ESTIMATION OF VISUAL QUALITY AND CANOPY CHARACTERISTICS OF TURFGRASS USING SPECTRAL REFLECTANCE AND DIGITAL IMAGERY

by

HYEONJU LEE

B.A., Sunchon National University, 2004

A THESIS

submitted in partial fulfillment of the requirements for the degree

MASTER OF SCIENCE

Department of Horticulture, Forestry and Recreation Resources
College of Agriculture

KANSAS STATE UNIVERSITY
Manhattan, Kansas

2008

Approved by:

Major Professor
Dale J. Bremer

Abstract

Radiometric methods may provide more objective and quantitative assessments of turf quality and density than visual ratings and may be useful in measuring green leaf area index (LAI), aboveground biomass, and chlorophyll concentration. This three-year study was conducted near Manhattan, KS to examine: 1) relationships between canopy reflectance and visual quality and density ratings in four cool-season grasses tall fescue (*Festuca arundinacea* Schreb.), Kentucky bluegrass (*Poa pratensis* L.) and two hybrid bluegrasses (HBG); 2) effects of species, mowing height, and irrigation deficit on relationships between visual quality and reflectance; 3) comparisons of visual quality with reflectance and digital images of individual plots; and 4) relationships of LAI, aboveground biomass, and chlorophyll concentration with canopy reflectance in the same four grasses and in perennial ryegrass (*Lolium perenne*), zoysiagrass (*Zoysia japonica* Stued.), and bermudagrass [*Cynodon dactylon (L.*) Pers.]. Reflectance was strongly correlated with visual ratings in the normalized difference vegetation index (NDVI, [935-661]/[935+661] nm, r = 0.88), the near infrared to red (NIR/R [935/661] nm, r = 0.83), Stress1 (706/760 nm, r=-0.84), and Stress2 (706/813 nm, r=-0.70) ratios and at wavelengths 613 (r=-0.74) and 661 nm (r = -0.80), but correlations varied among years at each wavelength and vegetation index. For density, highest correlations were in NDVI (r=0.86), R661 (r=-0.84), and Stress2 (r=-0.82). Regressions between reflectance and quality and density ratings indicated cultivar- and mowing height-specific models. Irrigation-deficit strongly affected reflectance in KBG and both HBG but not in TF, indicating greater sensitivity to drought of bluegrasses than TF. Digital images indicated strong correlations between percentage green cover and visual quality (r=0.89). However, wide ranges in visual quality were observed in plots with similar green cover or NDVI for reasons that are not apparent. Correlations of LAI, aboveground biomass, and chlorophyll concentration with reflectance were strong in some species at different wavelengths and ratios. Results indicated both potential and limitations in using spectral reflectance to estimate turfgrass canopy characteristics.

Table of Contents

List of Figures

List of Tables

Acknowledgements

The author gratefully acknowledges funding by The Scotts Company, Golf Course Superintendents Association of America (GCSAA), and Kansas Turfgrass Foundation. Thanks are extended to the Drs. Dale Bremer, Jack Fry, and Harold Trick for their assistance and encouragement. The assistance of Kemin Su, Alan Zuk, Qi Zhang, and Junghoon Lee for the field work and Jason Lewis for statistical consultation were greatly appreciated. The author acknowledges the assistance of Dr. Dale J. Bremer with planning of experiment, evaluation of data, and consultation of statistical analysis. Advice and encouragement of Dr. Steve Keeley were also appreciated.

CHAPTER 1 - General Introduction

Visual quality of turfgrass is evaluated by integrating the factors of color, canopy density, texture, and uniformity (Turgeon, 1991). The most traditional way to evaluate turfgrass quality is with a visual rating system (scale from 1 to 9), in which an observer rates the aesthetic appearance of turfgrass. Although this method is relatively quick, it tends to be subjective and non-reproducible and may vary widely among evaluators (Horst et al., 1984). Density is defined as an estimate of living shoots or tillers per unit area (NTEP, 2005) and may be estimated subjectively, separately from visual quality, on a scale from 1 to 9. Manually counting shoots in a specified area, however, requires significant time and labor. Therefore, alternative methods are needed that provide more objective, consistent, and time - saving assessments of turfgrass quality and density.

Multispectral radiometry (MSR) quickly measures light reflectance from plant canopies at a number of wavelengths and has been used to monitor appearance, growth status, disease, environmental stresses, and nitrogen deficiency (Raikes and Burpee, 1998; Trenholm et al., 1999; Trenholm et al., 2000; Fitz-Rodríguez and Choi, 2002; Jiang et al., 2003; Kruse et al., 2006) in turfgrasses.

Digital photography has also been used to detect stresses such as N deficiencies in *Zea mays* L. (Ewing and Horton 1999) and salinity and drought stress in bermudagrass (*Cynodon dactylon* [L.], ‘Princess 77’) and in a hybrid bluegrass (HBG; *Poa arachnifera* (Torr.) × *Poa pratensis* [L.], ‘Reveille’) (Ikemura and Leinauer, 2007). High correlations have been found between estimates of percentage green canopy cover and color quality in turfgrass (e.g., hue) using visual and digital image analysis methods in zoysiagrass (*Zoysia japonica* Stued.), creeping bentgrass (*Agrostis palustris* Huds.), and bermudagrasses (*Cynodon dactylon* [L.], Pers., 'Tifway') (r^2> 0.99)(Karcher and Richardson, 2003: Richardson et al., 2001).). Direct comparisons have not been made, however, among estimates of turfgrass quality using visual ratings, digital imagery, and spectral reflectance methods.

Green leaf area index (LAI) is an important indicator of photosynthetic and transpirational capacity in turfgrass canopies. Additionally, aboveground biomass is an indicator of ecosystem productivity and is strongly related to LAI (Loomis and Conner, 1992). Chlorophyll concentration is a vital factor that links leaf light reflectance at certain wavelengths and photosynthetic activity (Danks et al., 1983: Haboudane et al., 2002) and is an indicator of both nitrogen (N) concentration and visual quality in turfgrasses. Measuring LAI in particular, and to a lesser extent aboveground biomass and chlorophyll content in turfgass is tedious, time consuming, usually destructive, and is complicated by the small size of the canopies (Brede and Duich, 1980; Kopec et al., 1987). Therefore, faster methods of accurately estimating green LAI, aboveground biomass, and chlorophyll content in turfgrasses are needed.

Normalized difference vegetation index (NDVI) and the ratio of near infrared to red (NIR/R) are calculated from reflectance data and have been used to detect relationships with LAI and aboveground biomass in other crops. For example, Daughtry et al. (1992) determined that NDVI was highly correlated with LAI, and NIR/R was correlated with shoot biomass in corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.]. In a grassland in Italy, NDVI was strongly correlated with effective LAI ($r^2 = 0.74$) and dry biomass ($r^2 = 0.78$) (Vescovo et al., 2004).

Strong correlations also were found between chlorophyll concentration and canopy reflectance at 705 nm, and the ratios of reflectance at 750/705 nm in *Aescules hippocastanum* L. and *Acer platanoides* L. leaves, at 675/700 nm in soybean leaves (Gitelson and Merzlyak, 1994;

Chappelle et al., 1992). Kruse et al. (2006) found that NDVI, Stress1 (R706/R760), and Stress2 (R706/R813) ratios were highly correlated with N concentration in creeping bentgrass (*Agrostis stolonifera* L. 'Penncross'). However, few relationships between vegetation indices and LAI, biomass, or chlorophyll concentrations in turfgrasses have been reported.

The objectives of this study were to determine: 1) relationships of visual quality and density with canopy spectral reflectance among four cool-season turfgrasses under different irrigation regimes and mowing heights; 2) differences in turfgrass quality as estimated by methods of digital imagery, canopy reflectance, and visual ratings; and 3) relationships of LAI, aboveground biomass, and chlorophyll concentration with canopy spectral reflectance among different species and mowing height.

References

Brede, A. D., and J. M. Duich. 1980. "A mathematical estimate of the leaf area index of Kentucky bluegrass turf". *p*. 114. In Agronomy abstracts. ASA. Madison, WI.

Chappelle, E.W., M.S. Kim, and J.E. McMurtrey, III. 1992. "Ratio analysis of reflectance spectra (RARS): An algorithm for the re mote estimation of the concentrations of chlorophyll a, chlorophyll b, and carotenoids in soybean leaves". Remote Sensing of Environment 39: 239–247.

Danks, S.M., E.H. Evans, and P.A. Whittaker. 1983. *Structure function and assembly*. In Photosynthetic systems, NY. Wiley.

Daughtry, C.S.T., K.P. Gallo, N.S. Goward, S.D. Prince, and W.P. Kautas. 1992. "Spectral estimates of absorbed radiation and phytomass production in corn and soybean canopies". *Remote Sensing of Environment* 39:141-152.

Ewing, R.P., and R. Horton. 1999. "Quantitative color image analysis of agronomic images". *Agronomy Journal* 91:148-153.

Fitz-Rodriguez, E. and C.Y. Choi. 2002. "Monitoring turfgrass quality using multispectral Radiometry". *American Socienty of Agricultural Engineers ISSN* 45(3): 865-867.

Gitelson, A. and M.N. Merzlyak. 1994. "Spectral reflectance changes associated with autumn senescence of *Aesculus-Hippocastanum* (L.) and *Acer-Platanoides* (L.) leaves: spectral features and relation to chlorophyll estimation". *J. Plant Physiol*. 143:286-292.

Haboudane, D., J.R. Miller, N. Tremblay, P.J. Zarco-Tejada, and L. Dextraze. 2002. "Integrated narrow-band vegetation indices for prediction of crop chlorophyll content of application to precision agriculture". *Remote Sensing of Environment* 81 (2-3):416-426.

Horst, G.L., M.C. Engelke, and W. Meyers. 1984. “Assessment of visual evaluation techniques”.*Agronomy Journal* 76:619-622.

Ikemura Y. and B. Leinauer. 2007. “Remote sensing of stressed turfgrass”. Abstract of ASA international annual meetings.

Jiang, Y.W., R.N. Carrow and R.R. Duncan. 2003. “Correlation analysis procedures for canopy spectral reflectance data of seashore paspalum under traffic stress”. *HortScience* 128(3):343-348.

Karcher, D.E., and M.D. Richardson. 2003. “Quantifying turfgrass color using digital imaging analysis”. *Crop Science* 43:943-951.

Kopec D.M., J.M. Norman, R.C. Shearman, and M.P. Peterson. 1987. “An indirect method for estimating turfgrass leaf area index”. *Crop Science* 27:1298-1301.

Kruse, J.K., N.E. Christians, and M.H. Chaplin. 2006. “Remote sensing of nitrogen stress in creeping bentgrass”. *Agron. J. Remote Sensing* 98:1640-1645.

Loomis, R.S., D.J. Connor. 1992. *Crop ecology: productivity and management in agricultural systems*. Cambridge University Press.

Morris, Kevin N. 2005. “A guide to NTEP turfgrass ratings”. (http://www.ntep.org/reports/ratings.htm).

Raikes, C. and L.L. Burpee. 1998. “Use of multispectral radiometry for assessment of Rhizoctonia blight in creeping bentgrass”. *The American Phytopathological Society* 88:446-449.

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

Trenholm, L.E., R.N. Carrow, and R.R. Duncan.1999. “Relationship of multispectral radiometry data to qualitative data in turfgrass research”. *Crop Science* 39:763-769.

Trenholm, L.E., M.J. Schlossberg, G.. Lee, and W. Parks. 2000. “An evaluation of multi-spectral responses on selected turfgrass species”. *International Journal of Remote Sensing* 21(4):709-721.

Turgeon, A. 1991. *Turfgrass management*. Prentice-Hall, Englewood Cliffs, NJ.

Vescovo L., Zorer R., Belli C., Cescatti A., and Gianelle D. 2004. “Use of vegetation indexes to predict biomass and LAI of Trentino grasslands”. *Land Use Systems in Grassland Dominated Regions:* proceeding of the 20th general meeting of the European grassland federatin, Luzern, Switzerland.

CHAPTER 2 - Comparisons of Visual Ratings of Turfgrass Quality with Multispectral Radiometry and Digital Imagery

Abstract

Radiometric methods may provide more objective and quantitative assessments of turf quality than visual ratings. This study was conducted under a rainout shelter near Manhattan, KS for two years to examine: 1) relationships between canopy reflectance and visual quality ratings in four cool-season grasses tall fescue (*Festuca arundinacea* Schreb. 'Dynasty'), Kentucky bluegrass (*Poa pratensis* L. 'Apollo') and two hybrid bluegrasses (HBG ['Thermal Blue'] and ['Reveille']); 2) effects of species, mowing height, and irrigation deficit on relationships between visual quality and reflectance; and 3) comparisons of turfgrass quality rated visually, with reflectance and digital photographs of individual plots. Correlation analyses indicated significant relationships between reflectance and visual ratings at normalized difference vegetation index (NDVI, [935-661]/[935+661] nm, r = 0.88), the near infrared to red (NIR/R [935/661] nm, r = 0.83), and R661 (r = -0.80) in 2004 and 2005. Additionally, visual ratings were highly correlated with Stress1 (706/760 nm, r=-84), Stress2 (706/813 nm, r=-0.70) ratios, and R613 (r=-0.74) in 2005. Analysis of covariance revealed different regression models among species at each wavelength and index and within each mowing height in both years. Differences in reflectance between well-watered and irrigation-deficit plots were observed in KBG and both HBG but not in TF in 2005; TF was not as strongly affected by irrigation deficit as KBG and both HBG.

Digital images indicated strong correlations between percentage green cover and visual quality (r=0.89). In some instances, wide ranges in visual quality were observed in plots with similar percentage green cover or NDVI for reasons that are not apparent. Results indicated significant potential but also important limitations in using spectral reflectance as a method of estimating turfgrass quality.

Introduction

Visual quality of turfgrass is evaluated by integrating the factors of color, canopy density, texture, and uniformity (Turgeon, 1991). The most traditional way to evaluate turfgrass quality is with a visual rating system (scale from 1 to 9), in which an observer rates the aesthetic appearance of turfgrass. Although this method is relatively quick, it has several disadvantages including a tendency to be subjective and non-reproducible (Horst et al., 1984). In addition, visual ratings may vary among evaluators or even with the same evaluator over time. Therefore, alternative methods are needed that provide more objective and consistent assessments of turfgrass quality.

Multispectral radiometry (MSR) measures light reflectance from plant canopies at a number of wavelengths and has been used to monitor appearance, growth status, disease, environmental stresses, and nitrogen deficiency (Raikes and Burpee, 1998; Trenholm et al., 1999a; Trenholm et al., 2000; Fitz-Rodríguez and Choi, 2002; Jiang et al., 2003; Kruse et al., 2006). Trenholm (1999a), using MSR, reported significant correlations between light reflectance and visual quality, density, shoot tissue injury, and shoot growth on seashore paspalum (*Paspalum vaginatum* Swartz) ecotypes and hybrid bermudagrass cultivars (*Cynodon dactylon* L. x *C. transvaalensis* Burtt-Davy); spectral discrimination between wear-treated and untreated plots was also found. In another study (Fitz-Rodríguez and Choi, 2002), vegetation indices calculated from reflectance data (i.e., NDVI [normalized difference vegetation index], RVI [ratio vegetation index], and DVI [difference vegetation index]) were strongly correlated with visual quality ($r^2 = 0.73$, $r^2 = 0.71$, and $r^2 = 0.70$, respectively) under different irrigation regimes on bermudagrass. Differences in spectral reflectance were found between C_4 (bermudagrass) and C_3 (bentgrass) turfgrasses at all wavelengths (except 706 nm) and with NDVI and NIR/R (Trenholm et al., 2000). In the latter study, NDVI in particular was useful for detecting growth differences between species.

Although significant correlations between visual quality and canopy reflectance have been reported, there is sufficient unexplained variability in the relationships to warrant further, more refined examinations of the use of MSR in evaluating visual quality. Previous turfgrass studies have revealed r^2 values as high as 0.82. However, r^2 values in those studies, even when significant, were frequently <0.50 (Trenholm et al., 1999; Fitz-Rodríguez and Choi, 2002; Jiang and Carrow, 2005), which indicates >50% unexplained variability in the relationship between visual quality and reflectance values. Undoubtedly, some of this error can be attributed to the subjectivity of human evaluations of turfgrass appearance as described above (Horst et al., 1984). Measurements of canopy reflectance, however, are also subject resulting from differences in solar elevation and viewing angles, atmospheric conditions (e.g., clouds), soil background effects, and instrument calibration and operator error (Avery and Berlin, 1992; Chang et al., 2005; Jensen, 2007).

A number of turfgrass management practices, which may not necessarily affect visual quality, may nevertheless affect spectral reflectance and therefore, could confound attempts to evaluate turfgrass quality with MSR. For example, turfgrass species or cultivars with similar visual quality may have differences in reflectance values because of differences in leaf angles, canopy structure, wetness, or color among species (Turgeon, 1991; Loomis and Connor, 1992; Madeira et al., 2001; Jiang and Carrow, 2005, 2007). Mowing heights may affect leaf area index (LAI) and aboveground biomass, which may result in difference in vegetation indices (e.g., NDVI) using reflectance data, even when visual quality among mowing heights is similar (Fitz-Rodríguez and Choi, 2002). High correlations between NDVI and LAI (r^2 = 0.96) and between

NIR/R and shoot biomass was reported in corn (*Zea mays* L.)**,** soybean [*Glycine max* (L.) Merr.] (Daughtry et al., 1992), and wheat (*Triticum aestivum* L.) (Asrar et al., 1984).

As turfgrasses progressively become water-stressed under dry and hot conditions, their leaves lose turgor and roll or fold to reduce surface area and water loss from ET (Salisbury and Ross, 1969; Carrow et al., 2001; Park et al., 2007). Other researchers have reported that multispectral data detected differences in turfgrass performance and health under drought stress (Fenstermaker-Shaulis et al., 1997; Jiang and Carrow, 2005; Jiang et al., 2007).

Digital photography has also been used to detect stresses in a number of crops. For example, N deficiencies in *Zea mays* L. were detectable by analyzing differences in hue values among fertility treatments (Ewing and Horton 1999). Salinity and drought stress in bermudagrass (*Cynodon dactylon* [L.], 'Princess 77') and in a hybrid bluegrass (HBG; *Poa arachnifera* (Torr.) × *Poa pratensis* [L.], 'Reveille') were detected with digital image analysis (Ikemura and Leinauer, 2007). In the latter study, drought and salinity stresses were also detected with MSR, but only with digital image analysis could salinity stress be differentiated from drought stress. High correlations have been found between estimates of green canopy cover using visual and digital image methods in bermudagrasses (*Cynodon dactylon* [L.] Pers. x C. *transvaalensis*, 'Tifway') ($r^2 > 0.99$) (Richardson et al., 2001). Other research has demonstrated significant correlation between visual and digital image assessments of turf color among bentgrass cultivars (Thorogood et al., 1993; Landschoot and Mancino, 1997; Landschoot and Mancino, 2000).

Direct comparisons are needed of turfgrass quality estimates among plots using the methods of visual rating, digital imagery, and reflectance using MSR, with consideration given to effects of turfgrass management practices (e.g., mowing height, species differences). Therefore, the specific objectives of this research were to investigate: 1) the relationships between canopy spectral reflectance data and visual quality ratings in four cool-season turfgrasses; 2) effects of mowing height, species, and irrigation deficit on the relationship between visual quality and spectral reflectance; and 3) relationships between digital photographs of individual turfgrass plots with corresponding spectral reflectance and visual quality data.

Materials and Methods

Study site

This research was conducted under an automated rainout shelter (12 × 12 m) for two consecutive years from 26 July to 3 October (DOY 208 to 277) in 2004 and 20 June to 30 September (DOY 172 to 274) in 2005 at the Rocky Ford Turfgrass Research Center (39°13'53" N, 96°34'51" W) in Manhattan, KS. The rainout shelter allowed us to control water amount that was applied to each plot by person. A minimum of 1 mm of precipitation activated the shelter, which rested adjacent to the study area, to move on rails by an electronic drive system and completely cover the plots within two minutes. The shelter then returned to its resting position one hour after precipitation stopped. The soil at the site was a Chase silt loam (fine, smectitic, mesic Aquertic Argiudoll).

Turfgrass maintenance, treatments, and experimental design

Visual ratings, reflectance measurements, and digital images were collected from turfgrass plots in two concurrent experiments under the rainout shelter. The first was an investigation of the effects of mowing height and irrigation deficit on the performance of Kentucky bluegrass (KBG; *Poa pratensis* L. 'Apollo') and a HBG ('Thermal Blue'). Sixteen plots (1.36 × 1.76 m) of KBG and 16 plots of Thermal Blue were arranged in a randomized complete block design with whole plot treatment in a two (mowing height) by two (irrigation) factorial. Species was a split-plot factor. The mowing height factor (high mowing =7.62 cm and low mowing =3.81 cm) was randomized in a whole –plot strip to one of the two rows in each block. The irrigation factor (100% and 60% evapotranspiration [ET] replacement) was randomized to one of two columns in each block (Cochran and Cox, 1992). Therefore, in a block each of the four combinations of mowing height by irrigation treatments were applied to two plots and the two species (HBG and KBG) were randomly seeded in those two plots.

The second study was an investigation of irrigation deficit on the performance of four cool season turfgrasses that included eight plots each (1.36 × 1.76 m) of KBG, Thermal Blue, tall fescue (TF; *Festuca arundinacea* Schreb. 'Dynasty'), and a second HBG ('Reveille'). Two irrigation treatments include well watered (replacement of 100% of ET) and irrigation deficit (60% ET replacement) to impose water stress. Plots were mowed at 7.62 cm and were arranged in a randomized complete block design with four replications

Turfgrasses in both study were mowed twice weekly with a walk-behind rotary mower. Water was applied twice a week with a metered hand wand (Model 03N31, GPI, Inc., Wichita, KS) to accurately measure irrigation applications. All plots were bordered by 10-cm deep metal edging to prevent lateral water movement across plots after irrigation. Evapotranspiration was calculated with the Penman-Monteith equation (FAO, 1998) using data from an on-site weather station located within 50 m of study site.

Measurements of visual quality, spectral reflectance, and canopy image

Quality of each plot was rated visually on a scale from 1 to 9 (1=brown and dead turf, 9=optimum turf, and 6= minimally acceptable turf for use in home lawns) by the same person in both years. Spectral reflectance of the canopy was measured in eight wavebands from 507 to 935 nm with a hand-held multispectral radiometer (model MSR16, CropScan, Inc. Rochester, MN). Two reflectance measurements (0.5 m diam. Each according to manual) were collected near the center of each plot with the sensor at 1 m above ground level and the two measurements were then averaged. To reduce variation, canopy reflectance was taken between 1200 and 1430 h central standard time (CST) with no cloud cover. All turfgrass plots were fully vegetated and thus, soil background effects were negligible.

Turfgrass quality was compared with reflectance at each wavelength as well as with vegetation and stress indices (Trenholm et al., 1999). Four vegetation and stress indices were evaluated: 1) Normalized difference vegetation index (NDVI) computed as R935-R661/R935+R661; 2) near infrared to red (NIR/R) computed as R935/R661; 3) Stress1 computed as R706/R760; 4) Stress2 computed as R706/R813. In 2004, an intermittently loose cable between the sensor and datalogger caused significant error in the 706 waveband. Because W706 was used in calculations of Stress1 and Stress2, these data (i.e., R706, Stress1, and Stress2) were omitted from analyses for 2004.

Green cover images were taken by the First Growth Digital Canopy Camera (Version 1.1 Decagon Devices, Inc., Pullman, WA). Data from all plots were collected on seven measurement days (DOY 193, 210, 216, 224, 231, 245, and 274), concurrent with MSR measurements. All measurements were collected from 1 m above ground level, which was the same height as the MSR.

Statistical analysis

Data were analyzed with the regression and correlation procedures of SAS (SAS Institute Inc., Cary, NC) for comparisons of visual quality versus reflectance and visual quality versus percentage green color at each wavelength, vegetation indices, and stress indices. Data analyses included pooling all data among plots and days, although separately for each year. Data were also evaluated to determine the effects of 1) turfgrass height; 2) turfgrass species; 3) day of year; and 4) solar elevation angle on relationships between visual quality and reflectance. The GLM procedure was used to analyze the effects of irrigation deficit as the study progressed and to conduct on analysis of covariance test for equal slopes and intercepts in regression models among species.

Results and Discussion

Relationship between visual quality ratings and canopy spectral reflectance

When reflectance data from all turfgrass plots were pooled, significant correlations ($p < 0.05$) were found between turf quality and reflectance at all wavelengths and vegetation and stress ratios during both years of the study (Table 2.1). In 2004, R661, R760, R813, R935, NDVI and NIR/R were most highly correlated with visual ratings with correlation coefficients ranging from 0.65 to 0.75. In 2005, correlations were generally stronger than in 2004, with correlations as high as r=0.88. Similar to 2004, correlations with visual quality in 2005 were strong at R661, R760, NDVI, and NIR/R. Correlations were also high in 2005 at Stress1 and Stress2, which were not available in 2004, and at R613. Reflectance at 661 nm was strongly correlated with visual quality in both 2004 and 2005. 661 nm is the band that absorbs light for photosynthetic activity, which affects reflectance. The generally stronger correlations in 2005 were likely caused by drought and heat stress, which were more severe than in 2004 (Su et al., 2008). Greater stress in 2005 generally expanded differences in quality and provided a broader base for comparing qualitative with quantitative data (Fig. 2.1).

Interestingly, correlations with visual quality in 2005 were the weakest in R813 (r=0.38) and R935 (r=0.40), which was contrary to strong correlations at those wavelengths in 2004. Reflectance in the NIR range (e.g., R813 and R935) is caused primarily by intracellular light scattering from cellular air-water interfaces within mesophyll cells (Salisbury and Ross, 1969; Gupta and Woolley, 1971; Taiz and Zeiger, 2002). Therefore, as the amount of water increases in grass leaves, reflectance in the NIR also increases. Under the hotter and drier conditions of 2005 than 2004 (Su et al., 2008), water content in leaves may have decreased before visible reductions in quality were evident, which may explain the weaker relationship between reflectance in the NIR and visible quality.

Relationships with visual quality were linear at R661, NDVI, Stress1, and Stress2, and quadratic at NIR/R (Fig. 2.2). Other researchers have reported high correlations between visual ratings and reflectance at 661 and 813 nm, as well as the ratios NDVI, NIR/R, Stress1, and Stress2 (r ranging from 0.77 to 0.80) on seven seashore paspalum (*Paspalum vaginatum* Swartz) ecotypes and three hybrid bermudagrass cultivars (*Cynodon dactylon* L. Pers. x *C. transvaalensis* Burtt-Dacy, 'Midiron') (Trenholm et al., 1999a). Additionally, Fitz-Rodríguez (2002) reported that NDVI and reflectance at 710, 760, and 810 nm were strongly correlated with visual quality for a hybrid bermudagrass cultivar (*Cynodon dactylon* L. Pers. x *C. transvaalensis* Burtt-Dacy, 'Midiron'). In our research, correlations between visual quality and NDVI were consistently stronger between visual quality and NDVI across years than between visual quality and other wavelengths and vegetation ratios (Table 2.1).

Mowing height effects on spectral reflectance

Despite higher correlations between visual quality and NDVI than visual quality and other indices and wavelengths, data revealed distinct mowing effects that confounded the relationship between NDVI and visual quality in 2005 (Fig. 2.3). For example, early in 2005 (DOY 172-224), NDVI values were consistently greater in high- than in low-mown turfgrasses even though visual ratings were similar (Fig. 2.3A). Higher NDVI in high-mown plots in 2004 and early in 2005 may indicate greater green biomass and LAI than in low-mown plots (Asrar et al., 1984; Gallo et al., 1985; Daughtry et al., 1992; and Goward and Huemmrich, 1992). Regression analyses for the early season in 2005 indicated separate relationships between mowing heights of visual quality with reflectance; differences between mowing heights were observed at all wavelengths and indices (including NDVI) (data not shown). Clearly, this demonstrates that turfgrasses should be at similar heights when using MSR to evaluate turf quality.

Interestingly, differences in NDVI diminished between high- and low- mown plots later in 2005 (Fig. 2.3A). Low mowing may stimulate tillering in bluegrasses, which may cause green LAI and biomass to increase (Kraft and Keeley, 2005). In our study, increased tillering in response to mowing may have caused green LAI and biomass to increase in low-mown plots as the season progressed. Consequently, increased tillering may have caused NDVI to increase in low-mown plots and thus, have diminished differences in NDVI between high- and low-mown plots. Further research is needed to determine relationships between spectral reflectance and green LAI and biomass in turfgrass.

In 2004, visual quality and NDVI were both consistently lower in low- than in high-mown plots throughout the study (Fig. 2.3B). The differences in quality and NDVI between mowing heights may be partially explained by a scalping effect in low-mown plots in 2004. The scalping, which occurred in late June, exposed the leaf sheaths and resulted in a lighter color and hence, lower visual quality in low- than high-mown plots, even long after the mowing height was adjusted upward in low mown plots (i.e., from 2.54 cm to 3.81 cm, on DOY 194, 2004, before the study began).

Early in 2004, NDVI declined with visual quality from DOY 208 to 247, and NDVI was strongly correlated with visual quality at both mowing heights (r=85; Fig. 2.3B). As in early 2005 (Fig. 2.3A), regression analyses of visual quality versus reflectance for early 2004 indicated discriminate relationships between low-mown and high-mown treatments for NDVI as well as for wavelengths 507 through 661 nm (data not shown). Late in 2004 (i.e., from DOY 254 to 277), however, NDVI increased from 0.65 to 0.80 in low-mown plots and from 0.73 to 0.87 in high mown plots but visual quality remained relatively steady. A similar trend was observed in 2005 between DOY 224 and 245, when NDVI increased from 0.61 to 0.7, while visual quality remained at about 5. These patterns indicate that while canopy reflectance is demonstrably related to visual quality, there are significant deviations from these relationships that are poorly understood.

Species effects on reflectance

Within the high mowing treatment, analyses of covariance revealed discriminate regression models among grass species at each wavelength and index during both years (data not shown). This is similar to the results of Jiang and Carrow (2005), who also reported differences in the relationship between turf quality and reflectance among species of warm-season turfgrasses. Those authors attributed differences in spectral reflectance among species to varying smoothness and shininess of leaf surfaces.

In the current study, relationships were consistently strongest between visual quality and NDVI and visual quality and NIR/R among wavelengths and indices and therefore, relationships between visual quality with NDVI and NIR/R are presented in detail among species (Fig. 2.4 and 2.5). Regression models between visual quality and NDVI were linear in both years, but separate models were evident among species in both years (Figs. 2.4A and 2.4B). The relationships between visual quality and NIR/R were quadratic, and differences in regression models were also observed among species in both years (Figs. 2.5A and 2.5B). In general, models were weaker for TF, probably because TF was less affected by the irrigation-deficit treatment; lesser effects of irrigation deficit on visual quality and reflectance in TF resulted in narrower ranges of data for comparing qualitative with quantitative data (Trenholm et al., 1999a).

Visual quality was significantly correlated with reflectance within each of the four turfgrasses at the high mowing height (Table 2.2). Furthermore, in 2005, correlations between reflectance and turf quality were significant at each wavelength and index in each turfgrass with the exception of at 813 nm in TF. In 2004, correlations were weaker, but remained significant among grasses at all wavelengths except at 507 and 613 in KBG, 559 in TB and R, and at 760, 813, and 935 in TF. In general, correlations between quality and reflectance were strongest for the three bluegrasses. In 2005, peak correlations for the bluegrasses were in NDVI (r = 0.85 to 0.91), NIR/R (r = 0.81 to 0.9), and Stress1 (r = -0.82 to -0.89), while peak correlations in 2004 were at 760 nm (r = 0.69 to 0.75) and 935 nm (r = 0.67 to 0.75).

At the low mowing height, which included only KBG and TB, discriminate regression models were also found between turfgrasses but differences were not consistent across wavelengths and indices during the two years of the study (data not shown). For example, in 2004, separate models between KBG and TB were found at 507, 613, and 661 nm and in the NDVI and NIR/R indices. In 2005, however, no differences in regression models were found between species at those wavelengths or indices. In 2005, significant differences were found between KBG and TB at 760, 813, and 935 nm and in the Stress1 index.

Within each turfgrass at the low mowing height, significant correlations between reflectance and visual quality were found at all wavelengths and indices during both years with the exceptions in 2004 at 559 nm in KBG and at 507, 559, and 613 nm in TB (Table 2.3). Correlations were consistently high at 760 nm in both KBG and TB during both years. Otherwise, correlations at other wavelengths and in the indices varied by year but were similar between

KBG and TB. For example, highest correlations (in addition to at 760 nm) in both grasses were at 813, and 935 nm in 2004, but were at 613 and 661 nm and in the NDVI, NIR/R, and Stress1 indices in 2005. In 2004, correlations were also high in KBG at 661 nm and in the NDVI index.

In general, correlations between visual quality and reflectance data were stronger in KBG and Thermal Blue and weaker in Reveille and TF when separated rather that pooling data among species (Tables 2.2 and 2.3). This further indicates that different species or cultivars may require separate models in estimating visual quality from reflectance data. Therefore, it is likely less effective or even inappropriate to estimate turfgrass quality with reflectance data using models derived from pooled data among species.

Effects of irrigation deficit on reflectance

Irrigation-deficit effects were not evident among species on DOY 179, 2005 (Table 2. 4), which was two days after irrigation-deficit treatments began. By DOY 196, however, irrigation deficit significantly affected visual quality and reflectance data at all but two wavelengths in Kentucky bluegrass. In Thermal Blue, irrigation-deficit effects were also evident on visual quality by DOY 196, but the only reflectance data affected were NDVI and NIR/R. By DOY 216, however, all four indices and all but two wavelengths revealed irrigation-deficit effects in Thermal Blue; this indicated an increasing severity of drought symptoms. In Reveille, no effects of irrigation deficit were evident until DOY 216, when visual quality, all indices, and all but two wavelengths revealed significant drought effects. No irrigation deficit effects were evident in TF on any dates with the exception of in visual quality on DOY 216. Tall fescue was never significantly affected by irrigation deficit, presumably because of its deep rooting system combined with deep soils at this site (Bremer et al., 2006; Su et al., 2008)).

Reveille, and to a lesser extent Thermal Blue (i.e., both HBG), were apparently less sensitive to irrigation deficit than KBG as illustrated by the time between initiation and detection of the effects of irrigation deficit treatments (Table 2.4). For example, by DOY 196, visual quality and reflectance data at all but two wavelengths in KBG were affected by irrigation deficit, while Thermal Blue was affected only in visual quality and NDVI and NIR/R and Reveille was not affected until DOY 216. Our observations of visual quality are generally in agreement with others who reported greater drought resistance in Reveille than in KBG, but negligible differences in drought resistance between Thermal Blue and KBG (Read et al., 1999; Supplick-Ploense and Qian, 2005; Bremer et al., 2006; Su, 2007; Su et al., 2007, 2008). Research with irrigated and non-irrigated bermudagrasses also indicated that subtle treatment differences could be detected by NIR/R (Park et al., 2007)

It is not clear why Stress1 and Stress2 indices and reflectance at all but two wavelengths detected irrigation-deficit effects in KBG but not in Thermal Blue despite visible symptoms in quality in both cultivars on DOY 196 (Table 2.4). Similarly, in TF, visual quality but not reflectance data was affected by irrigation deficit on DOY 216. These results indicate that irrigation-deficit symptoms were detected with the human eye before detection with canopy reflectance or may not have detected at all. Reflectance at 613 and 661 nm are strongly affected by photosynthetic activity and thus, are generally sensitive to stress symptoms. Reflectance at those wavelengths, however, was not affected in Thermal Blue on DOY 196 or in TF on DOY 216 even though irrigation-deficit symptoms were visible. One possibility is that human bias may have influenced estimates of visual quality between well-watered and irrigation-deficit plots.

In 2004, overall, differences in visual quality and reflectance at individual wavelengths and vegetation indices between well-watered and water-deficit plots were generally not significant among species (data not shown). Air temperatures were cooler in 2004 than in 2005, in part because the study was conducted later in 2004, which minimized the effects of irrigation deficit (Su et al., 2008).

Digital images of plots compared with NDVI and visual quality

Strong correlations have been reported between visual and digital image assessments of turf color and between visual quality and NDVI (Thorogood et al., 1993; Landschoot and Mancino, 1997; Trenholm, 1999a; Landschoot and Mancino, 2000; Karcher and Richardson, 2003). Digital images of plots in 2005, however, clearly illustrated disparities in relationships among visual appearances and percentage of green cover among plots with similar NDVI (Fig. 2.6). For example, three plots of a HBG (Thermal Blue) with similar NDVI (i.e., 0.61 to 0.63) had subjective quality ratings that ranged from 4 to 6 and percentage green cover that ranged from 31 to 61% (Fig. 2.6A, 2.6B, and 2.6C). Similarly, photos of other HBG (Thermal Blue) plots with similar NDVI (i.e., 0.70 to 0.71) revealed ranges of visual quality from 5 to 7 and green cover from 55 to 88% (Fig. 2.6D, 2.6E, and 2.6F). Images of TF plots with comparable NDVI (i.e., 0.79 to 0.80) also exhibited a wide range in visual quality (i.e., from 5 to 8) and green cover from (i.e., from 56 to 95%) (Fig. 2.6G, 2.6H, and 2.6I).

Percentage green cover, estimated digitally, was strongly correlated to visual quality (r^2 = 0.79) (Fig. 2.7). Nevertheless, there were also disparities in the relationships between visual quality and percentage green cover. For example, two plots of a HBG (Thermal Blue) with a visual quality of five exhibited green cover of 41% and 55% (Figs. 2.6B and 2.6D). Similarly, two other plots of Thermal Blue with visual qualities of six had green cover of 61% and 77% (Figs. 2.6C and 2.6E). From Figure 2.7, it is evident that for each percentage green value on the abscissa, values of visual quality differed by two to four. For example, at 20% green cover, visual quality ranged from 4 to 7. The subjective nature of visual quality ratings undoubtedly contributed to variability in these relationships. Other variables that affect visual quality, however, may not have been detected by estimates of percentage green cover from digital images, such as canopy density, texture, uniformity, and hue of green.

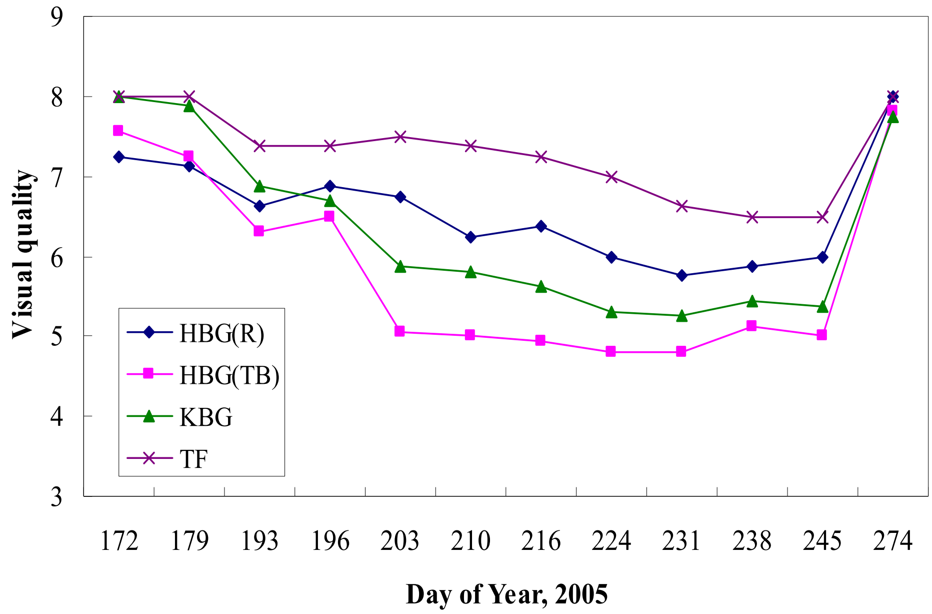
Conclusions

This study revealed strong correlations of turfgrass quality with spectral reflectance and percentage green cover from digital images (r = 0.65 to 0.88). Furthermore, data indicated that separate models are required among turfgrass species when estimating turfgrass quality with reflectance and that mowing height confounds relationships between visual quality and spectral reflectance. In a number of instances, however, significant disparities were observed among estimates of quality obtained visually, from reflectance using MSR, and from percentage green cover using digital imagery. For example, significant changes in NDVI were sometimes observed despite negligible, concurrent changes in visual quality, and vice versa. Similarly, there were instances when visual quality varied substantially despite similar percentage green cover, and vice versa.

Results from this study illustrate the complexity in estimating turfgrass quality, whether subjectively or objectively. Each of the variables that may affect visual quality (e.g., canopy uniformity, texture, density, and color) may affect spectral reflectance differently, which in turn may confound estimates of turfgrass quality using reflectance data. Additional confounding effects of canopy architecture, soil background, solar elevation angles, atmospheric conditions, operator error, and turfgrass cultural practices (e.g., mowing height, turfgrass species) may exacerbate attempts to estimate visual quality with spectral reflectance data. Because of the subjectivity and inherent error in human evaluations of turfgrass visual quality, reflectance measurements may be useful in providing more objective and accurate estimation of visual quality. Nevertheless, it may not be appropriate to totally discredit evaluations of turfgrass quality with the human eye because ultimately that is how turfgrass will be judged and evaluated, particularly for aesthetic purposes. In this study, we found important limitations in using reflectance data to estimate visual quality. Therefore, the replacement of traditional visual assessments of turfgrass with reflectance measurements will require circumspection.

Figures and Tables

Figure 2.1 Visual quality among the four turfgrasses in the rainout shelter during the growing season in 2005 and 2004. HBG (R), HBG (TB), KBG, and TF indicate Reveille, Thermal Blue, Kentucky bluegrass, and tall fescue, respectively.



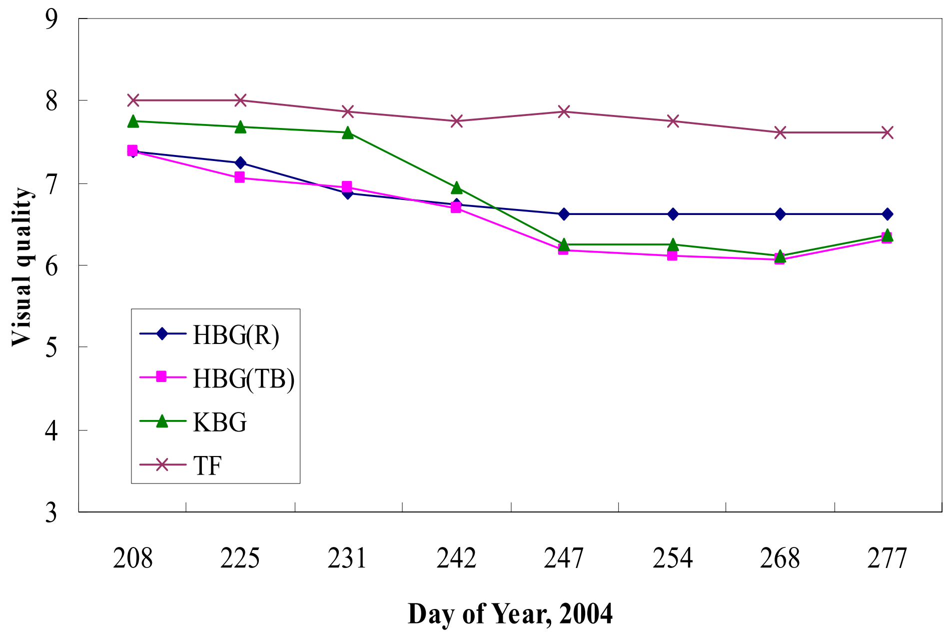


Figure 2.2 Relationship between visual quality ratings and reflectance at 661 nm (A) the normalized difference vegetation index (NDVI) (B), near infrared to red (NIR/R) (C), Stress1 (D) and Stress2 (E) in 2005. Data were regressed across the entire study period for four cool-season turfgrasses from all mowing height and water deficit treatments.

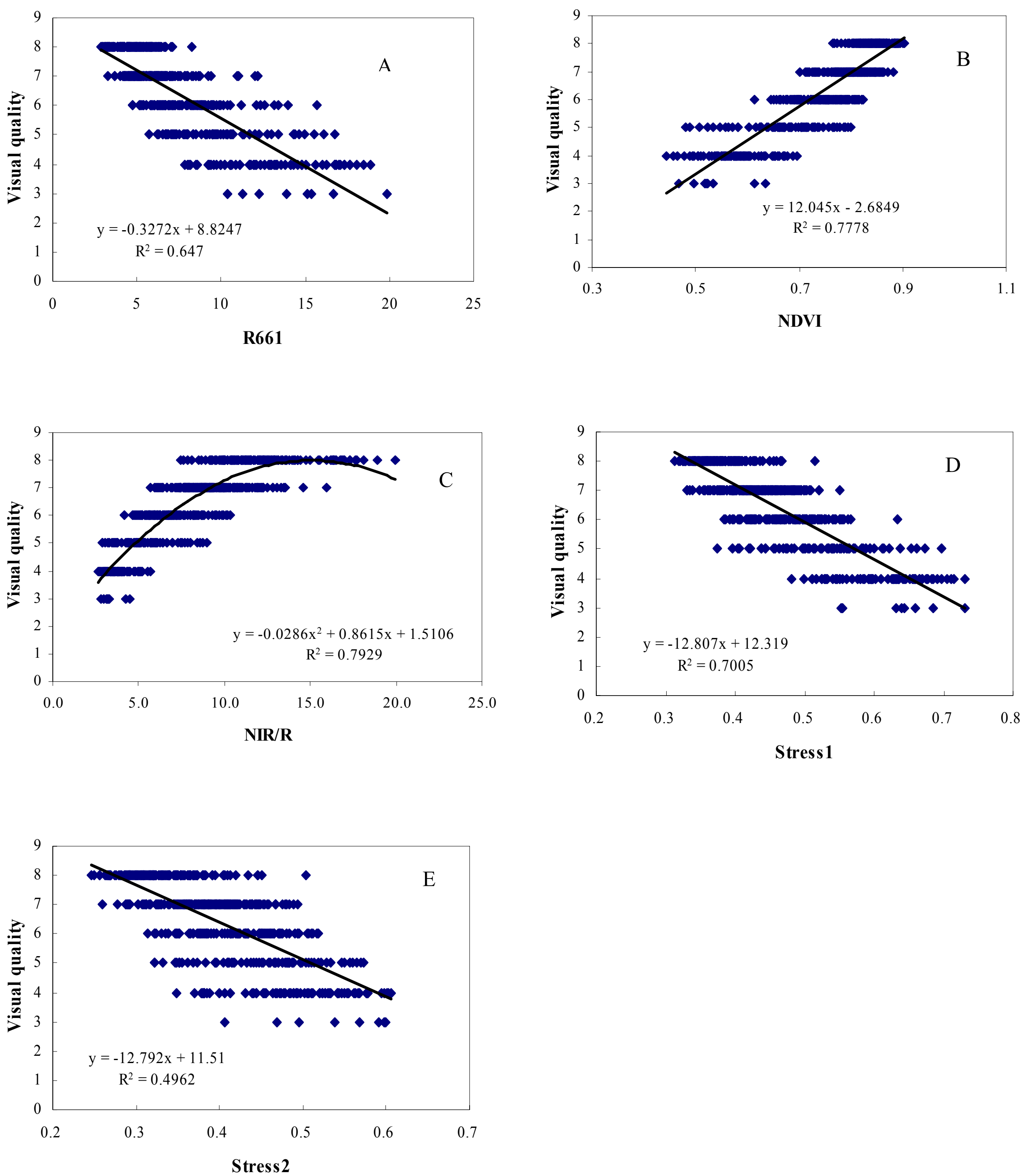
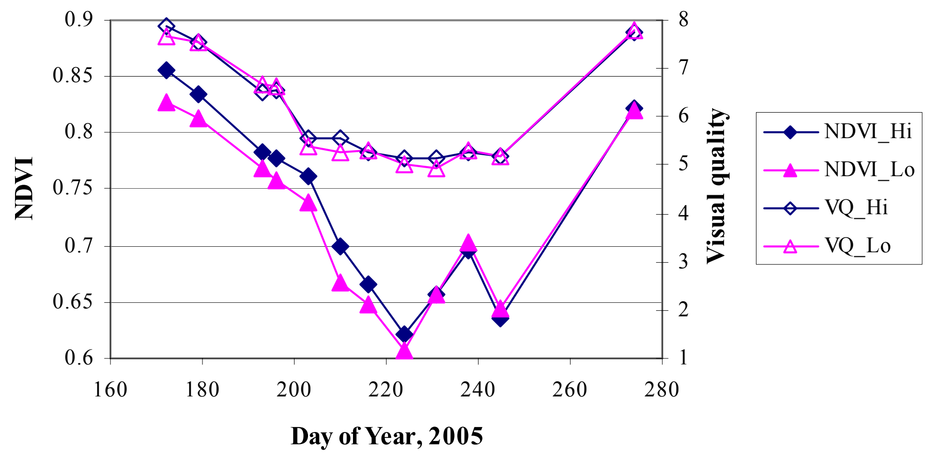


Figure 2.3 Normalized difference vegetation index (NDVI) and visual quality ratings (VQ) at high and low mowing heights in KBG and Thermal Blue during the study periods in 2005 (A) and 2004 (B).

A



B

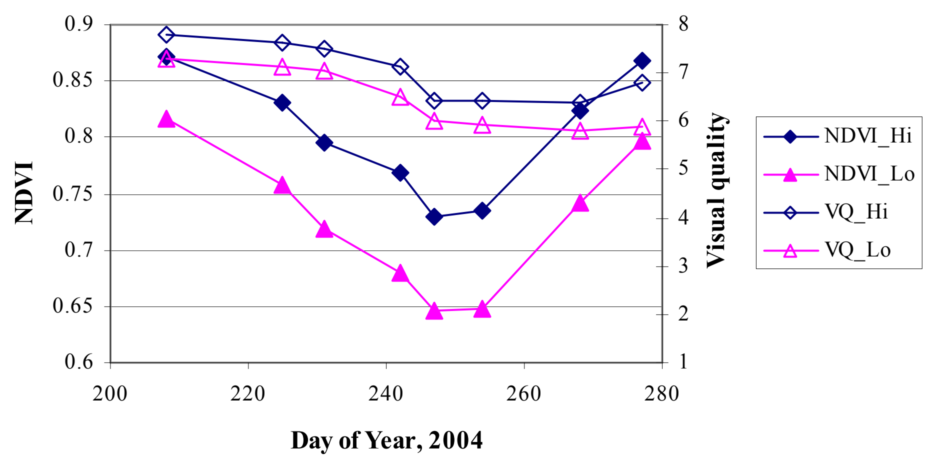
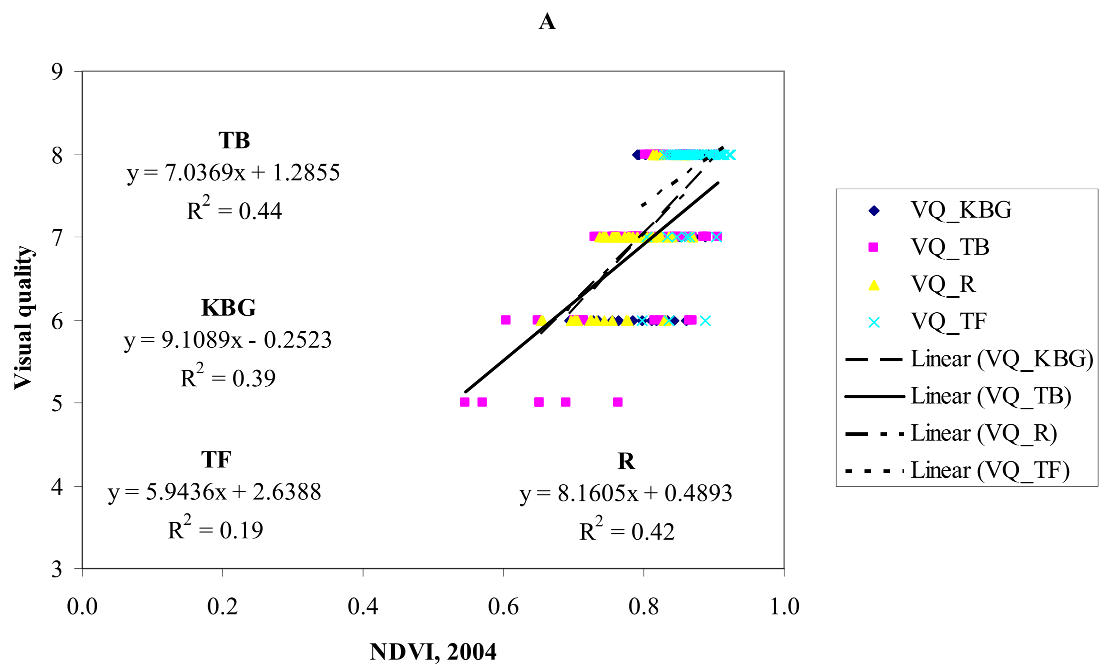


Figure 2.4 Regression models of individual species between visual quality (VQ) and normalized difference vegetation index (NDVI) at the high mowing height in 2004 (A) and 2005 (B).



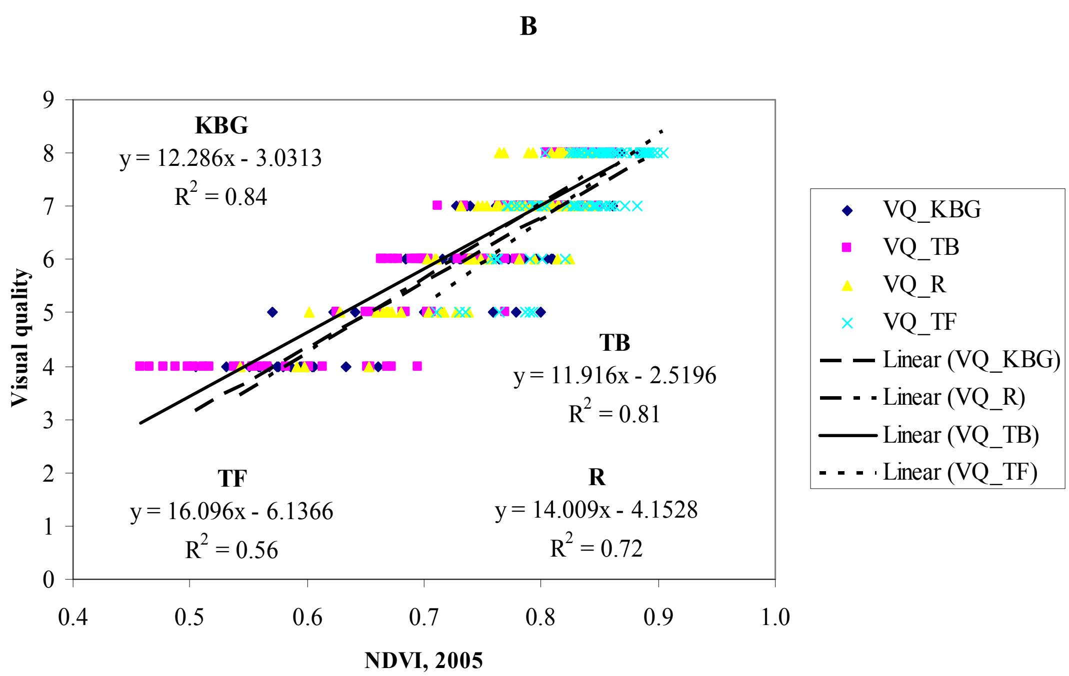
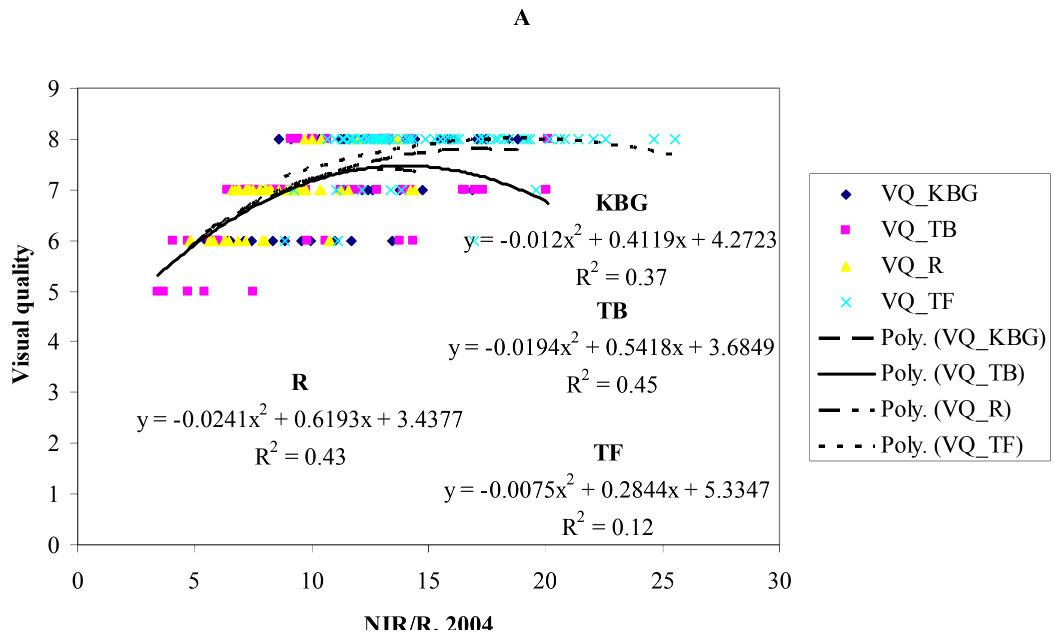


Figure 2.5 Regression models of individual species between visual quality (Q) and near infrared to red (NIR/R) at the high mowing height in 2004 (A) and 2005 (B).



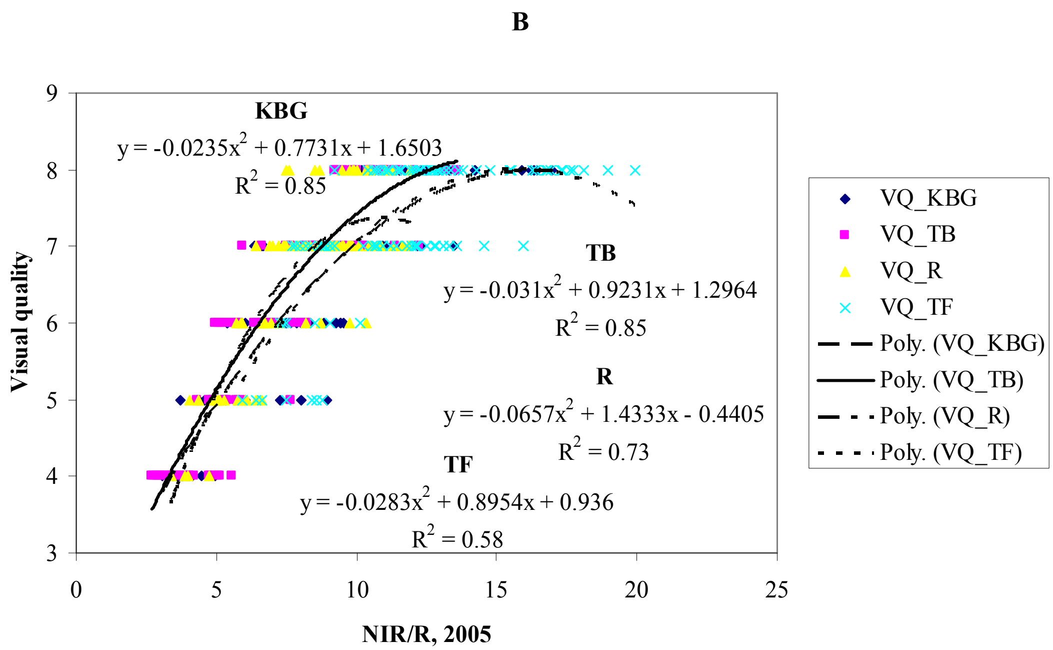


Figure 2.6 Digital images of individual turfgrass plots taken in 2005. Text on each image represents (left to right); species (HBG = hybrid bluegrass, TB = Thermal Blue, and TF = tall fescue); visual quality ratings; normalized difference vegetation index; day of year; and percentage green cover.

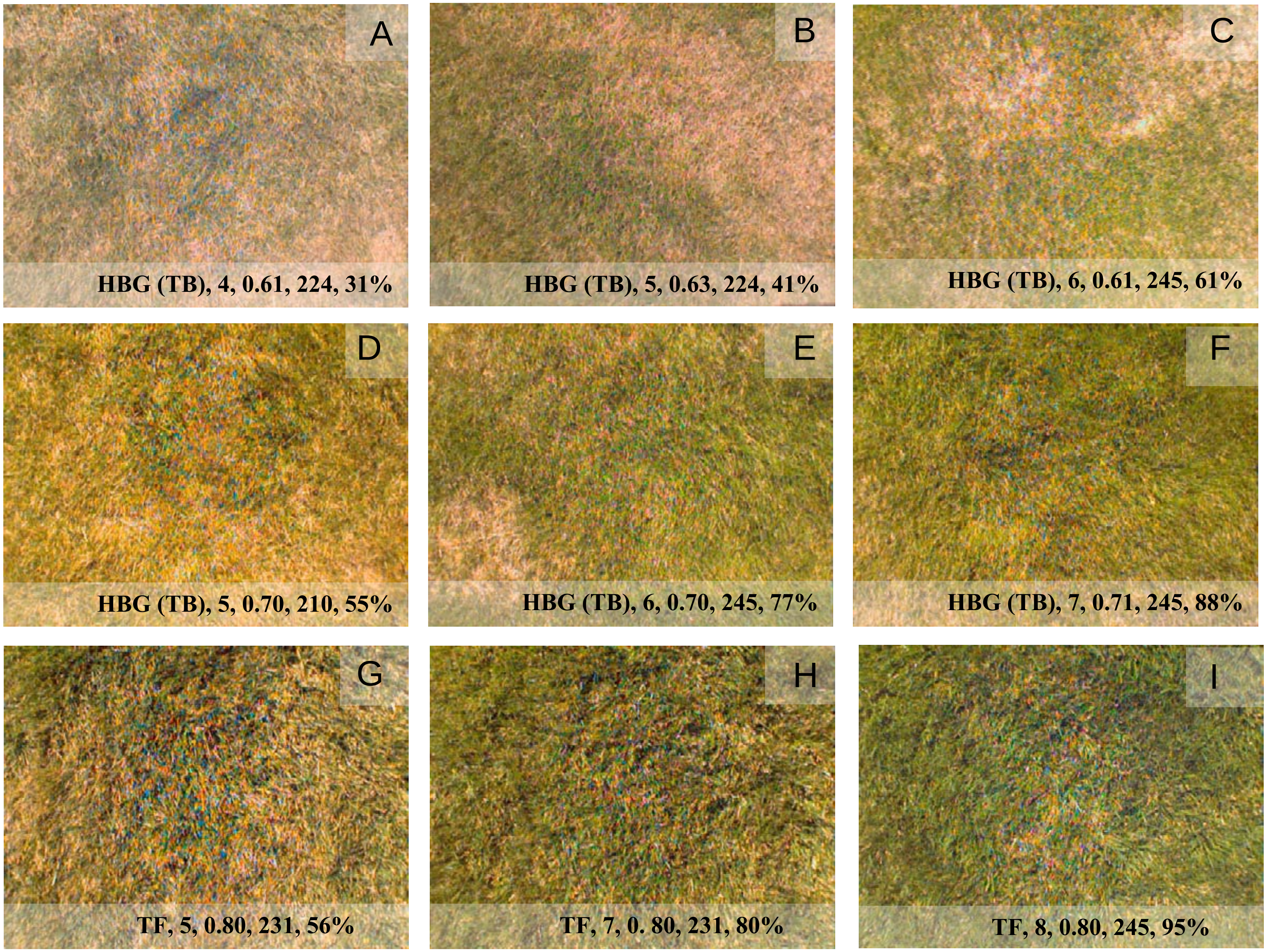

A
HBG (TB), 4, 0.61, 224, 31%
B
HBG (TB), 5, 0.63, 224, 41%
C
HBG (TB), 6, 0.61, 245, 61%
D
HBG (TB), 5, 0.70, 210, 55%
E
HBG (TB), 6, 0.70, 245, 77%
F
HBG (TB), 7, 0.71, 245, 88%
G
TF, 5, 0.80, 231, 56%
H
TF, 7, 0. 80, 231, 80%
I
TF, 8, 0.80, 245, 95%

Figure 2.7 Relationship between percentage green cover as estimated from digital image analysis and visual quality ratings. All turfgrass species and mowing height and water deficit treatments were pooled in this analysis.

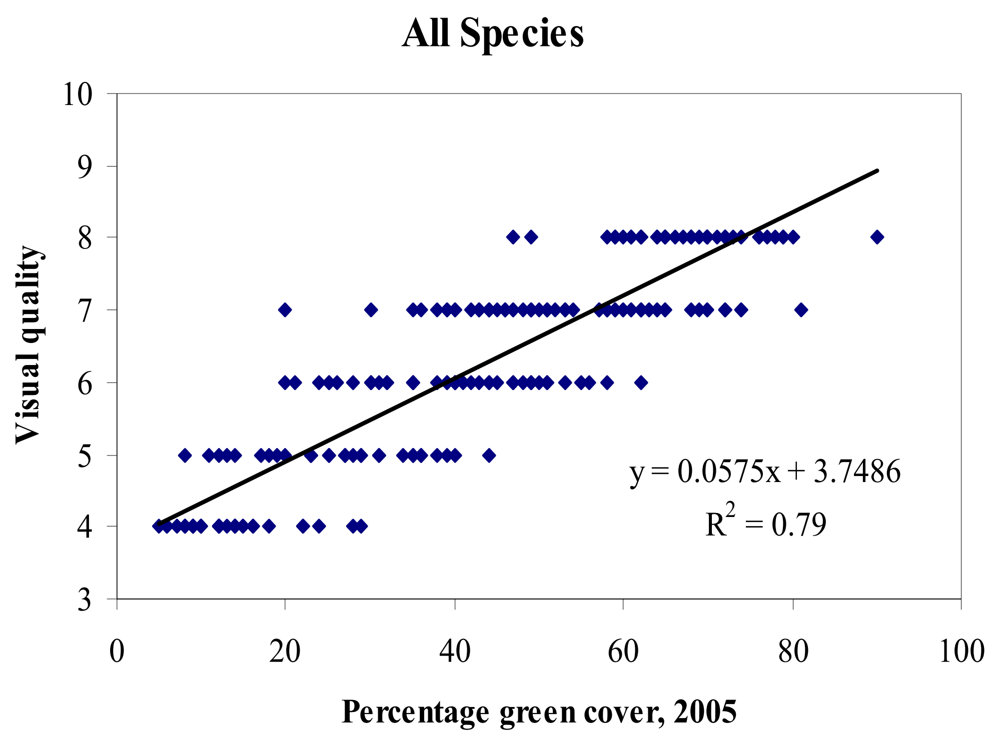


Table 2.1 Correlation coefficients of visual quality with spectral reflectance at each wavelength and ratio in four cool-season turfgrasses in 2004 (n = 384) and 2005 (n =576) (data for all four turfgrasses, treatments, and measurement dates pooled). Coefficients of R706, Stress1 and Stress2 in 2004 were deleted due to instrument error.

Wavelength & Ratio¥	Correlation	
	r (2004)	r (2005)
R507	-0.55	-0.48
R559	-0.30	-0.64
R613	-0.57	-0.74
R661	-0.69	-0.80
R706	--	-0.54
R760	0.74	0.76
R813	0.73	0.38
R935	0.75	0.40
NDVI	0.74	0.88
NIR/R	0.65	0.83
Stress1	--	-0.84
Stress2	--	-0.70

¥ Percentage of reflectance at selected wavelengths of ratios. NDVI, normalized difference vegetation index computed as (R935-R661)-(R935+R661); NIR/R, near infrared to red computed as R935/R661; Stress1 computed as R706/R760; and Stress2 computed as R706/R813

Table 2.2 Correlation between visual quality and reflectance data at each wavelength and ratio within four turfgrasses at the high mowing height (7.62 cm) in 2004 and 2005. Shaded cells denote highest correlations in a given species and year. Coefficients of R706, Stress1 and Stress2 in 2004 were deleted due to instrument error.

Wavelength & Ratio¥	KBG†		TB‡		R¶		TF§	
	r (2004)	r (2005)	r (2004)	r (2005)	r (2004)	r (2005)	r (2004)	r (2005)
R507	ns◊	-0.48	-0.44	-0.48	-0.35	-0.31	-0.38	-0.39
R559	0.3	-0.69	ns	-0.67	ns	-0.49	-0.25	-0.6
R613	ns	-0.75	-0.44	-0.76	-0.42	-0.63	-0.32	-0.64
R661	-0.51	-0.82	-0.62	-0.81	-0.57	-0.71	-0.4	-0.69
R706	--	-0.69	--	-0.56	--	-0.31	--	-0.51
R760	0.75	0.86	0.69	0.76	0.7	0.77	ns	0.38
R813	0.71	0.32	0.68	0.33	0.64	0.42	ns	ns
R935	0.75	0.36	0.7	0.35	0.67	0.45	ns	-0.13
NDVI	0.62	0.91	0.67	0.9	0.65	0.85	0.32	0.75
NIR/R	0.58	0.89	0.51	0.9	0.61	0.81	0.25	0.66
Stress1	--	-0.89	--	-0.86	--	-0.82	--	-0.63
Stress2	--	-0.81	--	-0.7	--	-0.61	--	-0.39

◊ ns = non significant correlation (p<0.05)

† Kentucky bluegrass; ‡ Thermal Blue; ¶ Reveille; § tall fescue.

¥ Percentage of reflectance at selected wavelengths of ratios. NDVI, normalized difference vegetation index computed as (R935-R661)-(R935+R661); NIR/R, near infrared to red computed as R935/R661; Stress1 computed as R706/R760; and Stress2 computed as R706/R813.

Table 2.3. Correlation between visual quality and reflectance data at each wavelength and ratio within two turfgrasses at low mowing height in 2004 and 2005. Shaded cells denote higher correlations (i.e., r ≤ -0.6 and r ≥ 0.6) and the boxes indicate the highest correlations. Coefficients of R706, Stress1 and Stress2 in 2004 were deleted due to instrument error.

Wavelength & Ratio¥	KBG†		TB‡	
	r (2004)	r (2005)	r (2004)	r (2005)
R507	-0.57	-0.44	ns	-0.4
R559	ns[◊]	-0.57	ns	-0.52
R613	-0.58	-0.7	ns	-0.69
R661	-0.71	-0.77	-0.42	-0.77
R706	--	-0.36	--	-0.33
R760	0.79	0.86	0.71	0.8
R813	0.75	0.48	0.67	0.36
R935	0.81	0.55	0.72	0.36
NDVI	0.75	0.85	0.53	0.87
NIR/R	0.68	0.86	0.45	0.88
Stress1	--	-0.81	--	-0.81
Stess2	--	-0.68	--	-0.59

◊ ns = non significant correlation ($p<0.05$)

† Kentucky bluegrass; ‡ Thermal Blue

¥ Percentage of reflectance at selected wavelengths of ratios. NDVI, normalized difference vegetation index computed as (R935-R661)-(R935+R661); NIR/R, near infrared to red computed as R935/R661; Stress1 computed as R706/R760; and Stress2 computed as R706/R813.

Table 2.4 Probability values for irrigation-deficit effects on four turfgrasses by selected day of year (DOY) among visual quality, reflectance ratios, and individual wavelengths in 2005. Two irrigation treatments included 100% evapotranspiration (ET) replacement (well watered) and 60% ET replacement (irrigation deficit). Irrigation treatments began on DOY 177 and were terminated on DOY 246. Shaded cells denote significant irrigation effects ($p < 0.05$).

Spp.	DOY	Quality	NDVI	NIR/R	Stress1	Stress2	R507	R559	R613	R661	R706	R760	R813	R935
KBG†	179	0.1340	0.3675	0.4734	0.3432	0.5472	0.4150	0.3225	0.3947	0.3849	0.4313	0.8586	0.9557	0.6940
	196	<.0001	0.0330	0.0232	0.0338	0.0273	0.0452	0.0590	0.0319	0.0220	0.0875	0.0467	0.0494	0.1241
	216	0.0011	0.0002	0.0005	0.0001	<.0001	<.0001	0.0003	<.0001	<.0001	0.0002	0.0114	0.0098	0.1198
	238	0.0011	0.0003	0.0008	0.0003	0.0003	0.0003	0.0018	0.0003	0.0003	0.0077	<.0001	0.0001	0.0003
TB‡	179	0.5370	0.5060	0.3874	0.3464	0.2872	0.4622	0.4579	0.2657	0.4155	0.4154	0.5456	0.4985	0.5227
	196	0.0240	0.0448	0.0544	0.1017	0.1396	0.1368	0.4150	0.1238	0.0650	0.4794	0.0764	0.1077	0.1110
	216	0.0106	0.0127	0.0139	0.0239	0.0208	0.0386	0.0698	0.0309	0.0259	0.0801	0.0061	0.0050	0.0033
	238	0.0001	0.0081	0.0033	0.0100	0.0077	0.0329	0.1528	0.0176	0.0104	0.5585	0.0055	0.0054	0.0080
R¶	179	0.3559	0.4128	0.3420	0.1002	0.1763	0.2300	0.0513	0.0742	0.1890	0.0816	0.7114	0.8048	0.8794
	196	0.3559	0.2892	0.3230	0.3790	0.4626	0.7614	0.4485	0.5032	0.3175	0.4266	0.2841	0.3607	0.2055
	216	0.0038	0.0080	0.0028	0.0117	0.0117	0.0069	0.0161	0.0071	0.0064	0.0556	0.0334	0.0962	0.1219
	238	0.0033	0.0022	0.0001	0.0012	0.0014	0.0071	0.2255	0.0040	0.0013	0.5045	0.0029	0.0052	0.0059
TF§	179	·	1.0000	0.9394	0.9152	1.0000	0.5956	0.6724	0.8385	0.7710	0.6399	0.5898	0.6329	0.7541
	196	0.5370	0.8864	0.9123	0.9172	0.8345	0.6230	0.6639	0.7473	0.7075	0.5244	0.4557	0.6415	0.4866
	216	0.0300	0.1775	0.2674	0.2234	0.2639	0.5716	0.4603	0.2801	0.1958	0.3168	0.3547	0.3321	0.9281
	238	0.0686	0.1002	0.1324	0.2376	0.2571	0.1870	0.2048	0.1270	0.0935	0.1577	0.8600	0.6925	0.8268

† Kentucky bluegrass; ‡ Thermal Blue; ¶ Reveille; § tall fescue.

References

Asrar, G., M. Fuchs, E.T. Kanemasu, and J.L. Hatfield. 1984. “Estimating absorbed photosynthetic radiation and leaf area index from spectral reflectance in wheat”. *Agronomy Journal* 76:300-306.

Avery, T.E. and G..L. Berlin. 1992. *Fundamentals of remote sensing and airphoto interpretation*. 5th edition. Prentice Hall Inc., Upper Saddle River. NJ.

Bell, G.E., D.L. Martin, M.L. Stone, J.B. Solie, and G.V. Johnson. 2002. “Turf area mapping using vehicle-mounted optical sensors”. *Crop Science* 42:648-651.

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”. Applied *turfgrass Science* [Online]. Available at http://www.plantmanagementnetwork.org/sub/ats/research/2006/hybrid/ (Published 8 Aug. 2006; Verified 23 April. 2007).

Carrow, R.N., R.R. Duncan, and R.C. Shearman. 2001. “Providing relevant information to turfgrass managers: challenges and implications”. *Int. Turfgrass Soc. Res. J.* 9:53–60.

Chang, J., S.A. Clay, D.E. Clay, D. Aaron, D. Helder, and K. Dalsted. 2005. “Clouds influence precision and accuracy of ground-based spectroradiometers”. *Communications in soil science and plant analysis* 36:1799-1807.

Daughtry, C.S.T., K.P. Gallo, N.S. Goward, S.D. Prince, and W.P. Kautas. 1992. “Spectral estimates of absorbed radiation and phytomass production in corn and soybean canopies”. *Remote Sensing of Environment* 39:141-152.

Ewing, R.P., and R. Horton. 1999. “Quantitative color image anaylsis of agronomic images”. *Agronomy Journal* 91:148-153.

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”. *Journal of Turfgrass management* 2:65-80.

Fitz-Rodriguez, E. and C.Y. Choi. 2002. “Monitoring turfgrass quality using multispectral radiometry”. *American Society of Agricultural Engineers ISSN* 45(3): 865-867.

Fry, J. and B. Huang. 2004. *Applied turfgrass science and physiology*. John Wiley & Sons, Inc., Hoboke, NJ.

Gallo, K.P., C.S.T. Daughtry, and M.E. Bauer. 1985. “Spectral estimation of absorbed photosynthetically active radiation in corn canopies”. *Remote Sensing of Environment* 17:221-232.

Goward, S.N. and K.F. Huemmrich. 1992. “Vegetation canopy PAR absorptance and the normalized difference vegetation index: An assessment using the SAILmodel”. *Remote Sensing of Environment*. 39:119-140.

Gupta, R.K. and J.T. Woolley. 1971. “Spectral properties of soybean leaves”. *Agronomy Journal* 63:123-126.

Horler, D.N.H., M. Dockray, and J. Barber. 1983. “The red edge of plant leaf reflectance”. *International Journal of Remote Sensing* 4(2):273-288.

Horst, G.L., M.C. Engelke, and W. Meyers. 1984. “Assessment of visual evaluation techniques”.. *Agronomy Journal* 76:619-622.

Ikemura Y. and B. Leinauer. 2007. “Remote sensing of stressed turfgrass”. Abstract of ASA international annual meetings.

Jensen, J.R. 2007. *Remote sensing of the environment; an earth resource perspective*. 2nd Edition. Pearson Prentice Hall Inc. Upper Saddle River, NJ.

Jiang, Y.W., R.N. Carrow and R.R. Duncan. 2003. “Correlation analysis procedures for canopy spectral reflectance data of seashore paspalum under traffic stress”. *HortScience* 128(3):343-348.

Jiang, Y. and R.N. Carrow. 2005. “Assessement of narrow-band canopy spectral reflectance and turfgrass performance under drought stress”. *HortScience* 40(1):242-245.

Jiang, Y.W., R.N. Carrow and R.R. Duncan. 2007. “Broadband spectral reflectance models of turfgrass species and cultivars to drought stress”. *Crop Science* 47:1611-1618.

Karcher, D.E., and M.D. Richardson. 2003. “Quantifying turfgrass color using digital imaging analysis”. *Crop Science* 43:943-951.

Kraft, R.W. and S.J. Keeley. 2005. “Evaluation of improved *poa pratensis* cultivars for transition zone fairway use”. *Intl. Turfgrass Soc. Res. J.* 10: 368-372.

Kruse, J.K., N.E. Christians, and M.H. Chaplin. 2006. “Remote sensing of nitrogen stress in creeping bentgrass”. *Agron. J. Remote Sensing* 98:1640-1645.

Landschoot, P.J. and C.F. Mancino. 1997. “Assessment of the Minolta CR-310 Chroma Meter for predicting nitrogen status of *Agrostis stolonifera* L”. *Intl. Turfgrass Soc. Res. J.* 8:711-718.

Landschoot, P.J. and C.F. Mancino. 2000. “A comparison of visual vs. instrumental measurement of color differences in bentgrasses turf”. *HortScience* 35(5):914-916.

Loomis, R.S., D.J. Connor. 1992. *Crop ecology: productivity and management in agricultural systems*. Cambridge University Press.

Madeira A.C., T.J. Gillespie, and C.L. Duke. 2001. “Effect of wetness on turfgrass canopy reflectance”. *Agricultural and Forest Meteorology*. 107(2):117-130.

Morris, Kevin N. 2005. "A guide to NTEP turfgrass.ratings".
(http://www.ntep.org/reports/ratings.htm).

Park D.M., J.L. Cisar, K.E. Williams, D.K. McDermitt, W.P. Miller, and M.A. Fidanza. 2007.
"Using spectral reflectance to document water stress in bermudagrass grown on water repellent sandy soils". *Hydrological processes* 21:2385-2389.

Raikes, C. and L.L. Burpee. 1998. "Use of multispectral radiometry for assessment of rhizoctonia blight in creeping bentgrass". *The American Phytopathological Society* 88:446-449.

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

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

Salisbury F.B. and C.W. Ross. 1969. *Plant physiology*. 3rd edition. Wadsworth: Belmont, CA.

Steddom, K., M.W. Bredehoeft, M. Khan, and C.M. Rush. 2005. "Comparison of visual and multispectral radiometric disease evaluations of Cercospora leaf spot of sugar beet". *The American Phytopathological Society* 89:153-158.

Su, K. 2007. "Performance of Texas bluegrass hybrids in the transition zone". Ph. D. dissertation. Kansas State University, Manhattan, KS.

Su, K., D.J. Bremer, S.J. Keeley, and J.D. Fry. 2007. "Effects of high temperature and drought on a hybrid bluegrass compared with Kentucky bluegrass and tall fescue". *Crop Science* 47:2152-2161.

Su, K., D.J. Bremer, S.J. Keely, and J.D. Fry. 2008. “Rooting characteristics and responses of photosynthesis to irritation deficit of two hybrid bluegrasses, Kentucky bluegrasses, and tall fescue”. *Agronomy Journal* 100:949-956 .

Supplick-Ploense, M.R., and Y. Qian. 2005. “Evapotranspiration, rooting characteristics, and dehydration avoidance: Comparisons between hybrid bluegrass and Kentucky bluegrasses”. *Int. Turf. Soc. Rec. J.* 10:891-898.

Taiz, L. and E. Zeiger. 2002. *Plant physiology*. 3rd edition. Sinauer Associates, Inc. Sundrland, MA

Thorogood, D., P.J. Bowling, and R.M. Jones. 1993. “Assessment of turf colour change in *Lolium perenne* L. cultivars and lines”. *Intl. Turfgrass Soc. Res.* J. 7:729-735.

Trenholm, L.E., R.N. Carrow, and R.R. Duncan.1999a. “Relationship of multispectral radiometry data to qualitative data in turfgrass research”. *Crop Science* 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 Science* 39:1147-1152.

Trenholm, L.E., M.J. Schlossberg, G.. Lee, and W. Parks. 2000. “An evaluation of multi-spectral responses on selected turfgrass species”. *International Journal of Remote Sensing* 21(4):709-721.

Turgeon, A. 1991. *Turfgrass management*. Prentice-Hall, Englewood Cliffs, NJ.

CHAPTER 3 - Estimation of Visual Quality, Canopy density, Leaf Area Index, Aboveground Biomass, and Chlorophyll Concentration Using Multi-spectral Radiometry in Turfgrasses

Abstract

Measurements of visual quality, canopy density, leaf area index (LAI), aboveground biomass, and leaf chlorophyll content in turfgrasses are typically subjective or time- and labor-intensive. Spectral reflectance may provide faster, more objective estimates of canopy characteristics than conventional methods. This study was conducted near Manhattan, Kansas, USA to determine relationships of canopy characteristics with spectral reflectance among different species and mowing heights. Relationships of canopy reflectance with visual quality and density were evaluated in four turfgrasses including tall fescue (*Festuca arundinacea* Schreb. 'Dynasty'), Kentucky bluegrass (*Poa pratensis* L. 'Apollo') and two hybrid bluegrasses ('Thermal Blue' and 'Reveille'). Relationships of reflectance with green LAI, aboveground biomass, and chlorophyll content were evaluated in the same four grasses along with perennial ryegrass (*Lolium perenne*, 'Alliance' Blend), zoysiagrass (*Zoysia japonica,* 'Meyer'), and bermudagrass (*Cynodon dactylon*, 'Midlawn'). Strongest correlations with visual quality were in the normalized difference vegetation index (NDVI, [935-661]/[935+661] nm, r=0.77), at 613 nm (r=-0.71), and in the near infrared to red (NIR/R [935/661] nm; r=0.68) and Stress2 (706/813 nm, r=-0.70) ratio. For density, highest correlations were with NDVI (r=0.86), reflectance at 661 nm (r=-0.84), and Stress2 (r=-0.82). Analyses of covariance revealed different models for visual quality and density among grasses at each wavelength and index in KBG, TB, and R. Significant correlations of LAI, aboveground biomass, and chlorophyll concentration with reflectance were

found in some species at different wavelengths and ratios and the strongest was r=0.63. Weak relationships of reflectance with green LAI and aboveground biomass indicates further research, perhaps using hyperspectral technology, is needed to determine the suitability of using reflectance to determine LAI and aboveground biomass in turfgrasses.

Introduction

Visual quality of turfgrass is typically evaluated by an observer on a scale from 1 to 9 based on integrating the factors of canopy density, texture, uniformity, and color (Turgeon, 1991). Although this method is relatively quick and convenient, it is subjective and may vary widely among evaluators (Horst et al., 1984). Among the factors that affect visual quality, density is defined as an estimate of living shoots or tillers per unit (NTEP, 2005). Density may be estimated subjectively, separately from visual quality, using a similar rating scale where 9 is maximum density. Density also can be measured by counting shoots in a specified area. Manually counting shoots, however, requires significant time and labor. Therefore, alternative methods are needed that provide more objective, consistent, and time saving assessments of turfgrass quality and density.

Multispectral radiometry (MSR) provides a method for measuring light reflectance from canopies at a number of wavelengths and has been used to evaluate appearance, growth status, and physiological changes caused by environmental stresses in a number of turfgrass species (Trenholm et al., 1999; Trenholm et al., 2000; Fitz-Rodríguez and Choi, 2002; Jiang and Carrow, 2005). Trenholm (1999), using MSR, detected significant correlations between light reflectance and both visual quality and density in seashore paspalum ecotypes and hybrid bermudagrass cultivars.

Green leaf area index (LAI) is an important indicator of photosynthetic and transpirational capacity in turfgrass canopies. Additionally, aboveground biomass is an indicator of ecosystem productivity and is strongly related to LAI (Loomis and Conner, 1992). Despite the importance of LAI to such basic physiological factors as canopy-level photosynthesis and transpiration, few LAI data are reported for turfgrass in the literature. Measuring LAI in turfgass is tedious, time consuming, usually destructive, and is complicated by the small size of the canopies (Brede and Duich, 1980; Kopec et al., 1987). Therefore, faster methods of accurately estimating green LAI in turfgrasses are needed.

Vegetation indices, such as normalized difference vegetation index (NDVI) and the ratio of near infrared to red (NIR/R) are calculated from reflectance data and have been used to detect relationships with LAI and aboveground biomass in other crops. For example, Daughtry et al. (1992) determined that NDVI was highly correlated with LAI, and NIR/R was correlated with shoot biomass in corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.]. In a grassland in Italy, NDVI was strongly correlated with effective LAI ($r^2 = 0.74$) and dry biomass ($r^2 = 0.78$) (Vescovo et al., 2004). Asrar et al. (1984) detected that NDVI was correlated with absorbed photosynthetically active radiation (APAR) in wheat (*Triticum aestivum* L.) ($r^2 = 0.97$); APAR is directly related to LAI (Loomis and Conner, 1992). Moreover, strong relationships between NDVI and plant biomass were found in spinach ($r^2 = 0.98$) (Weckler et al., 2003). However, few relationships between vegetation indices and LAI or biomass have been reported for turfgrasses.

Chlorophyll concentration is the vital factor that links leaf light reflectance at certain wavelengths and photosynthetic activity (Danks et al., 1983: Haboudane et al., 2002). Wavelengths in the visible spectral range (i.e., 400-700 nm), especially blue and red light, are absorbed by chlorophyll and consequently, reflectance is relatively low at those wavelengths. Chlorophyll content typically decreases when plants are under environmental stresses, attacked by diseases, or lacking sufficient nitrogen (N), which in turn lead to increased reflectance in the visible range (Raikes and Burpee, 1998) and decreased reflectance in the near infrared as the internal leaf structure degenerates (Guyot, 1990, Raikes and Burpee 1998). Strong correlations were found between chlorophyll concentration and canopy reflectance at 705 nm and at the reflectance ratios of 750/705 nm in *Aescules hippocastanum* L. and *Acer platanoides* L. leaves, and 675/700 nm in soybean leaves (Gitelson and Merzlyak, 1994; Chappelle et al., 1992). In addition, the red edge, which is the sharp change in wavelengths between 680 (used as an indicator of red absorbance) and 760 nm (near infrared region which is sensitive to high internal scattering of light within mesophyll cells) was strongly affected by chlorophyll concentration in winter wheat (Munden et al, 1994).

In turfgrass, chlorophyll concentration is an indicator of both N concentrations and visual quality. For example, strong correlations were detected between canopy reflectance and chlorophyll ($r^2 = 0.79$), N concentration ($r^2 = 0.71$), and visual ratings ($r^2 = 0.74$) of St. Augustinegrass [*Stenotaphrum secondatum* (Walt.) Kuntze] (Rodriguez and Miller, 2000). Kruse et al. (2006) found that NDVI, Stress1 (R706/R760), and Stress2 (R706/R813) ratios were highly correlated with N concentration in creeping bentgrass (*Agrostis stolonifera* L. 'Penncross'). Additionally, chlorophyll content have been correlated with turfgrass visual ratings ($r^2 = 0.91$) (Madison and Anderson, 1963). Because different species of turfgrasses, even in non-stressed conditions, may exhibit different colors that may result from differing amounts of chlorophyll in the leaves, specific relationships of canopy reflectance with chlorophyll content and visual quality may exist among species as plants undergo stress. Such relationships, however, have not been reported.

The objectives of this study were to determine: 1) relationships of visual quality and density with canopy spectral reflectance among four cool-season turfgrasses; 2) relationships of green LAI, aboveground biomass, and chlorophyll concentrations with reflectance among seven cool- and warm-season turfgrasses; and 3) effects of mowing height on visual quality, density, green LAI, aboveground biomass, and chlorophyll concentration and on their respective relationships with canopy reflectance.

Materials and Methods

Two research projects were conducted at the Rocky Ford Turfgrass Research Center (39°13'53" N, 96°34'51" W) near Manhattan, Kansas, USA, during the periods 26 April to 28 July (Study 3-1) and 29 July to 11 October (Study 3-2) in 2006. The soil at the study site was classified as a Chase silt loam (fine, smectitic, mesic Aquertic Argiudoll).

Visual quality and Density

Turfgrass species included tall fescue (TF, *Festuca arundinacea* Schreb. 'Dynasty'), Kentucky bluegrass (KBG, *Poa pratensis* L. 'Apollo') and two hybrid bluegrasses (HBG, 'Thermal Blue' and 'Reveille'), which are genetic crosses between native Texas bluegrass (*Poa arachnifera* Torr.) and Kentucky bluegrass. The experimental area was under an automated rainout shelter (12 x 12 m). Forty eight plots (1.36 × 1.76 m each) were arranged in a randomized complete block design with four replications. Two irrigation treatments included well watered (replacement of 100% of the water lost from plans and soil via evapotranspiration [ET]) and water deficit (replacement of 60% of ET). Irrigation treatments were applied from DOY 143 to 174 but irrigation treatments were halted after DOY 175 due to an infestation of billbugs (*Sphenophorus parvulus* Gyllenhal). Two mowing height treatments (high mowing = 7.62 cm and low mowing = 3.81 cm) were applied to KBG and Thermal Blue for the whole duration of the experiment.

A hand-held multi-spectral radiometer (model MSR16, CropScan, Inc. Rochester, MN) was used to measure spectral reflectance of the canopy surface from l m above ground level. Reflectance at eight wavelengths in the visible and near infrared region of the electromagnetic spectrum (i.e., at 507, 559, 613, 661, 706, 760, 813, and 935 nm) were acquired weekly. Two readings (approximately 0.5 m diam. each plot) were collected from each plot and were later averaged. Data from all plots were collected on 12 days (DOY 117, 133, 139, 148, 159, 168, 174, 182, 188, 194, 201, and 210) with no cloud cover, between 1200 and 1300 h central standard time (CST). Four vegetation and stress indices were calculated from reflectance data: 1) NDVI, computed as (R935-R661)/(R935+R661); 2) NIR/R (near infrared to red), computed as R935/R661; 3) Stress1 computed as R706/R760; 4) Stress2 computed as R706/R813.

Visual quality was rated weekly on a scale of 1 to 9 (1 = brown and dead turf, 6 = minimally acceptable turf for use in home lawns, and 9 = optimum turf); turfgrass quality was based on integrated, visual estimates of uniformity, texture, density, and color. Density ratings, which were evaluated weekly by the same person who estimated visual ratings, also consisted of ratings from 1 to 9 but were based only on shoot density (1 = no grass, 6 = minimally acceptable density, and 9 = dense grass) (Trenholm et al., 1999). Measurements of visual quality and density were collected on the same day as spectral reflectance readings.

Green leaf area index, aboveground biomass, and chlorophyll concentration

In Study 3-2, green leaf area index (LAI), aboveground biomass and chlorophyll concentration were compared with reflectance data from each plot to evaluate the potential to estimate green LAI, aboveground biomass, and chlorophyll concentration in turfgrass with reflectance data . Data were collected from five cool-season turfgrasses including TF (Dynasty), KBG (Apollo), two HBG (Reveille and Thermal Blue), and perennial ryegrass (*Lolium perenne*, ‘Alliance’ Blend), and from two warm-season grasses including zoysiagrass (*Zoysia japonica,* ‘Meyer’) and bermudagrass (*Cynodon dactylon*, ‘Midlawn’). All turfgrasses except TF and Reveille were maintained at two heights to evaluate the effect of mowing on LAI, aboveground biomass and chlorophyll concentration and the ability of the MSR to detect those differences.

The high and low mowing heights varied among species. For example, the high mowing height of all grasses except perennial ryegrass was 7.62 cm; ryegrass was mowed at 8.89 cm. Low mowing heights were 3.81 cm for KBG and Thermal Blue, 0.56 cm for bermudagrass and zoysiagrass, and 5.08 cm for perennial ryegrass. Reveille and TF were maintained only at 7.62 cm.

Data were collected from plots (approximately 1.36 × 1.76 m) from random locations in established swards of each turfgrass at the study site; each species × mowing height combination was replicated three times. Two reflectance readings were taken per plot and then averaged. Turfgrasses were then clipped at ground level from three 45.58 cm^2 areas within each plot (7.62 diam. polyvinyl chloride ring). Clippings were collected and transported to the laboratory to estimate LAI, aboveground biomass, and chlorophyll concentration. Thus, a total of nine samples were collected from each mowing height by species combination. In the laboratory, green and dead leaves and shoots were separated and green leaf area was measured using an image analysis system (WinRHIZO™ 2002a,b,c., Régent Instruments Inc., Quebec City, Canada). Biomass samples were then dried in a forced-air oven for 24 hours at 70 C and weighed to determine dry biomass.

For chlorophyll analysis, small amounts of green leaf tissue from both mowing heights (approximately 0.06 g from each species) were collected from the same plots concurrently with reflectance and LAI samples. Chlorophyll was extracted in dimethyl-sulphoxide (DMSO) for five days in a dark cabinet. Chlorophyll extractions were then transferred to a cuvette and absorbance was measured using a spectrophotometer (Spectronic Genesis 2, Spectronic Instruments Inc., Rochester, NY) set as 665 and 649 nm. Chlorophyll *a* and *b* concentration were calculated as $Ch\ a = 12.19A_{665} - 3.45A_{649}$ and $Ch\ b = 21.99\ A_{649} - 5.32\ A_{665}$ (Wellburn, 1994).

Data analysis

In Study 3-1, data among plots were analyzed with the regression and correlation procedures of SAS (SAS Institute Inc., Cary, NC) for comparisons of visual quality and density with reflectance at each wavelength and index. The best fit (higher r value) describing the relationship between visual quality and density with reflectance data was determined by evaluating both linear and quadratic models for all wavelengths and vegetation indices. Correlation and regression analyses included pooling data among plots from all species on all measurement days. Data were also separated to determine the effects of turfgrass mowing height and species on relationships of visual quality and density with reflectance. The general linear model procedure of SAS was used to conduct an analysis of covariance test to test for equal slopes and intercepts in regression models among species.

In Study 3-2, data among plots were analyzed separately by species and mowing height with the correlation procedures of SAS (SAS Institute Inc., Cary, NC) to determine relationships among species and mowing heights between reflectance at each wavelength and green LAI, biomass, Ch *a*, and Ch *b*.

Results and Discussion

Visual quality and Density

Relationships between visual quality and reflectance

Significant correlations ($p < 0.0005$) were found between turf quality and reflectance at all wavelengths and vegetation and stress ratios during the study when data from all plots and measurement days were pooled (Table 3.1). In 2006, the strongest correlation between reflectance and visual quality ratings was at the ratio NDVI (r=0.77). Reflectance was also highly correlated with visual quality at wavelengths 507, 613, and 661, and the indices NIR/R, Stress1 and Stress2, with correlation coefficients ranging from 0.68 to 0.73. Conversely, correlations with visual quality were weakest at R706 (r = -0.37). Relationships with visual quality were linear through R706 and for the indices NDVI, Stress1 and Stress2 and quadratic at R760, R813, R935, and NIR/R.

Our results are similar to those of Trenholm et al. (1999), who reported high correlations between visual ratings and reflectance at R661 and at the ratios NDVI, NIR/R, and Stress2 (r = 0.72 to 0.91) in seven seashore paspalum (*Paspalum vaginatum* Swartz) ecotypes and three hybrid bermudagrass cultivars (*Cynodon dactylon* L. Pers. x *C. transvaalensis* Burtt-Dacy, 'Midiron'). Those authors also reported that visual quality was not correlated with reflectance at wavelength 706. Others have reported strong correlations between visual quality and NDVI (r = 0.85) and NIR/R (r = 0.84) for a hybrid bermudagrass cultivar (*Cynodon dactylon* L. Pers. x *C. transvaalensis* Burtt-Dacy, "Midiron") (Fitz-Rodriguez and Choi, 2002).

Correlations between visual quality and reflectance were generally greater in years when turfgrasses were under more stress with the notable exception of in the NIR (Table 2.1; Table 2.2 in Chapter 1). Presumably, correlations strengthened with stress because stress caused larger ranges in both visual quality and reflectance among plots. For example, correlations were stronger in 2005, when drought and heat stresses were greater than in 2004 (Chapter 2; Su et al., 2008). In 2006, drought and heat stress was not severe as in 2005 because irrigation-deficit treatments were halted due to an infestation of billbugs. Average of daytime air temperature (1000 – 18000 h CST) on measurement days was 30^{o}C in 2005, but was 28^{o}C in 2006. Consequently, correlations were usually weaker in 2006 than in 2005 between reflectance and visual quality. Correlations in 2006, however, were typically stronger than in 2004, probably because of stress related to billbug damage in 2006.

Interestingly, correlations in the NIR range (e.g., R813 and R935) with visual quality in 2006 were higher than correlations in 2005, but lower than correlations in 2004. Reflectance in the NIR range is caused primarily by intracellular light scattering from cellular air-water interfaces within mesophyll cell (Taiz and Zeiger, 2002). Therefore, more water in leaves causes greater reflectance in the NIR range. Because the irrigation-deficit treatment was stopped in 2006 to relieve drought stress and enhance recovery from billbug injury, water content in grass leaves likely increased. Under stresses, water content may have decreased before visible reductions were evident, which would affect correlations in the NIR. The latter may explain the stronger relationships in 2006 between reflectance in the NIR and visual quality compared to 2005, when the grasses were under greater drought stress (Su et al., 2008). Lower drought and heat stress and the lack of stress from billbug damage probably resulted in higher reflectance in the NIR in 2004 than in 2005 or 2006.

Species effects on relationships between visual quality and reflectance

Within the high mowing height, visual quality was significantly correlated with reflectance at all wavelengths and indices in KBG, TB, and R (Table 3.2). The strength of the correlations, however, varied considerably among the three turfgrasses with the highest correlations in KBG and the lowest in TB. For example, correlations between visual quality and NDVI were 0.83 in KBG, 0.77 in R, and 0.65 in TB. In all three grasses, correlations were highest between NDVI and visual quality compared with all other indices and wavelengths. Among species, TF showed weaker relationships at most wavelengths and vegetation indices, and correlations were not significant at R760, R813, R935, and Stress1. Similar to the above discussion, correlations were generally stronger in species that exhibited greater stress symptoms because of subsequent greater ranges in visual quality during the study. Visual quality among plots ranged from a high of 8 in all grasses to a low of 3 in KBG, 5 in R and TB, and only 6 in TF. Visual quality averaged 6.02 in KBG, 6.53 in R, 6.79 in TB, and 7.48 in TF (Fig. 3.1) and thus, the strength of correlations was inversely proportional to average visual quality.

Analyses of covariance revealed discriminate regression models among grasses at each wavelength and index during the study (data not shown). Relationships between visual quality and reflectance were greatest at the indices NDVI and NIR/R (Figure 3.2). Regression models, which were significantly different among species, all indicated linear relationships between visual quality and NDVI. Relationships between visual quality and NIR/R, however, were quadratic with the exception of TF, which was linear. In general, models were weaker for TF, probably because TF was less affected by the irrigation-deficit treatment; lower effects of irrigation deficit on visual quality and reflectance in TF resulted in narrower ranges of data for comparing qualitative with quantitative data (Trenholm et al., 1999a).

Jiang and Carrow (2005) also reported differences in relationships between turf quality and reflectance among warm and cool-season turfgrass cultivars and species (i.e., bermudagrass, seashore paspalums, zoysiagrass, and st. augustinegrass and tall fescue). Those authors attributed the differences among species to varying smoothness and shininess in leaf surfaces. When measuring reflectance, factors such as canopy architecture and leaf color may influence light reflectance even given similar qualities and thus, result in discriminate models of quality among turfgrasses. Also, different effects of stresses on individual cultivar and species may affect reflectance. These data indicate that turfgrass species or cultivars require separate models and that it may be inappropriate to estimate turf quality from models derived from pooled reflectance data from among species.

Relationships between turfgrass density and reflectance

Correlations between reflectance and canopy density were generally high (r = 0.54 to 0.86) when data from all plots and measurement days were pooled (Table 3.3). Highest r values were obtained from NDVI (0.86), R661 (-0.84), R613 (-0.81), NIR/R (0.76), Stress1 (-0.80), and Stress2 (-0.82). Similar results were reported by Trenholm et al. (1999), who found highest correlations between density and reflectance at R661, NDVI, NIR/R, and Stress2. Regression analyses revealed linear relationships between density and reflectance at all wavelengths and indices except for NIR/R, which was quadratic. Generally, correlation values were higher for density (r = 0.54 to 0.86) than for visual quality (r = 0.37 to 0.77) except at R760 and R813. Our results were contrary to those of Trenholm et al. (1999), who reported that visual quality had a stronger relationship with reflectance data than density.

Species effects on relationships between density and reflectance

Within the high mowing height, density ratings were significantly correlated with reflectance at all wavelengths and indices although correlations were generally strongest in KBG and weakest in TF (Table 3.4). Correlations between NDVI and density were 0.89 for KBG, 0.83 for TB, 0.82 for R, and only 0.51 for TF. The highest correlations between density and reflectance for TF was at NIR/R ($r = 0.66$). Lower correlations in TF resulted from a narrower range in densities among TF plots because TF was not damaged by billbugs. Conversely, higher correlations indicated greater sensitivity to environmental stresses, which in this instance was primarily billbug damage.

Analyses of covariance revealed different density models among grasses at each wavelength and index during study year ($P<0.05$; data not shown). Relationships were strongest among species between density and NDVI and NIR/R (Figure 3.2). Regression models were linear between density and NDVI and quadratic between density and NIR/R with the exception of TF, which was linear. Our data indicate that separate models are required when using reflectance data to evaluate canopy densities in different turfgrass cultivars or species.

Green leaf area index, aboveground biomass, and chlorophyll concentration

Relationships of green LAI and aboveground biomass with reflectance

When data from all species and mowing heights were pooled, significant correlations were found between green LAI and reflectance at R507, R559, R613 and R706 (Table 3.5). No relationships, however, were evident between green LAI and NDVI or NIR/R ($r = -0.04$ and $r = 0.06$, respectively).

When data were analyzed separately by species (Table 3.6), stronger correlations between LAI and reflectance were found in some species at different wavelengths and ratios. For example, KBG had high correlations in the R507 (r = -0.82), R559 (r = -0.90), R613 (r = -0.91), and R706 (r = -0.88), which were the same wavelengths that exhibited significant correlations when data were pooled (Table 3.5). Green LAI was strongly correlated with R813 in TB (r = 0.87). The NDVI was highly correlated with LAI in R (r = 0.85), bermuda (r = -0.80), and zoysia (r = 0.99). In TF, however, no significant correlations were found between LAI and reflectance at any wavelengths or ratio.

When all data were pooled, aboveground biomass was significantly (albeit not strongly) correlated with R559 (r = -0.34), R661 (r = 0.46), R706 (r = -0.34), and NDVI (r = -0.38) (Table 3.5). No relationship between biomass and NIR/R was found in this study. Other researchers reported that shoot biomass was associated with NIR/R in corn and soybean (r^2 = 0.99) (Daughtry et al., 1992). Trenholm et al. (1999) reported some correlation between shoot growth as clipping yield was and R661 (r^2 = 0.29 and 0.11), R813 (r^2 = 0.39 and 0.12), R935 (r^2 = 0.35 and 0.10), NDVI (r^2 = 0.36 and 0.13), NIR/R (r^2 = 0.39 and 0.16), and Stress1 (r^2 = 0.12 and 0.12) (r ranging from 0.32 to 0.59) although the associations were not consistent during their two year study.

When data were analyzed separately by species (Table 3.6), results were similar to the relationships between green LAI and reflectance described above. For example, KBG had high correlations in the R507 (r = -0.87), R559 (r = -0.93), R706 (r = -0.93), R760 (r = -0.82), and R813 (r = -0.80). Aboveground biomass was strongly correlated with R613 (r = -0.88), R760 (r = 0.83), R813 (r = 0.89), R935 (r = 0.86), NDVI (r = 0.81), and NIR/R (r = 0.81) in TB. Stronger correlations between aboveground biomass and reflectance were found in bermuda at NDVI (r =

-0.83) and NIR/R (r = -0.82), in zoysia at R507 (r = -0.97), R559 (r = -0.97), R613 (r = -0.97), R661(r = -0.97), R706(r = -0.98), NDVI (r = 0.99) and NIR/R (r = 0.99). In rye, the strong correlations were found at R706 (r = -0.92), R760 (r = -0.91), and R813 (r = 0.90). In TF, however, no significant correlations were found between aboveground biomass and reflectance at any wavelengths or ratio.

In summary, our results did not indicate reflectance data as a strong predictor of green LAI and aboveground biomass in turfgrasses when data were pooled, although there were significant correlations at some wavelengths and NDVI. Stronger relationships were observed between LAI and aboveground biomass and reflectance when data were evaluated separately by species (e.g., r as high as 0.99). Small sample sizes (n=6) at only two heights per species, however, resulted in somewhat of a bimodal distribution in LAI and biomass between heights, which likely inflated r values artificially. Further measurements at smaller increments of height may increase confidence in the strength of the r values. Nevertheless, data indicated clear trends in the relationships between canopy reflectance and LAI and aboveground biomass.

Leaf area index and aboveground biomass among species and mowing heights

Green LAI varied significantly among species at all mowing heights (Fig. 3.4). At the high mowing height, LAI was greatest in TF and lowest in bermuda among species (Fig. 3.4.A). In TF, canopy density was visibly and consistently greater among species. In bermuda, a thick thatch layer probably reduced the canopy density and hence, reduced LAI. The LAI was similar among KBG, zoysia, and R. At lower mowing heights, LAI was greater in KBG than TB at 3.81 cm while at 0.56 cm, LAI was greater in zoysia than in bermuda (Fig. 3.4.B). Presumably, factors such as canopy structure and cultural management practices (e.g., that affect thatch layer development) result in differences in LAI among species mowed at the same heights. Not surprisingly, lower mowing reduced LAI in KBG, bermuda, zoysia, and PR (Fig. 3.5). In TB, however, LAI was not statistically different between two mowing heights.

Tall fescue had the greatest biomass and bermuda the least among species, which was similar to the trend observed in green LAI (Figs. 3.6.A and 3.4.A). Interestingly, KBG and TB were not significantly different at the low mowing height despite their differences in LAI (Fig. 3.6.B and 3.4.B). Zoysia was greater than bermuda at the low mowing height, however, which was the same trend as LAI. As with LAI, biomass was reduced with lower mowing in KBG, bermuda, zoysia, and PR (Figure 3.7). However, aboveground biomass in TB was not statistically different between mowing heights.

Relationships of chlorophyll concentration on reflectance

When data were pooled among species, no relationship was evident between chlorophyll a and reflectance at any wavelength or vegetation index. Chlorophyll *b*, however, had correlations with R661, R706, and NDVI (r = 0.35 to 0.44; Table 3.5). When chlorophyll concentration data were analyzed separately by species (Table 3.6), both bermuda and zoysia were correlated well with Ch *a* and Ch *b* at R507 (r = -0.86 and -0.93, respectively), R559 (r = -0.92 and -0.93, respectively), R613 (r = -0.97 and -0.92, respectively), R661 (r = -0.93 and -0.93, respectively), R706 (r = -0.91 and -0.94, respectively), NDVI (r = 0.86 and 0.93, respectively), and NIR/R (r = 0.87 and 0.92, respectively). In addition, Ch b had strong relationships with R760 (r = 0.99), and R935 (r = 0.99) in R and with R507 (r = 0.81) in rye. In other research, strong correlations were found between chlorophyll concentration and canopy reflectance at 705 nm and at the reflectance ratios of 750/705 nm in *Aescules hippocastanum* L. and *Acer platanoides* L.

leaves (Gitelson and Merzlyak, 1994), and 675/700 nm in soybean leaves ($r^2 > 0.97$) (Chappelle et al., 1992).

Conclusions

The strongest correlation between canopy spectral reflectance and visual quality ratings was at R507, R613, and R661, and the indices NDVI, NIR/R, Stress1 and Stress2, with correlation coefficients ranging from 0.68 to 0.77; correlations were weakest at R706 (r = -0.37).

Within each high mowing height, visual quality was significantly correlated with reflectance at all wavelengths and indices in KBG, TB, and R. However, TF showed weaker relationships at most wavelengths and vegetation indices. Analyses of covariance revealed discriminate regression models among grasses at each wavelength and index during the study. Relationships between visual quality and reflectance were greatest at the indices NDVI (linear) and NIR/R (quadratic).

Canopy density showed strong relationships with reflectance (r = 0.54 to 0.86) when data from all plots and measurement days were pooled. The highest correlations were obtained with NDVI, R661, R613, NIR/R, Stress1, and Stress2. When evaluated by species, different relationships were found between density ratings and reflectance at all wavelengths and indices although correlations were generally strongest in KBG and weakest in TF.

When data from all species and mowing heights were pooled, significant correlations were found between green LAI and reflectance at R507, R559, R613 and R706 (r = -0.54 to -0.63). Similar to LAI, aboveground biomass was significantly (albeit not strongly) correlated with R559 (r=-0.34), R661 (r=0.46), R706 (r=-0.34), and NDVI (r=-0.38). When data were analyzed separately by species and mowing height, stronger correlations between LAI or biomass and reflectance were found in some species at different wavelengths and ratios (r = 0.80 to 0.99).

No relationship was evident between chlorophyll a and reflectance at any wavelength or vegetation index, but Chlorophyll *b* had correlations with R661, R706, and NDVI when data were pooled among species. When data were analyzed by species, however, significant relationships were found of reflectance with both chlorophyll *a* (r = 86 to 94) and *b* (r = 0.83 to 0.99) although relationships with chlorophyll *a* were evident only with warm-season grasses (i.e., bermudagrass and zoysiagrass). Effects of sampling on warm-season grasses as they were going dormant may affect chlorophyll concentration.

In summary, results from this study indicate that evaluation of canopy characteristics using reflectance methods should evaluated separately by species because differences in their canopies may have important effects on spectral reflectance. Further research, perhaps using hyperspectral technology, is needed to determine the suitability of using reflectance to determine LAI and aboveground biomass in turfgrasses.

Figures and Tables

Figure 3.1 Visual quality among the four turfgrasses in the rainout shelter during the growing season in 2006. HBG (R), HBG (TB), KBG, and TF indicate Reveille, Thermal Blue, Kentucky bluegrass, and tall fescue, respectively.

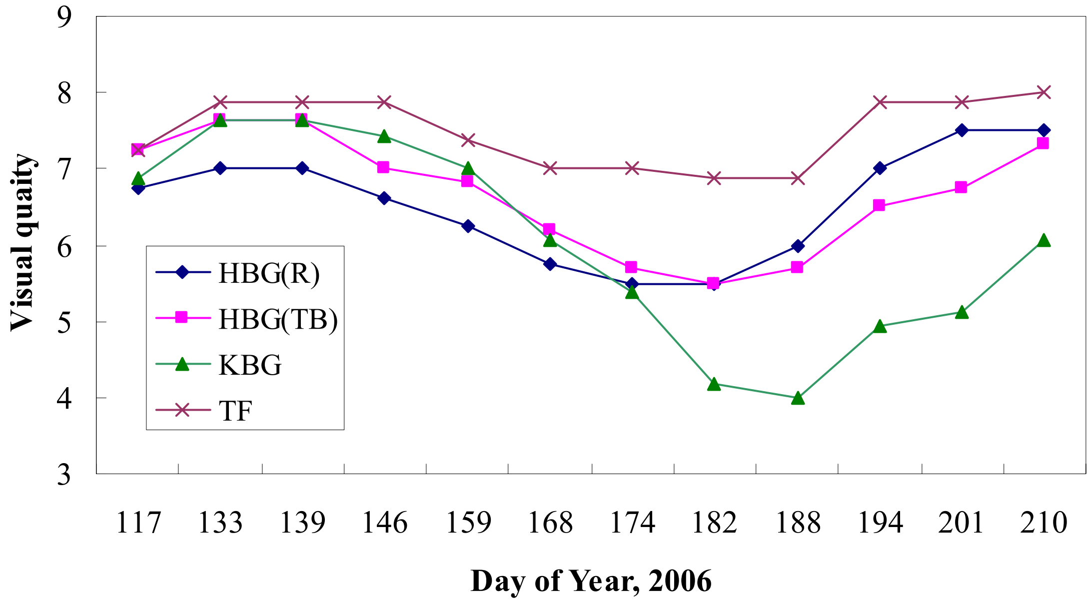
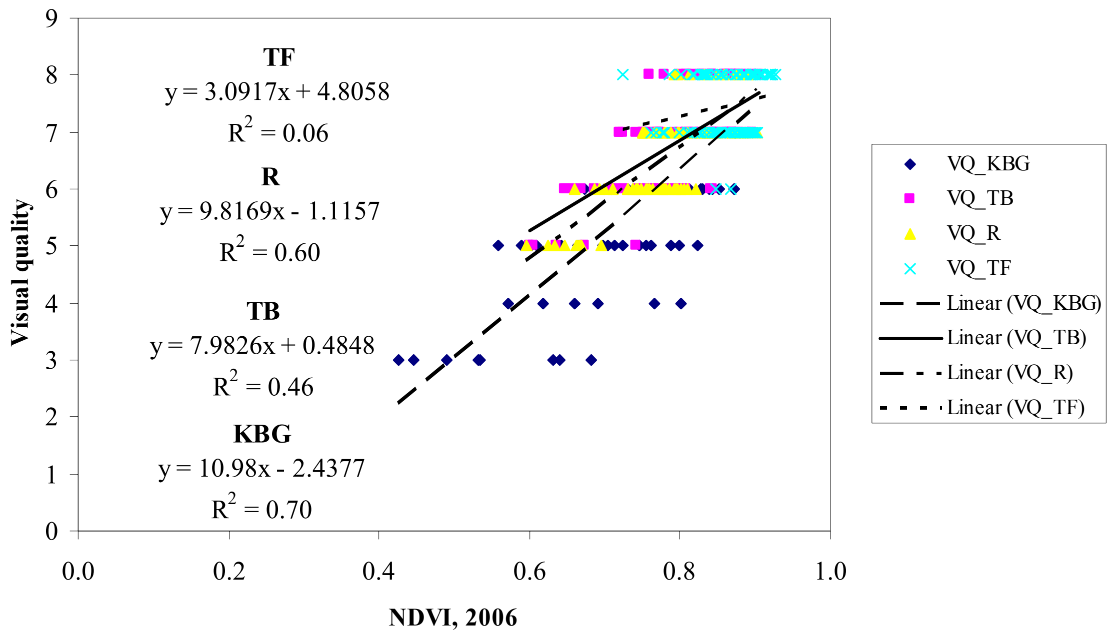


Figure 3.2 Regression models of individual species between visual quality (VQ) and normalized difference vegetation index (NDVI) (A), and near-infrared to red (NIR/R) (B) in 2006

A



B

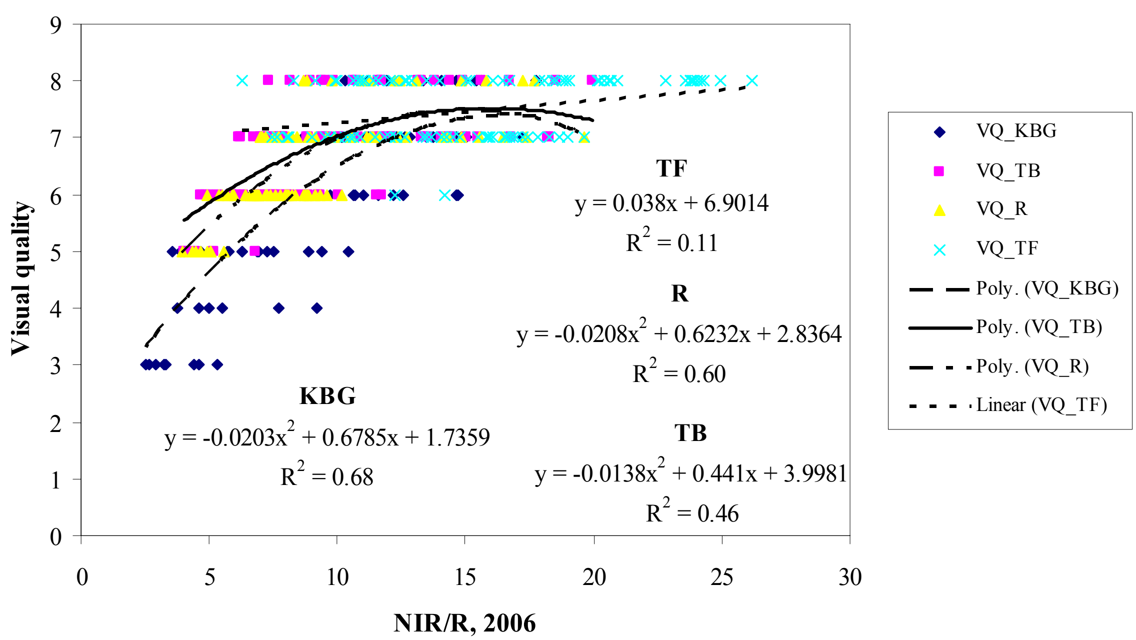
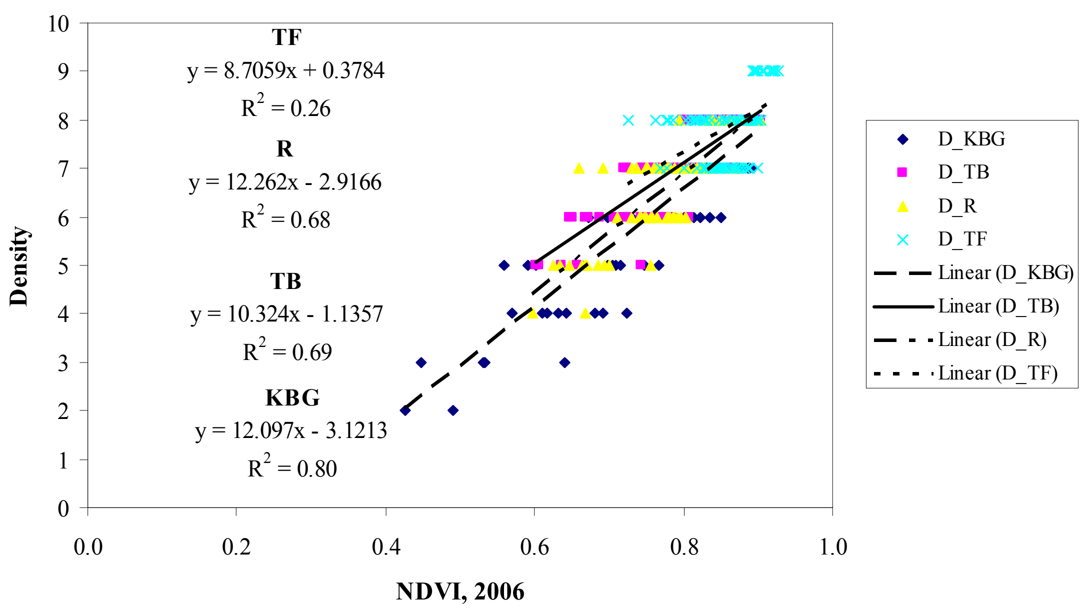


Figure 3.3 Regression models of individual species between density (D) and normalized difference vegetation index (NDVI) (A), and near-infrared to red (NIR/R) (B) in 2006

A



B

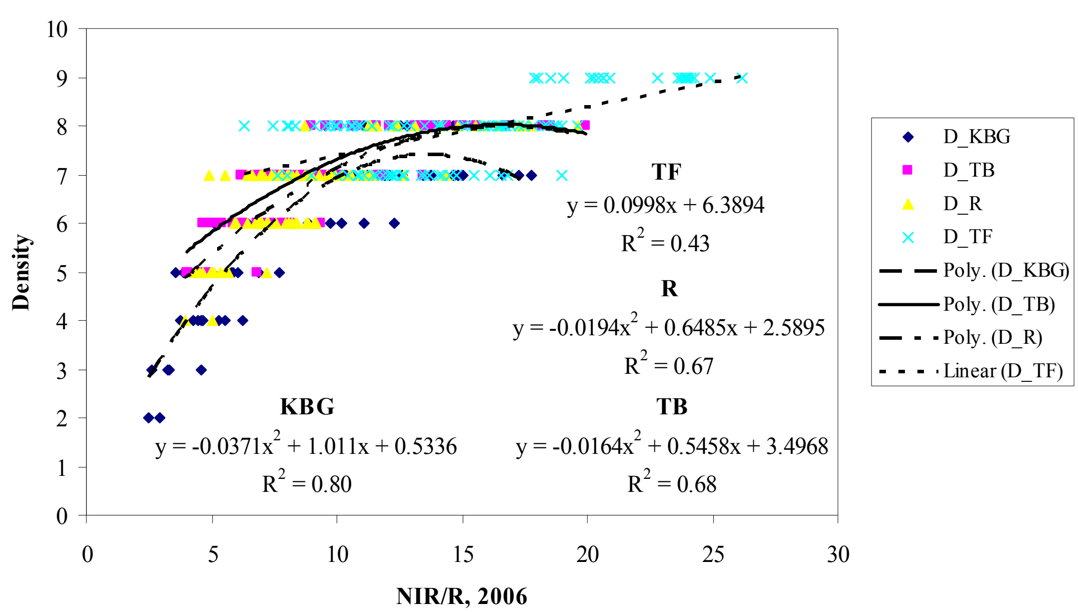


Figure 3.4 Species effects on leaf are index (LAI) at the each mowing height. High mowing height = 7.62 cm on all species (A); low mowing height = 3.81 cm in KB and TB, 0.56 cm in Bermuda and Zoysia (B). Means with the same letter are not significantly different.

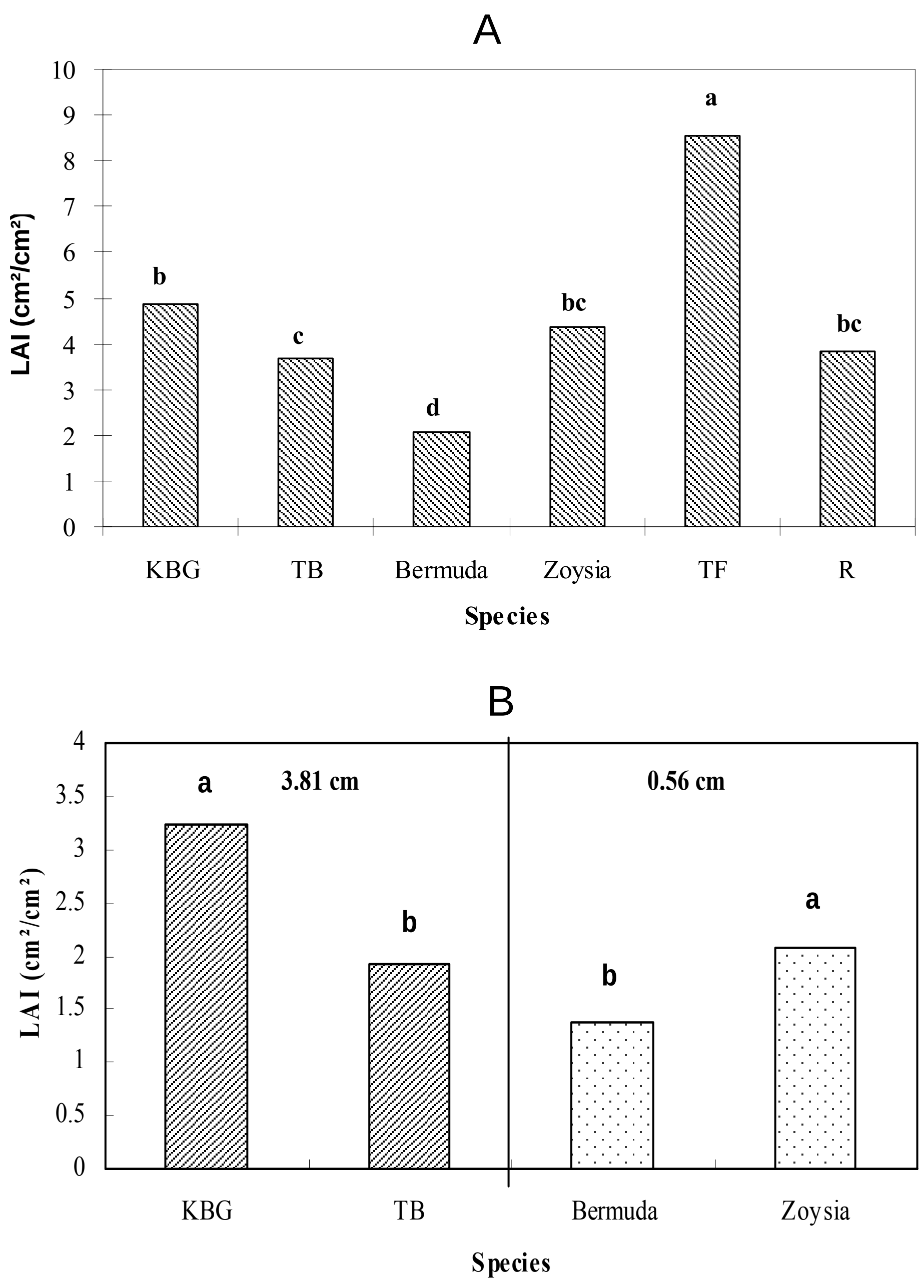


Figure 3.5 Effects of mowing height on leaf area index (LAI). High mowing height = 7.62 cm on all species except ryegrass = 8.89 cm; Low mowing height = 3.81 cm in KB and TB, 0.56 cm in Bermuda and Zoysia, 5.08 cm in Rye. Means with the same letter are not significantly different.

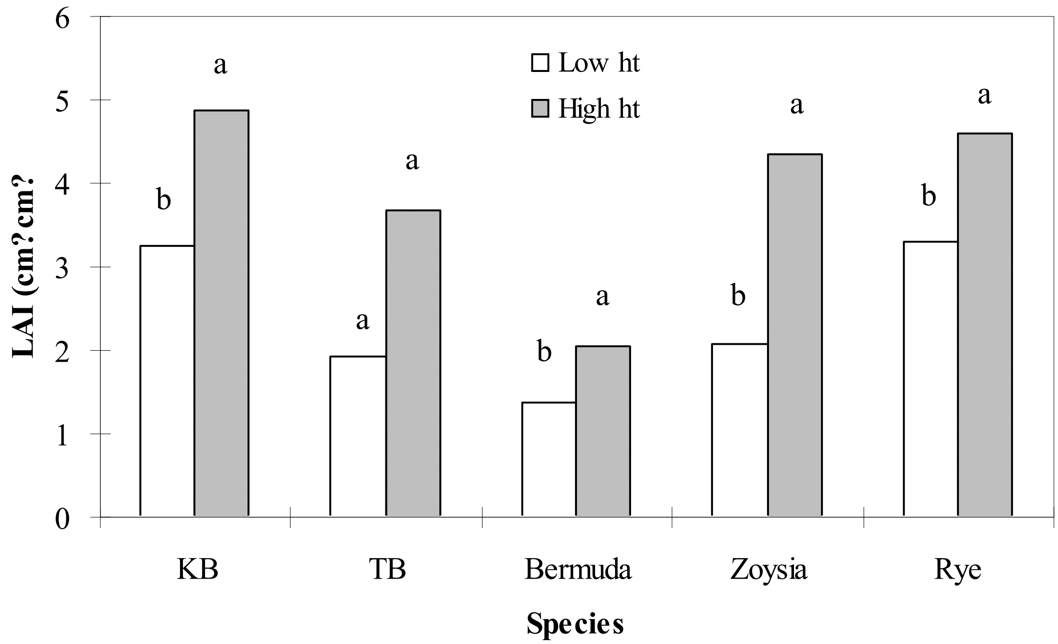
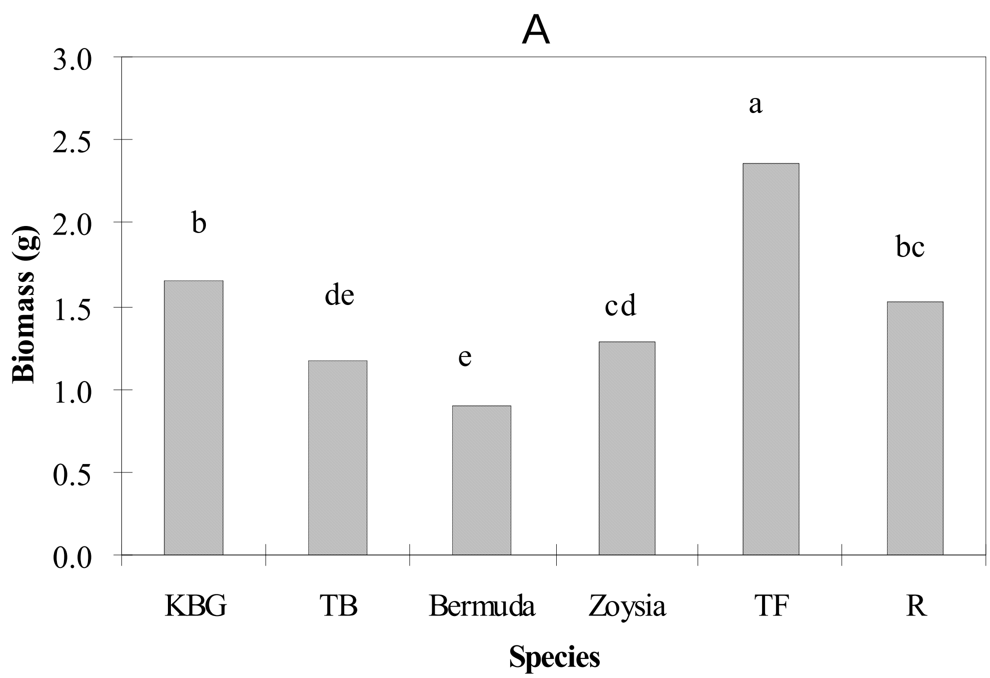


Figure 3.6 Species effects on aboveground biomass at the each mowing height. High mowing height = 7.62 cm on all species (A); low mowing height = 3.81 cm in KB and TB, 0.56 cm in Bermuda and Zoysia (B). Means with the same letter are not significantly different.



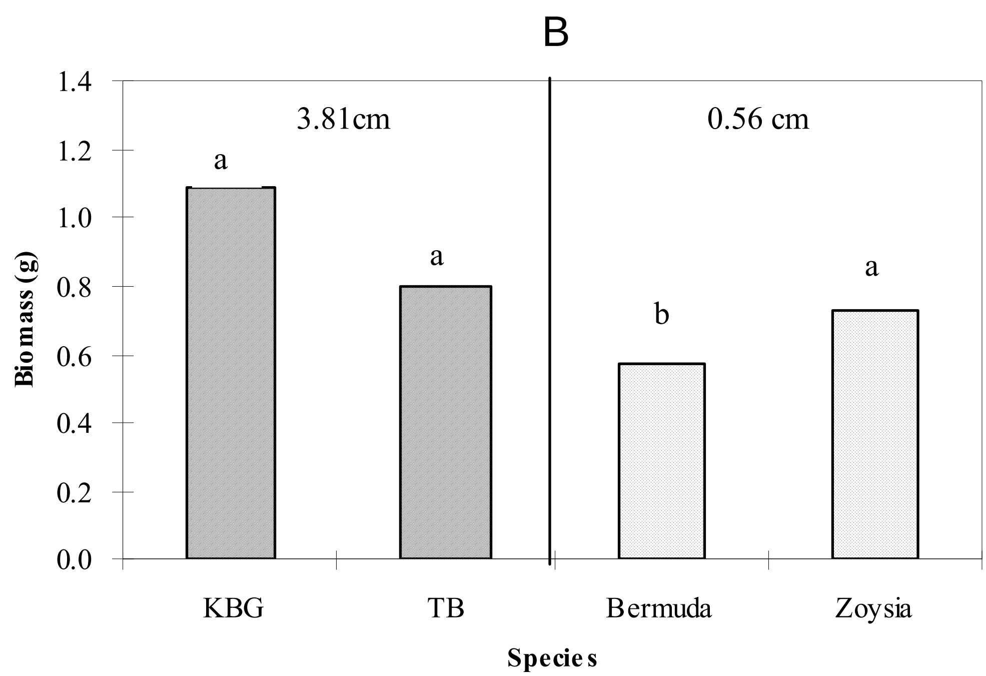


Figure 3.7 Effects of mowing height on aboveground biomass. High mowing height = 7.62 cm on all species except ryegrass = 8.89 cm; Low mowing height = 3.81 cm in KB and TB, 0.56 cm in Bermuda and Zoysia, 5.08 cm in Rye. Means with the same letter are not significantly different.

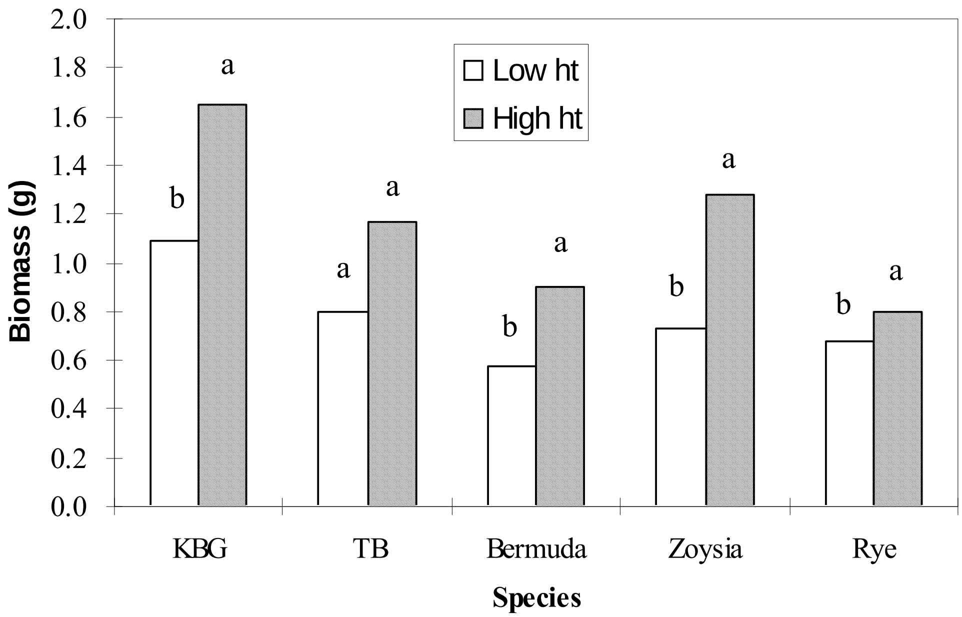


Table 3.1 Coefficient estimates of reflectance at each wavelength and ratio versus visual quality in four cool-season turfgrasses in 2006 (n =576) (data from all turfgrasses, mowing heights, and measurement dates were pooled).

Wavelengths & Ratios¥	β_0	β_1	β_2	r^2	Corr.
R507	9.95	-0.76	-	0.49	-0.70***
R559	10.79	-0.59	-	0.37	-0.61***
R613	9.29	-0.45	-	0.50	-0.71***
R661	8.64	-0.38	-	0.53	-0.73***
R706	10.25	-0.22	-	0.14	-0.37***
R760	-7.93	0.63	-0.0064	0.30	0.55***
R813	-10.88	0.69	-0.0064	0.38	0.62***
R935	-11.25	0.63	-0.0053	0.29	0.54***
NDVI	-1.43	10.15	-	0.59	0.77***
NIR/R	3.17	0.49	-0.0132	0.46	0.68***
Stress1	11.02	-10.07	-	0.46	-0.68***
Stress2	11.09	-11.37	-	0.49	-0.70***

*** Significant at 0.0001 probability level.

β_0, β_1, and β_2 represent the intercept, linear coefficient, and quadratic coefficient, respectively.

Abbreviation of corr. means correlation coefficient.

¥ Percentage of reflectance at selected wavelengths of ratios. NDVI, normalized difference vegetation index computed as (R935-R661)-(R935+R661); NIR/R, near infrared to red computed as R935/R661; Stress1 computed as R706/R760; and Stress2 computed as R706/R813.

Table 3.2 Correlation between visual quality and reflectance data at each wavelength and vegetation ratios within four turfgrasses at high mowing height in 2006 (n=96). Shaded cells denote highest correlations in a given species. The highest correlation coefficients each species are highlighted.

Wavelengths & Ratios¥	KBG† Corr.	TB‡ Corr.	R¶ Corr.	TF§ Corr.
R507	-0.80***	-0.50***	-0.55***	-0.23*
R559	-0.77***	-0.39***	-0.50***	-0.50***
R613	-0.77***	-0.55***	-0.64***	-0.45***
R661	-0.77***	-0.63***	-0.73***	-0.32**
R706	-0.45***	-0.25*	-0.34**	-0.53***
R760	0.78***	0.34**	0.60***	ns
R813	0.82***	0.41***	0.72***	ns
R935	0.78**	0.32***	0.67***	ns
NDVI	0.83***	0.65***	0.77***	0.24*
NIR/R	0.80***	0.59***	0.69***	0.34**
Stress1	-0.79***	-0.51***	-0.63***	ns
Stress2	-0.82***	-0.57***	-0.68***	-0.28**

*, **, *** Significant at 0.05, 0.001, and 0.0001 probability levels, respectively.

† Kentucky bluegrass; ‡ Thermal Blue; ¶ Reveille; § tall fescue.

Abbreviation of corr. means correlation coefficient.

¥ Percentage of reflectance at selected wavelengths of ratios. NDVI, normalized difference vegetation index computed as (R935-R661)-(R935+R661); NIR/R, near infrared to red computed as R935/R661; Stress1 computed as R706/R760; and Stress2 computed as R706/R813.

Table 3.3 Coefficient estimates of reflectance at each wavelength and ratio versus density ratings in four cool-season turfgrasses in 2006 (n =576) (data from all turfgrasses, mowing heights, and measurement dates were pooled).

Wavelengths & Ratios¥	β_0	β_1	β_2	r^2	Corr.
R507	10.79	-0.90	-	0.60	-0.77***
R559	12.08	-0.73	-	0.50	-0.71***
R613	10.14	-0.55	-	0.66	-0.81***
R661	-9.34	-0.46	-	0.71	-0.84***
R706	-12.73	-0.36	-	0.31	-0.56***
R760	-1.49	0.14	-	0.30	0.55***
R813	0.76-	0.14	-	0.37	0.61***
R935	-0.53	0.13	-	0.29	0.54***
NDVI	-2.77	12.13	-	0.74	0.86***
NIR/R	2.99	0.54	-0.01	0.58	0.76***
Stress1	-12.40	-12.71	-	0.64	-0.80***
Stress2	-12.43	-14.19	-	0.67	-0.82***

*** Significant at 0.0001 probability level

β_0, β_1, and β_2 represent the intercept, linear coefficient, and quadratic coefficient, respectively. Abbreviation of corr. means correlation coefficient.

¥ Percentage of reflectance at selected wavelengths of ratios. NDVI, normalized difference vegetation index computed as (R935-R661)-(R935+R661); NIR/R, near infrared to red computed as R935/R661; Stress1 computed as R706/R760; and Stress2 computed as R706/R813.

Table 3.4 Correlation between density ratings and reflectance data at each wavelength and vegetation ratios within four turfgrasses at high mowing height in 2006 (n=96). Shaded cells denote highest correlations in a given species. The highest correlation coefficients each species were highlighted.

wavelengths & Ratios¥	KBG† Corr.	TB‡ Corr.	R¶ Corr.	TF§ Corr.
R507	-0.84***	-0.71***	-0.66***	-0.38**
R559	-0.84***	-0.67***	-0.62***	-0.59***
R613	-0.86***	-0.78***	-0.73***	-0.54***
R661	-0.88***	-0.84***	-0.79***	-0.44***
R706	-0.68***	-0.57***	-0.52***	-0.48***
R760	0.70***	0.21*	0.55***	0.38**
R813	0.71***	0.28**	0.65***	0.47***
R935	0.66***	0.21*	0.60***	0.43***
NDVI	0.89***	0.83***	0.82***	0.51***
NIR/R	0.81***	0.77***	0.77***	0.66***
Stress1	-0.88***	-0.71***	-0.73***	-0.57***
Stress2	-0.89***	-0.78***	-0.78***	-0.67***

*, **, *** Significant at 0.05, 0.001, and 0.0001 probability levels, respectively.

† Kentucky bluegrass; ‡ Thermal Blue; ¶ Reveille; § tall fescue.

Abbreviation of corr. means correlation coefficient.

¥ Percentage of reflectance at selected wavelengths of ratios. NDVI, normalized difference vegetation index computed as (R935-R661)-(R935+R661); NIR/R, near infrared to red computed as R935/R661; Stress1 computed as R706/R760; and Stress2 computed as R706/R813.

Table 3.5 Correlation coefficients of spectral reflectance at each wavelength and vegetation indices versus chlorophyll b, green LAI, and aboveground biomass in seven turfgrasses in 2006 (n = 36) (data for all species and mowing height pooled).

	Wavelengths & Ratio¥	r^2 (Linear)	r^2 (Quadratic)	Correlation Coefficient	P-value
Green LAI	R507	0.36	0.38	-0.60	0.0001
	R559	0.40	0.41	-0.63	<.0001
	R613	0.30	0.42	-0.54	0.0006
	R706	0.35	0.36	-0.59	0.0002
Green Biomass	R559	0.11	0.26	-0.34	0.0443
	R661	0.21	0.42	0.46	0.0047
	R706	0.12	0.22	-0.34	0.0409
	NDVI	0.15	0.20	-0.38	0.0207
Chlorophyll b	R661	0.18	0.28	0.43	0.0089
	R706	0.12	0.17	-0.35	0.0381
	NDVI	0.19	0.35	-0.44	0.0079

¥ Percentage of reflectance at selected wavelengths of ratios. NDVI, normalized difference vegetation index computed as (R935-R661)-(R935+R661)

Table 3.6 Correlation table between green LAI, aboveground biomass, and chlorophyll concentration (chlorophyll a and chlorophyll b with each reflectance and vegetation indices by species in 2006. Significant at 0.05 probability level. Dash (-) means that no significant differences were found.

	KBG†	TB‡	R¶	Bermudaǂ	Zoysiaʡ	Ryeɸ	TF §
507	LAI(r= -0.82)* Bio(r= -0.87)*	-	-	Ch a(r= -0.86)* Ch b(r= -0.83)*	LAI(r= -0.97)** Bio(r= -0.97)** Ch a(r= -0.93)* Ch b(r= -0.88)	LAI(r= -0.92)* Ch b(r= 0.81)*	-
559	LAI(r= -0.90)* Bio(r= -0.93)*	-	-	Ch a(r= -0.92)* Ch b(r= -0.91)*	LAI(r= -0.97)** Bio(r= -0.97)** Ch a(r= -0.93)* Ch b(r= -0.89)*	LAI(r= -0.94)**	-
613	LAI(r= -0.91)*	Bio(r= -0.88)*	-	Ch a(r= -0.97)** Ch b(r= -0.97)**	LAI(r= -0.97)** Bio(r= -0.89)** Ch a(r= -0.92) Ch b(r= -0.88)	LAI(r= -0.88)*	-
661	-	-	LAI(r=0.99)*	Ch a (r= -0.93)* Ch b(r= -0.90)*	LAI(r= -0.97)** Bio(r= -0.98)** Ch a(r= -0.93)* Ch b(r= -0.90)*	-	-
706	LAI(r= -0.88)* Bio(r= -0.93)*	-	-	Ch a(r= -0.91),* Ch b(r= -0.89)*	LAI(r= -0.95)** Bio(r= -0.95)** Ch a(r= -0.94)** Ch b(r= -0.89)*	LAI(r= -0.96)**	-
760	Bio(r= -0.82)*	Bio(r=0.83)*	Ch b (r=0.99)	-	-	LAI(r= -0.92)** Bio(r= -0.94)*	-
813	Bio(r= -0.80)*	LAI(r=0.87)* Bio(r=0.89)*	Bio(r= -0.99)*	-	-	LAI(r= -0.91)** Bio(r= -0.93)*	-
935	-	Bio(r=0.86)*	Ch b (r=0.90)	-	-	LAI(r= -0.90)** Bio(r= -0.95)*	-
NDVI	-	Bio(r=0.81)*	LAI(r=0.85)*	LAI(r= 0.80) * Bio(r= -0.83)* Ch a(r= 0.86)* Ch b(r= 0.86)*	LAI(r= 0.99)** Bio(r= 0.99)** Ch a(r= 0.93)* Ch b(r= 0.90)	-	-
NIR/ R	-	Bio(r=0.81)*	-	Bio(r= -0.82)*, Ch a(r= 0.87)* Ch b(r= 0.87)*	LAI(r= 0.99)*** Bio(r= 0.99)** Ch a(r= 0.92)* Ch b(r= 0.90)*	-	-

*, **, *** Significant at 0.05, 0.005, and 0.0001 probability levels, respectively.

† Kentucky bluegrass; ‡ Thermal Blue; ¶ Reveille; § tall fescue; ǂ bermudagrass; ʡ zoysiagrass; ɸ ryegrass.

References

Asrar, G., M. Fuchs, E.T. Kanemasu, and J.L. Hatfield. 1984. "Estimating absorbed photosynthetic radiation and leaf area index from spectral reflectance in wheat". *Agron. J* 76:300-306.

Chappelle, E.W., M.S. Kim, and J.E. McMurtrey. 1992. "Ratio analysis of reflectance spectra (RARS): An algorithm for the remote estimation of the concentrations of chlorophyll a, chlorophyll b, and carotenoids in soybean leaves". *Remote Sens. Environ.* 39: 239–247.

Bell, G.E., Howell, B.M., Johnson, G.V., Raun, M.L., Solie, J.B., and Stone, M.L. 2004. "Optical sensing of turfgrass chlorophyll concentration and tissue nitrogen". *HortScience* 39(5):1130-1132.

Brede, A. D., and J. M. Duich. 1980. "A mathematical estimate of the leaf area index of Kentucky bluegrass turf". *p*. 114. *In Agronomy abstracts. ASA*. Madison, WI.

Danks, S.M., E.H. Evans, and P.A. Whittaker. 1983. *Structure function and assembly*. In Photosynthetic systems, Wiley, NY.

Daughtry, C.S.T., K.P. Gallo, N.S. Goward, S.D. Prince, and W.P. Kautas. 1992. "Spectral estimates of absorbed radiation and phytomass production in corn and soybean canopies". *Remote Sens. Environ* 39:141-152.

Fitz-Rodriguez, E. and C.Y. Choi. 2002. "Monitoring turfgrass quality using multispectral Radiometry". American Society of Agricultural Engineers ISSN. Vol. 45(3): 865-867.

Gitelson, A. and M.N. Merzlyak. 1994. "Spectral reflectance changes associated with autumn senescence of *Aesculus-Hippocastanum* (L.) and *Acer-Platanoides* (L.) leaves: spectral features and relation to chlorophyll estimation". *J. Plant Physiol.* 143:286-292.

Haboudane, D., J.R. Miller, N. Tremblay, P.J. Zarco-Tejada, and L. Dextraze. 2002. "Integrated narrow-band vegetation indices for prediction of crop chlorophyll content of application to precision agriculture". *Remote Sensing of Environment* 81 (2-3):416-426.

Hansen, P.M. and Schjoerring, J.K. 2003. "Reflectance measurement of canopy biomass and nitrogen status in wheat crops using normalized difference vegetation indices and partial least squares regression". *Remote Sensing of Environment* 86:542-553.

Jiang, Y. and R.N. Carrow. 2007. "Broadband spectral reflectance models of turfgrass species and cultivars to drought stress". *Crop Science* 47:1611-1618.

Jiang, Y. and R.N. Carrow. 2005. "Assessement of narrow-band canopy spectral reflectance and turfgrass performance under drought stress". *HortScience* 40(1):242-245.

Kopec D.M., J.M. Norman, R.C. Shearman, and M.P. Peterson. 1987. "An indirect method for estimating turfgrass leaf area index". *Crop Science* 27:1298-1301.

Mangiafico, S.S. and Guillard, K. 2005. "Turfgrass reflectance measurement, chlorophyll, and soil nitrate desorbed from anion exchange membranes". *Crop Science* 45:259-265.

Morris, Kevin N. 2005. "A guide to NTEP turfgrass ratings". (http://www.ntep.org/reports/ratings.htm).

Raikes, C. and L.L. Burpee. 1998. "Use of multispectral radiometry for assessment of hizoctonia blight in creeping bentgrass". *The American Phytopathological Society* 88:446-449.

Su, K., D.J. Bremer, S.J. Keely, and J.D. Fry. 2008. "Rooting characteristics and canopy responses to drought of turfgrasses including hybrid bluegrsses". *Agron. J.* 100:949-956.

Taiz, L. and E. Zeiger. 2002. *Plant physiology*. 3rd edition. Sundrland, MA: Sinauer Associates, Inc.

Trenholm, L.E., R.N. Carrow, and R.R. Duncan.1999. "Relationship of multispectral radiometry data to qualitative data in turfgrass research”. *Crop Science* 39:763-769.

Vescovo L., Zorer R., Belli C., Cescatti A., and Gianelle D. 2004. “Use of vegetation indexes to predict biomass and LAI of Trentino grasslands”. *Land Use Systems in Grassland Dominated Regions*: proceeding of the 20th general meeting of the European grassland federation, Luzern, Switzerland.

Wellburn, A. R. 1994. “The spectral determination of chlorophylls a and b, as well as total carotenoids, using various solvents with spectrophotometers of different resolution”. *Plant Physiol*. 144:307-313.

Yang, Y. and P. P. Ling. 2000. “Chlorophyll concentration change detection using derivative spectra”. Written for presentation at the 2000 ASAE annual international meeting.

Zarco-Tejada, P.J., Ustin, S.L., and Whiting, M.L. 2005. “Temporal and spatial relationships between within-field yield variability in cotton and high-spatial hyperspectral remote sensing imagery”. *Agronomy Journal* 97:641-653.

Appendix A - Abbreviations

DOY	day of year
MSR	multispectral radiometer
NDVI	normalized difference vegetation index
NIR/R	near infrared to red
R507	reflectance at waveband 507
KBG	Kentucky bluegrass
HBG (TB)	hybrid bluegrass. ‘Thermal Blue’
HBG(R)	hybrid bluegrass, ‘Reveille’
TF	tall fescue
Zoysia	zoysiagrass
Bermuda	bermudargrass
Rye	ryegrass
LAI	leaf area index
A_{649}	absorbance at 649 nm
Ch *a*	chlorophyll *a*
Ch *b*	chlorophyll *b*