers, St. Joseph, MI.

Everitt, J.H., D.E. Escobar, and M.A. Alaniz. 1987a. Drought-Stress Detection of Buffelgrass with Colour-Infrared Aerial Photography and Computer-Aided Image Processing. Photogrammetric Engineering & Remote Sensing 53:1255–1258.

Everitt, J.H., D.E. Escobar, and P.R. Nixon. 1987b. Near-Real-Time Video Systems for Rangeland Assessment. Remote Sensing of Environment 23:291-311.

Fenstermaker-Shaulis, L. K., A. Leskys, and D. A. Devitt. 1997. Utilization of remotely sensed data to map and evaluate turfgrass stress associated with drought. J. Turfgrass Manage. 2:65-81.

Fitz-Rodríguez, E., and C. Y. Choi. 2002. Monitoring turfgrass quality using multispectral radiometry. Trans. Proc. Am. Soc. Agric. Eng. 45:865-871.

Fu, J., J. Fry, and B. Huang. 2004. Minimum water requirements for four turfgrasses in the transition zone. HortScience. 39:1740-1744.

Green, D. E. II, L. L. Burpee, and K. L. Stevenson. 1998. Canopy reflectance as a measure of disease in tall fescue. Crop Sci. 38:1603-1613.

Guertal, E. A., and J. N. Shaw. 2004. Multispectral radiometer signatures for stress evaluation in compacted bermudagrass turf. HortScience. 39:403-407.

Hatfield, J.L. 1990. Measuring Plant Stress with an Infrared Thermometer. Hort Sci 25:1535-1538.

Hutto, K.C., R.L. King, J.D.Byrd, Jr., and D.R. Shaw, 2006. Implementation of Hyperspectral Radiometry in Irrigation Management of Creeping Bentgrass Putting Greens. Crop Sci. 46:1564-1569.

Idso, S.B., R.D. Jackson, P.J. Pinter, Jr., R.J. Reginato, and J.L. Hatfield. 1981. Normalizing the Stress-Degree-Day Parameter for Environmental Variability. Agricultural Meteorology 24:45-55.

Ikemura, Y., and B. Leinauer. 2006. Remote sensing technology detects turfgrass stress. TurfGrass Trends. 63-64, 66.

Ikemura, Y. 2004. Spectroscopy analysis of salinity stressed tall fescue. Annu. Meet. Abstr. p.1

Ikemura, Y., D.E. Karcher, and M.D. Richardson. 2002. Predicting nitrogen content of turfgrass using digital image analysis. Annu. Meet. Abstr. p.na

Jalali-Farahani, H. R., D. C. Slack, D. M. Kopec, and A. D. Matthias. 1993. Crop water stress index models for bermudagrass turf: A comparison. Agron. J. 85:1210-1217.

Jiang, Y., and R. N. Carrow. 2005. Assessment of narrow-band canopy spectral reflectance and turfgrass performance under drought stress. HortScience. 40:242-245.

Karcher, D.E. and M.D. Richardson. 2003. Quantifying Turfgrass Color Using Digital Image Analysis. Crop Sci. 43:943-951.

Karcher, D.E. and M.D. Richardson. 2005. Batch Analysis of Digital Images to Evaluate Turfgrassgrass Characteristics. Crop Sci. 45:1536-1539.

Kim, K. S., and J. B. Beard. 1988. Comparative Turfgrass Evapotranspiration Rates and Associated Plant Morphological Characteristics. Crop Sci. 28:328-331.

Kjelgren, R., L. Rupp, and D. Kjelgren. 2000. Water conservation in urban landscapes. HortSci 35:1037-1040.

Kruse, J. K., N. E. Christians, and M. H. Chaplin. 2005. Remote sensing of phosphorus deficiencies in Agrostis stolonifera. Int. Turfgrass Soc. Res. J. 10:923-928.

Lee, J. H., J. B. Unruh, and L. E. Trenholm. 2004. Multi-spectral reflectance of warm-season turfgrasses as influenced by deficit irrigation. Annu. Meet. Abstr. p. 1.

Park, D. M., J. L. Cisar, D. K. McDermitt, K. E. Williams, J. J. Haydu, and W. P. Miller. 2005. Using red and infrared reflectance and visual observation to monitor turf quality and water stress in surfactant-treated bermudagrass under reduced irrigation. Int. Turfgrass Soc. Res. J. 10:115-120.

Ploense, M. R. 2002. Physiological, Morphological, and Spectral Reflectance Characteristics of Kentucky Bluegrass, Texas Bluegrass, and their Hybrids in Response to Water Stress. Ph.D. Dissertation: Colorado State University

Qian, Y., and J. D. Fry. 1997. Water relations and drought tolerance of four turfgrasses. J. Am. Soc. Hortic. Sci. 122:129-133.

Raikes, C., and L. L. Burpee. 1998. Use of multispectral radiometry for assessment of rhizoctonia blight in creeping bentgrass. Phytopathology. 88:446-449.

Read, J. C., J. A. Reinhart, P. F. Colbaugh, and W. E. Knoop. 1999. Registration of 'Reveille' hybrid bluegrass. Crop Sci. 39:590.

Richardson, M. D., D. E. Karcher, and L. C. Purcell. 2001. Quantifying turfgrass cover using digital image analysis. Crop Sci. 41:1884-1888.

Rinehart, G. J., J. H. Baird, R. N. Calhoun, and O. Schabenberger. 2001. Remote sensing of brown patch and dollar spot on creeping bentgrass and annual bluegrass turf using visible and near-infrared spectroscopy. Int. Turfgrass Soc. Res. J. 9:705-709.

Rodgers, C. 2003. You've come a long way, bermuda: The new seeded bermudagrasses offer high-quality turf and the obvious convenience of seed. Golf Course Manage. 71:91-95.

SAS Institute Inc., SAS/STAT software: Changes and enhancements through release9.1, Cary, NC: SAS Institute inc., 2002.

Sinclair, T.R. and M.M. Ludlow. 1985. Who taught plants thermodynamics? The unfulfilled of plant water potential. Austral. J. Plant Ohysiol. 33:213-217.

Taiz, L. and E. Zeiger. 1998. Plant physiology. 2nd ed. Sinauer Assoc., Sunderland, Mass.

Taliaferro, C. M. 2004. Breeding and evaluation of turf bermudagrass varieties. Turfgrass Environ. Res. Summ. p.30.

Throssell, C. S., R. N. Carrow, and G. A. Milliken. 1987. Canopy Temperature Based Irrigation Scheduling Indices for Kentucky Bluegrass Turf. Crop Sci. 27:126-131.

Trenholm, L.E., R.N. Carrow, and R.R. Duncan. 1999a. Relationship of Multispectral Radiometry Data to Qualitative Data in Turfgrassgrass Research. Crop Sci. 39:763-769.

Trenholm, L. E., R. R. Duncan, and R. N. Carrow. 1999b. Wear tolerance, shoot performance, and spectral reflectance of seashore paspalum and bermudagrass. Crop Sci. 39:1147-1152.

TABLES AND FIGURES

Table 1-1. Analysis of variance, testing the main effects and interactions of experiments (Exp), drought treatments (Trt), species on relative water content (RWC), osmolality, visual rating, percent green cover, normalized hue (NHue), and NDVI.

Source	RWC	Osmolality	Visual rating	Percent green cover	NHue	NDVI
Exp	NS‡	NS	NS	NS	NS	NS
Trt	***	***	***	***	***	***
Exp*Trt	NS	NS	NS	NS	NS	NS
Species	***	***	**	***	***	**
Exp*Species	***	**	**	NS	NS	***
Trt*Species	*	**	*	*	**	*
Exp*Trt*Species	NS	NS	NS	NS	NS	NS

***, **, * Significant F test at the 0.001, 0.01, 0.05 level of probability, respectively

‡ NS Not significant at the 0.05 probability level

Table 1-2. Differences in relative water content (RWC), osmolality, visual rating, percent green cover, normalized hue (NHue), and NDVI between turfgrass species and drought treatments (percent of reference evapotranspiration) expressed as Fisher's Least Square Differences (LSD).

	Percent of reference evapotranspiration														
Species	100			80			60			40			20		
	□RWC (%)														
Hybrid bluegrass	85.5	a†	A‡	69.4	b	B	64.6	b	B	43.6	b	C	29.1	b	C
Bermudagrass	84.4	a	A	85.9	a	A	79.5	a	A	74.3	a	A	49.6	a	B
	Osmolality (mmol kg-1)														
Hybrid bluegrass	661	a	D	890	a	CD	950	a	C	1317	a	B	1927	a	A
Bermudagrass	551	a	C	645	a	BC	714	a	BC	847	b	B	1251	b	A
	Visual rating														
Hybrid bluegrass	8.8	a	A	6.5	a	B	5.9	a	B	3.5	b	C	2.0	a	C
Bermudagrass	7.8	a	A	7.6	a	A	7.4	a	A	6.3	a	A	2.6	a	B
	Percent green cover (%)														
Hybrid bluegrass	91.6	a	A	77.5	b	B	78.1	a	AB	48.9	b	C	34.6	b	D
Bermudagrass	94.9	a	A	94.5	a	A	90.5	a	A	86.6	a	A	57.0	a	B
	NHue														
Hybrid bluegrass	18.1	a	D	84.5	a	BC	50.8	a	CD	117.7	a	B	165.3	a	A
Bermudagrass	13.6	a	B	20.2	b	B	43.3	a	AB	38.1	b	AB	65.8	b	A
	NDVI														
Hybrid bluegrass	0.89	a	A	0.86	a	A	0.87	a	A	0.80	b	B	0.76	a	B
Bermudagrass	0.88	a	A	0.88	a	A	0.87	a	A	0.87	a	A	0.80	a	B

†a, b: Within each column and variable, means sharing a letter are not significantly different according to Fisher's LSD (α=0.05)

‡A, B, C, and D: Within each row, means sharing a letter are not significantly different according to Fisher's LSD (α=0.05)

Figure 1-1. Coefficient of determination for percent green cover, hue, and NDVI vs. relative water content (RWC), osmolality, and visual rating of hybrid bluegrass.

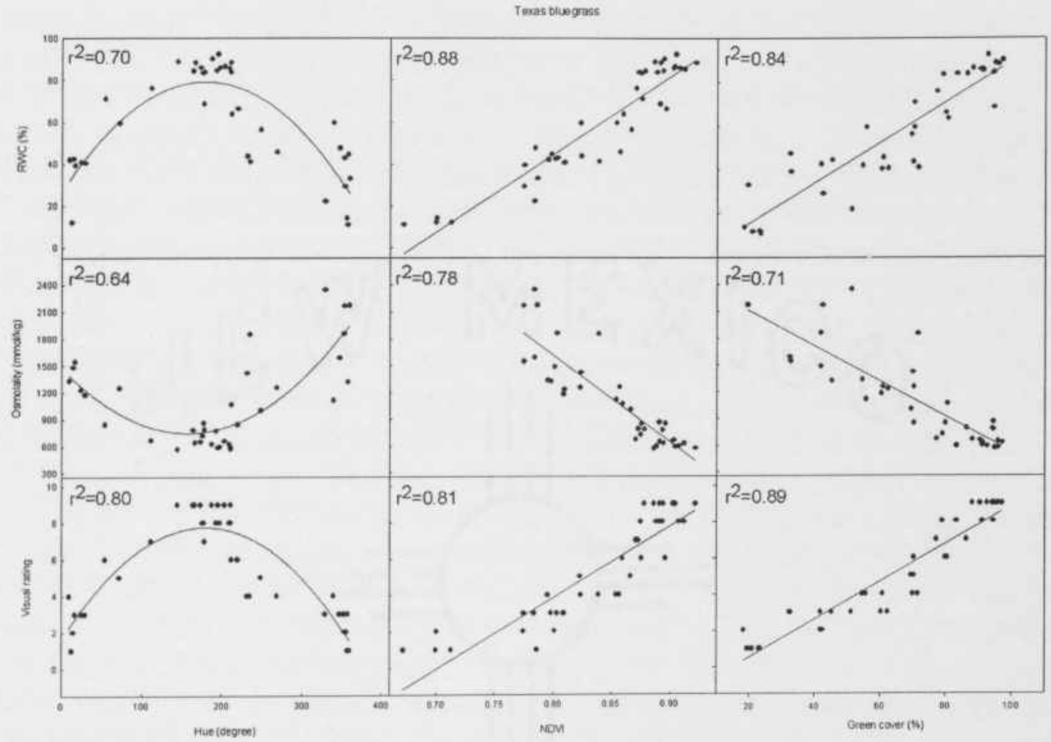

Figure 1-2. Coefficient of determination for percent green cover, hue, and NDVI vs. relative water content (RWC), osmolality, and visual rating of bermudagrass.

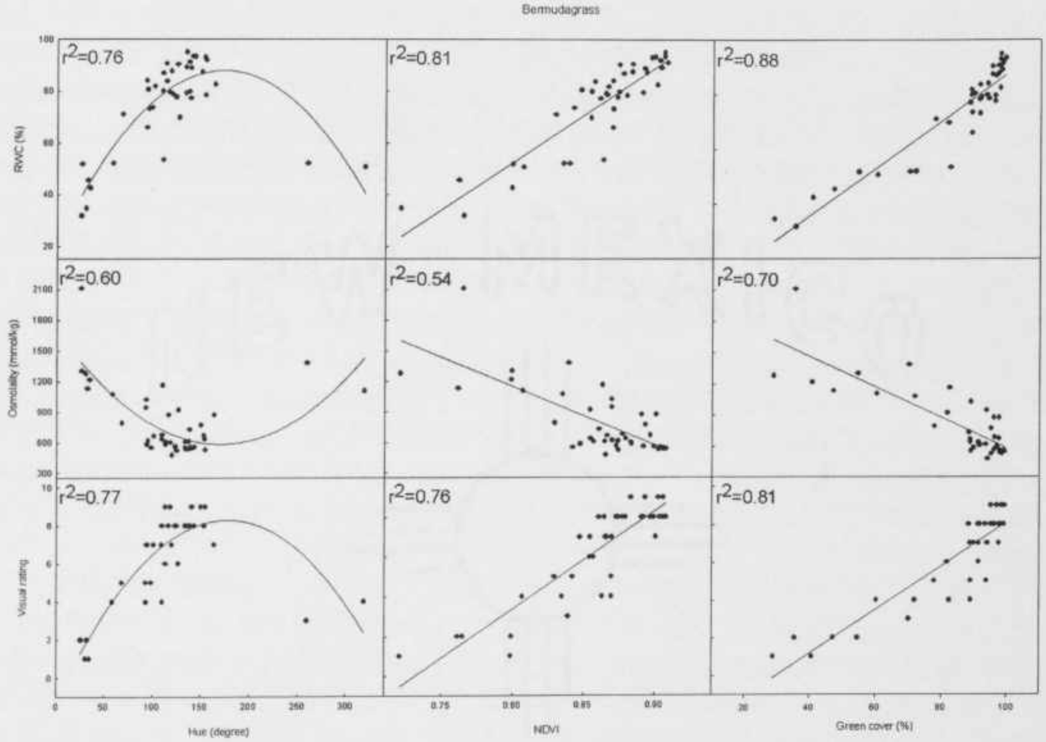

Figure 1-3. Variation in hue response for hybrid bluegrass and bermudagrass at drought treatments (percent of reference evapotanspiration.