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Relationships between Normalized Difference Vegetation Index and Visual Quality in Cool-Season Turfgrass: I. Variation among Species and Cultivars

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ABSTRACT

Canopy spectral reflectance may provide an objective means to evaluate visual quality of turfgrass, but evaluations of visual quality may be confounded by differences in reflectance among species or cultivars. In this 3-yr study near Manhattan, KS, we examined effects of species and cultivars on relationships between normalized difference vegetation index (NDVI) and visual quality ratings in Kentucky bluegrass (*Poa pratensis* L., 'Apollo'), two Kentucky bluegrass × Texas bluegrass (*Poa arachnifera* Torr.) hybrids ('Thermal Blue' and 'Reveille'), and tall fescue (*Festuca arundinacea* Schreb., 'Dynasty'). A broad range of visual quality was imposed on all four grasses through deficit irrigation and NDVI was measured using broadband spectral radiometry across this range for each grass. Distinct linear regression models of visual quality were found for each grass, and models were also distinct among years in each grass. Relationships between NDVI and visual quality were stronger in the bluegrasses (r^2 = 0.41 to 0.83) because they had a greater range in quality under deficit irrigation than tall fescue. The 95% confidence intervals surrounding predictions of visual quality from NDVI ranged from ± 1.25 to 2.10 (on a 1 to 9 scale). Results indicated that the requirement to develop separate models for each grass and in each year, combined with relatively wide confidence intervals, represents a practical limitation to predicting visual quality with NDVI.

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Abbreviations: NDVI, normalized difference vegetation index; R661, reflectance at 661 nm; R935, reflectance at 935 nm.

Turfgrass quality is evaluated by integrating factors of canopy density, texture, uniformity, color, growth habit, and smoothness (Turgeon, 1991). The traditional method of evaluating turfgrass quality is visually, in which an observer rates the appearance of turfgrass on a numeric scale. Although this method is relatively fast to implement, it is subjective. Some researchers have contended that visual ratings may vary significantly among evaluators or even with the same evaluator over time, and that such ratings tend to be inaccurate and nonreproducible (Horst et al., 1984; Bell et al., 2002).

Multispectral radiometry, which measures the spectral reflectance of plant canopies at a number of wavelengths, has been proposed as an alternative to visual ratings because spectral reflectance may provide objective measurements of turfgrass quality. For example, Trenholm et al. (1999), using multispectral radiometry, reported significant correlations between spectral reflectance and visual quality in seashore paspalum (*Paspalum vaginatum* Sw.) ecotypes and hybrid bermudagrass cultivars [*Cynodon dactylon* (L.) Pers. × *C. transvaalensis* Burtt Davy, 'Midiron']. In other studies, vegetation indices calculated from reflectance data were also strongly correlated with visual quality in a number of turfgrass species and under

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different cultural practices (Bell et al., 2002; Fitz-Rodriguez and Choi, 2002; Keskin et al., 2008; Lee et al., 2011).

Turfgrass species and/or cultivar selection is an important management decision that may be determined by several factors at a given site, including its functional role (e.g., golf course tees, greens, fairways, or roughs, sports fields, home or commercial lawns), geographical location (e.g., climate, soils), drought resistance, personal preference, etc. Among turfgrass species and cultivars, there are significant differences in canopy characteristics that may affect reflectance. For example, differences in leaf angle, leaf width, cell wall constituents, shoot water content, leaf turgidity, and canopy density have been reported among cultivars of Kentucky bluegrass (*Poa pratensis* L.) (Berry et al., 1969; Brede and Duich, 1982; Brosnan et al., 2005). In tall fescue (*Festuca arundinacea* Schreb.), differences in leaf width, thickness, tissue density, and stomatal density were found among 12 cultivars (Fu and Huang, 2004). Differences in leaf characteristics and growth habits have also been reported among bentgrass species (*Agrostis* spp.) and bermudagrass cultivars [*Cynodon dactylon* (L.) Pers.] (Rodriguez et al., 2001; Bonos et al., 2002). Many of these canopy characteristics have been shown to affect spectral reflectance (Gausman, 1977; Penuelas et al., 1993; Trenholm et al., 2000; Stiegler et al., 2005; Jensen, 2007).

Information is limited and mixed about the effects of turfgrass species or cultivars on models used to predict visual quality from spectral reflectance. Keskin et al. (2008) developed a sensor to predict quality from reflectance and concluded that one model was sufficient for both hybrid bermudagrass and rough bluegrass (*Poa trivialis* L.). Jiang and Carrow (2005, 2007), however, reported different optimal models among 11 turfgrass species and cultivars although their objectives were not to statistically compare models to one another. Others found that correlations between visual quality and spectral reflectance varied substantially between years, suggesting that different models may be required in each year even in the same plots (Jiang et al., 2009). In fact, Lee et al. (2011) compared models between two turfgrass species over 2 yr and reported that the models were different between species and between years within each species.

Because of the increasing interest in the use of spectral reflectance to evaluate turfgrass visual quality, we felt it was timely to conduct a test to evaluate the practicality of using spectral reflectance models to predict visual quality across multiple turfgrasses and years. Therefore, in this 3-yr study our objectives were to statistically compare models of relationships between normalized difference vegetation index (NDVI) and visual quality ratings among four turfgrasses using the same method as Lee et al. (2011), who, in research investigating the effects of mowing height on NDVI, only evaluated two grasses over 2 yr. We evaluated relationships between NDVI and visual quality in Kentucky bluegrass, two hybrid bluegrasses, and tall fescue, which are all cool-season turfgrasses.

MATERIALS AND METHODS

Study Site

This 3-yr study was conducted from 26 July to 3 Oct. 2004, 20 June to 30 Sept. 2005, and 26 Apr. to 28 July 2006, under an automated rainout shelter (12 by 12 m) at the Rocky Ford Turfgrass Research Center near Manhattan, KS (39°13′53″ N, 96°34′51″ W). The rainout shelter shielded turfgrass plots from precipitation and, therefore, allowed for precise applications of water. A minimum of 0.25 mm of precipitation activated the shelter, which rested north of the study area, to completely cover the plots within 2 min. The shelter then returned to its resting position 1 h after precipitation stopped. The soil at the site was a Chase silt loam (fine, smectitic, mesic Aquertic Argiudoll).

Plots were established in September 2003 with a Kentucky bluegrass (‘Apollo’), two Kentucky × Texas bluegrass (*Poa arachnifera* Torr.) hybrids (‘Thermal Blue’ and ‘Reveille’), and tall fescue (‘Dynasty’). Thirty-two plots (1.36 by 1.76 m) were bordered by metal edging (10 cm depth) to prevent lateral soil water movement between adjacent plots. Two irrigation treatments were imposed to broaden the turfgrass quality range in the study. The two treatments were 60% (water deficit) and 100% (well watered) evapotranspiration replacement. Plots were arranged in a randomized complete block design with four replications.

Water was applied by hand twice a week through a fan spray nozzle attached to a hose; a meter (Model 03N31, GPI, Wichita, KS) was attached to ensure proper application rate. To determine irrigation amounts, evapotranspiration was calculated by using the Penman–Monteith equation (Allen et al., 1998) and climatological data obtained at an on-site weather station. Plots were mowed at 7.6 cm twice a week with a walk-behind rotary mower. Further details about plot preparation and maintenance are available in Su et al. (2008), who conducted their research concurrently with this project on the same plots.

Measurements of Visual Quality, Spectral Reflectance, and Leaf Area and Biomass

The visual quality of each plot was rated by one researcher in 2004 and by another researcher in 2005 and 2006. Both researchers were trained by experienced visual quality evaluators using materials from a National Turfgrass Evaluation Program Workshop. Visual quality was rated 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).

Spectral reflectance of the canopy was measured with a hand-held multispectral radiometer (model MSR16, Crop-Scan, Rochester, MN) concurrently with visual quality ratings. Reflectance was determined in 25 to 32 nm band widths centered on 507, 559, 613, 661, 706, 760, and 813 nm and in a 290 nm band width centered on 935 nm. To minimize solar radiation effects, matched upward and downward sensor arrays provided a measure of incident radiation as a baseline for the reflected radiation in the same band. Two reflectance measurements (0.5 m diam. each) of the turfgrass surface were collected near the center of each plot with the sensor at 1 m above ground level and the two measurements were averaged. To reduce variation,

Table 1. Models from Kentucky bluegrass, two hybrid bluegrasses ('Thermal Blue' and 'Reveille'), and tall fescue in 2004 (n = 64 per grass), 2005 (n = 96 per grass), and 2006 (n = 96 per grass), 95% confidence interval ranges (CI) of models in predicting visual quality (VQ) from normalized difference vegetation index (NDVI), coefficients of determination (r^2) between VQ and NDVI, and range in VQ and NDVI among grasses in each year.

Year	Turfgrass	Models	CI range: predicting visual quality from NDVI†	r^2‡	Range visual quality	Range NDVI
2004	Kentucky bluegrass	NDVI = 0.042 × VQ + 0.513	±2.10	0.38	6 to 8	0.69 to 0.90
	Hybrid bluegrass (Thermal Blue)	NDVI = 0.063 × VQ + 0.356	±1.89	0.44	5 to 8	0.55 to 0.91
	Hybrid bluegrass (Reveille)	NDVI = 0.052 × VQ + 0.424	±1.51	0.41	6 to 8	0.65 to 0.87
	Tall fescue	NDVI = 0.018 × VQ + 0.729	–§	0.09	6 to 8	0.80 to 0.92
2005	Kentucky bluegrass	NDVI = 0.068 × VQ + 0.330	±1.25	0.83	4 to 8	0.50 to 0.89
	Hybrid bluegrass (Thermal Blue)	NDVI = 0.068 × VQ + 0.310	±1.38	0.80	4 to 8	0.46 to 0.86
	Hybrid bluegrass (Reveille)	NDVI = 0.051 × VQ + 0.430	±1.36	0.71	4 to 8	0.54 to 0.85
	Tall fescue	NDVI = 0.035 × VQ + 0.580	±1.51	0.56	5 to 8	0.71 to 0.90
2006	Kentucky bluegrass	NDVI = 0.062 × VQ + 0.397	±1.96	0.68	3 to 8	0.43 to 0.89
	Hybrid bluegrass (Thermal Blue)	NDVI = 0.053 × VQ + 0.428	±1.39	0.42	5 to 8	0.60 to 0.90
	Hybrid bluegrass (Reveille)	NDVI = 0.061 × VQ + 0.380	±1.81	0.59	5 to 8	0.60 to 0.90
	Tall fescue	NDVI = 0.019 × VQ + 0.725	–§	0.05	6 to 8	0.73 to 0.93

†Inverse prediction method.

‡All values were significant (p = 0.05).

§CI could not be estimated because of large mean square error.

canopy reflectance was taken between 1100 and 1330 h central standard time on days with no cloud cover (Chang et al., 2005). Reflectance was measured 1 d after mowing, unless prevented by inclement weather, in which case measurements were made the following day. All turfgrass plots were fully vegetated and, thus, soil background effects were considered negligible. Measurements were collected on 8 d in 2004 and 12 d each in 2005 and 2006, resulting in 64 measurements per grass in 2004 and 96 measurements per grass each in 2005 and 2006.

Turfgrass visual quality was compared with reflectance at each wavelength as well as with four vegetation and stress indices; results from that extensive analysis were presented by Lee (2008). Of all wavelengths and indices evaluated, NDVI consistently had the greatest correlations with visual quality; NDVI was computed as (R935 – R661)/(R935 + R661), where R935 denotes reflectance at 935 nm and R661 denotes reflectance at 661 nm (Trenholm et al., 1999). Other studies have also reported strong correlations between NDVI and visual quality in turfgrasses (Trenholm et al., 1999; Fitz-Rodriguez and Choi, 2002; Jiang and Carrow, 2007; Keskin et al., 2008; Lee et al., 2011). In addition, a number of commercial instruments have the ability to measure NDVI but not necessarily additional multiple wavebands or indices. Therefore, results from NDVI were evaluated in this study.

Statistical Analysis

Data among plots were analyzed with correlation, regression, and general linear model procedures of SAS (SAS Institute, 2008) for comparisons between visual quality ratings and NDVI. Regression data were analyzed among grasses, separately in each year to determine whether relationships between NDVI and visual quality varied: (i) among grasses within each year and (ii) among years within each grass. The general linear model procedure was used to conduct analysis of covariance to test for equal slopes and intercepts in regression models among species and years (Milliken and Johnson, 2002). Inverse prediction was used to estimate visual quality from NDVI and 95% confidence intervals (Kutner et al., 2004). This is the same method that was used by Lee et al. (2011) to evaluate prediction models of visual quality from NDVI in two turfgrass species.

For each grass × year model, normality of residuals was tested in the SAS UNIVARIATE procedure (SAS Institute, 2008), with the result that all models except for the hybrid bluegrass Thermal Blue in 2004 and tall fescue in 2005 and 2006 had normally distributed residuals. For the hybrid Thermal Blue in 2004 and tall fescue in 2005, residuals were not normal but were symmetric and light tailed so that the standard errors for regression coefficient estimates were likely somewhat larger than they would be under normality and, hence, tests were more conservative with respect to Type I error rate. For tall fescue in 2006, residuals were negatively skewed. However, tests of Type II error rates are unbiased whether or not there is normality and, thus, the inverse predictions were also unbiased for tall fescue in 2006.

RESULTS AND DISCUSSION

Analysis of covariance revealed distinct linear models that defined the relationships between NDVI and visual quality among all grasses (Table 1; Fig. 1). The coefficients of determination (r^2) between NDVI and visual quality ranged from 0.38 to 0.83 in the bluegrasses and were lesser, albeit significant, in tall fescue (Table 1). These r^2 values are similar to results from other studies that have indicated significant relationships between NDVI and visual quality (Trenholm et al., 1999; Bell et al., 2002; Fitz-Rodriguez and Choi, 2002; Keskin et al., 2008; Lee et al., 2011).

In our study, correlations between NDVI and visual quality were greater in 2005, probably because of greater heat and drought stress than in 2004 and 2006. During the study, average weekly daytime temperatures in 2005 were 2°C greater than in 2006 and as much as 8.9°C greater in than in 2004 (Lee, 2008; Su et al., 2008). Greater stress in 2005 generally expanded the range of turfgrass quality

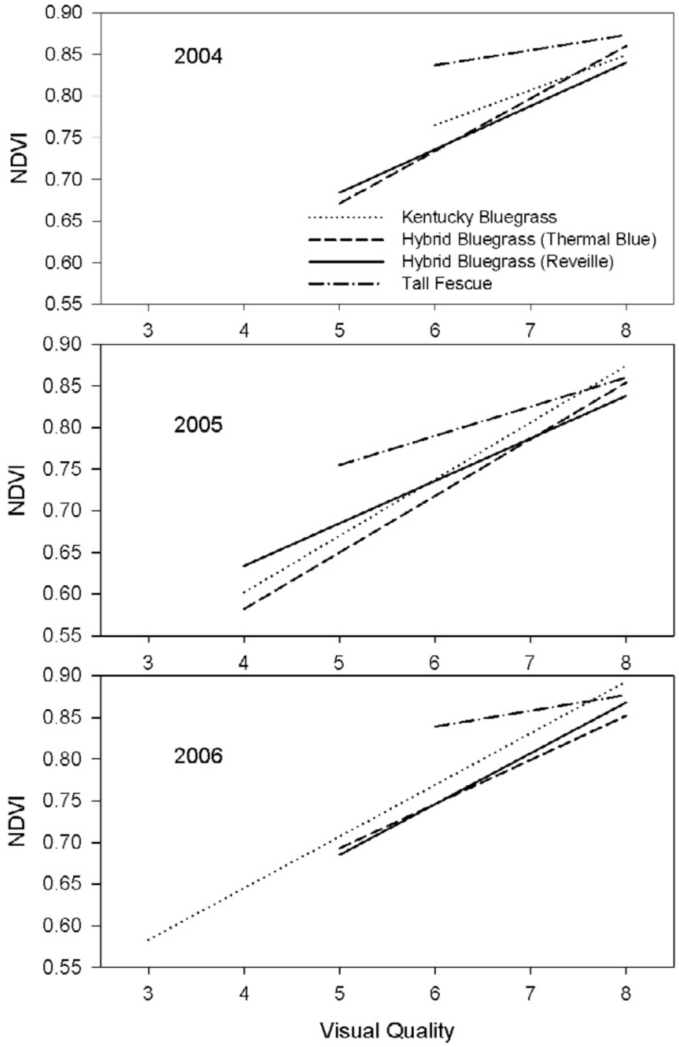

Figure 1. Relationships between normalized difference vegetation index (NDVI) and visual quality on a 1 to 9 scale with 9 the greatest quality. Models are presented for each grass in 2004 (n = 64), 2005 (n = 96), and 2006 (n = 96).

Table 2. Comparisons of models (defined in Table 1) among four turfgrasses in 2004, 2005, and 2006; models were developed to predict visual quality from normalized difference vegetation index (NDVI). Probability (p) values indicate levels of significance of differences between respective models. Two hybrid bluegrasses included 'Thermal Blue' and 'Reveille'.

Model comparisons	p-values†		
Between species	2004	2005	2006
Kentucky bluegrass – hybrid bluegrass (Thermal Blue)	0.03	<0.0001‡	0.002‡
Kentucky bluegrass – hybrid bluegrass (Reveille)	0.005‡	0.0003	0.007‡
Kentucky bluegrass – tall fescue	0.006‡	<0.0001	<0.0001
Hybrid bluegrass (Thermal Blue) – hybrid bluegrass (Reveille)	NS§	0.0004	NS
Hybrid bluegrass (Thermal Blue) – tall fescue	0.0005	<0.0001	0.002
Hybrid bluegrass (Reveille) – tall fescue	0.02	0.006	0.0002

†Determined with analysis of covariance; indicate level of significance of differences between slopes of respective models unless denoted with footnote symbols ‡ or §.

‡Equal slopes, but different intercepts between respective models.

§NS, no significant differences between respective models.

between well watered and irrigation deficit plots and provided a broader base for comparing NDVI with visual quality (Table 1). Lower r^2 values in tall fescue probably resulted from less susceptibility to drought stress than the bluegrasses. Su et al. (2008) reported higher visual quality and photosynthesis rates in tall fescue than in the bluegrasses in the same plots as this study, which also indicated less drought stress in tall fescue among grasses.

In general, the models were different among species and cultivars in each year (Table 2). The only exceptions were between the two hybrid bluegrasses (Thermal Blue and Reveille), which were similar in 2004 and 2006. In most direct comparisons between each of the models there were interactions (i.e., different slopes). However, in a number of instances there were no interactions between models but, nevertheless, they were significantly different from each other (p = 0.05; i.e., models had equal slopes but different intercepts). As illustrated in Fig. 1, models with equal slopes but different intercepts indicate that for the same value of NDVI, mean turf quality will differ between grasses and the differences in mean visual quality between grasses will remain consistent with changes in NDVI. In models with different slopes, however, the differences in mean visual quality between grasses will vary as NDVI changes. In our data, this was most apparent between tall fescue and the bluegrasses at lower NDVI values (Fig. 1).

As discussed earlier, different models among turfgrass cultivars and species may be related to differences in canopy characteristics. In our study, the hybrid bluegrass Thermal Blue was generally lightest in color among grasses and tall fescue was generally the densest, which probably affected both visual quality ratings and NDVI. In addition, tall fescue had wider leaves than the bluegrasses, which probably affected quality ratings and perhaps NDVI although Bell et al. (2002) reported NDVI was independent of turfgrass texture. In a companion paper (Part II) we present an analysis of underlying factors that may affect, either similarly or differently, visual quality and NDVI.

Models within each turfgrass also varied among years, either in slope or intercept (Table 3; Fig. 1). The only exceptions were between 2004 and 2005 in the hybrid bluegrass Reveille and between 2004 and 2006 in the hybrid Thermal Blue and in tall fescue. This interannual variability among models may have been related to differences in heat and drought stress among years, as indicated above. Atmospheric effects such as differences in illumination may also have contributed to differences among years. Year-to-year variability in correlations between NDVI and visual quality on the same plots has been reported by others (Jiang et al., 2009; Lee et al., 2011). This variability in models among grasses and years indicates that separate models may need to be developed for each grass and in each year.

The 95% confidence intervals surrounding predictions of visual quality from NDVI ranged from ± 1.25 to 2.10

Table 3. Comparisons of models (defined in Table 1) among years for each turfgrass including Kentucky bluegrass, two hybrid bluegrasses including 'Thermal Blue' and 'Reveille', and tall fescue; models were developed to predict visual quality from normalized difference vegetation index (NDVI). Probability (*p*) values indicate levels of significance of differences between respective years.

Model comparisons	*p*-values†			
Between years	Kentucky bluegrass	Hybrid bluegrass (Thermal Blue)	Hybrid bluegrass (Reveille)	Tall fescue
2004–2005	0.004	0.03‡	NS§	0.0002‡
2004–2006	0.02	NS	0.007‡	NS
2005–2006	<0.0001‡	0.002‡	0.006‡	0.03

†Determined with analysis of covariance; indicate level of significance of differences between slopes of respective models unless denoted with footnote symbols ‡ or §.

‡Equal slopes but different intercepts between respective models.

§NS, no significant differences between respective models.

(Table 1); in tall fescue the mean square error was too large to calculate a 95% confidence interval in 2004 and 2006. In general, the confidence intervals overlapped among grasses and years, which indicates that these models are not precise enough for practical detection of differences in visual quality among grasses and years with NDVI.

Variability in visual quality ratings and NDVI measurements both likely contributed to the lack of precision in the models used to predict visual quality from NDVI. Coefficients of variation were generally low for both visual quality ratings and NDVI but were consistently greater in visual quality than in NDVI (Table 4). For example, coefficients of variation ranged from 0.032 to 0.149 in NDVI measurements and from 0.064 to 0.236 in visual quality ratings. This indicates that variation in visual quality ratings contributed greater uncertainty than NDVI measurements into the prediction models. This is similar to results from other studies that reported more consistent measurements with optical sensors than with visual ratings (Bell et al., 2002; Lee et al., 2011).

It is likely that the different scales used by NDVI and visual quality ratings also contributed to the imprecision of the models. Specifically, visual quality is estimated on a discrete scale and NDVI is measured on a continuous scale. This probably predisposes NDVI to greater variability at each discrete increment of visual quality (Fig. 2). For example, at a visual quality rating of 4, NDVI ranged widely from 0.46 to 0.69 in the hybrid Thermal Blue in 2005, the year when the strongest relationships between NDVI and visual quality during the study were observed (Table 1). In the same grass and year, measurements of NDVI of 0.69 were observed across visual quality ratings from 4 to 6, and a similar NDVI of 0.71 was even observed at a visual rating of 7. Indeed it was typical for the same values of NDVI to be observed across three levels of visual quality among all cultivars in 2005.

Our results illustrate the difficulty in predicting subjective evaluations of visual quality with objective measurements of NDVI. An important question remains as to what exactly NDVI is measuring in the turf canopy as it relates to turf quality. Research has demonstrated that NDVI is correlated with turf color and percent live cover (Bell et al., 2002), chlorophyll (Stiegler et al., 2005), drought stress (Jiang and Carrow, 2005, 2007; Jiang et al., 2009), and turf injury (Trenholm et al., 1999) and is affected by mowing height (Lee et al., 2011), all of which may affect visual quality. However, there may be additional factors affecting the relationships between NDVI and visual quality such as green leaf area and biomass quantities, leaf properties, plant water status, and canopy architecture.

In summary, this research shows that using NDVI to predict visual quality would require development of separate models for each turfgrass and for each season. This requirement severely reduces the practicality of using NDVI for this purpose. Even if a single model could be used, the wide range in confidence intervals surrounding predictions of visual quality from NDVI would be problematic. A potentially confounding possibility is that visual quality is strictly a function of the visible (i.e., what the human eye can discern) while NDVI measures reflectance in both the visible and near-infrared (invisible) wavelengths. Consequently, NDVI may detect components of the turfgrass canopy that are not visible to the human eye. Further research is needed to investigate factors that may influence relationships between visual quality and NDVI among cultivars and species. In a companion paper (Part II), we evaluated a number of factors that may affect NDVI and its component reflectances (i.e.,

Table 4. Coefficients of variation (CV) in measurements of normalized difference vegetation index (NDVI) and visual ratings of turfgrass quality in Kentucky bluegrass, two hybrid bluegrasses including 'Thermal Blue' and 'Reveille', and tall fescue during 2004 ($n = 64$ per grass), 2005 ($n = 96$ per grass), and 2006 ($n = 96$ per grass).

		CV	
Year	Turfgrass	NDVI	Visual quality
2004	Kentucky bluegrass	0.067	0.111
	Hybrid bluegrass (Thermal Blue)	0.099	0.121
	Hybrid bluegrass (Reveille)	0.064	0.091
	Tall fescue	0.032	0.064
2005	Kentucky bluegrass	0.137	0.223
	Hybrid bluegrass (Thermal Blue)	0.149	0.236
	Hybrid bluegrass (Reveille)	0.085	0.165
	Tall fescue	0.049	0.121
2006	Kentucky Bluegrass	0.139	0.236
	Hybrid bluegrass (Thermal Blue)	0.087	0.124
	Hybrid bluegrass (Reveille)	0.086	0.129
	Tall fescue	0.049	0.073

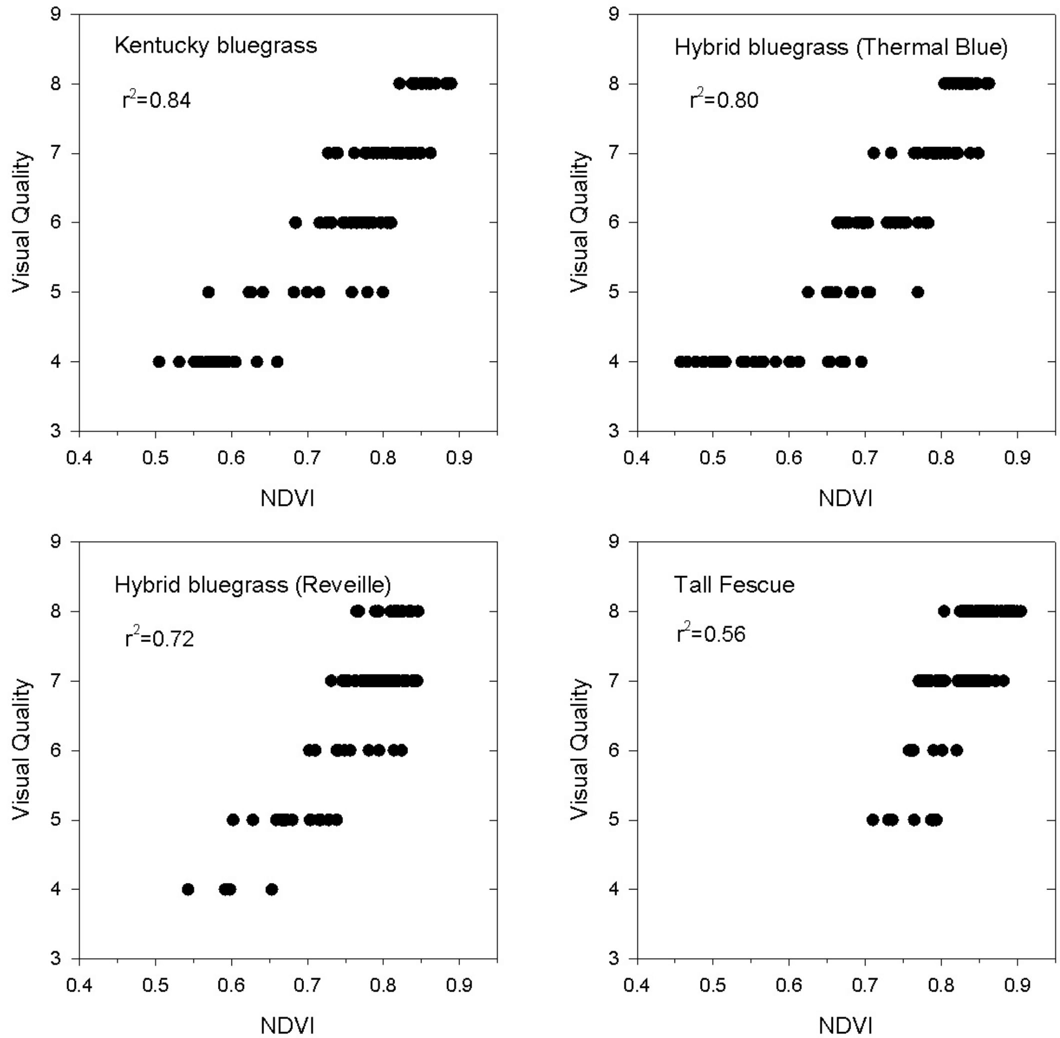

Figure 2. Normalized difference vegetation index (NDVI) corresponding to individual rankings of visual quality among grasses by human evaluators in 2005. The wide range in NDVI at each rating illustrates the difficulty in using objective measurements of canopy reflectance with subjective estimates of turfgrass quality.

visible and near infrared) and consequently, relationships between NDVI and visual quality in turfgrasses.

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References

Allen, R.G., L.S. Pereira, D. Raes, and M. Smith. 1998. Crop evapotranspiration: Guidelines for computing crop water requirements. Irrigation and Drainage Paper no. 56. FAO, Rome, Italy.

Bell, G.E., D.L. Martin, S.G. Wiese, D.D. Dobson, M.W. Smith, M.L. Stone, and J.B. Solie. 2002. Vehicle-mounted optical sensing: An objective means for evaluating turf quality. Crop Sci. 42:197–201. doi:10.2135/cropsci2002.0197

Berry, C.D., D.V. Glover, and W.H. Daniel. 1969. Phenotypic and genotypic variation and covariation of some quantitative turf characters of *Poa pratensis* L. Crop Sci. 9:470–473. doi:10.2135/cropsci1969.0011183X000900040025x

Bonos, S.A., K.A. Plumley, and W.A. Meyer. 2002. Ploidy determination in *Agrostis* using flow cytometry and morphological traits. Crop Sci. 42:192–196. doi:10.2135/cropsci2002.0192

Brede, A.D., and J.M. Duich. 1982. Cultivar and seeding rate effects on several physical characteristics of Kentucky bluegrass turf. Agron. J. 74:865–870. doi:10.2134/agronj1982.00021962007400050023x

Brosnan, J.T., J.S. Ebdon, and W.M. Dest. 2005. Characteristics in diverse wear tolerant genotypes of Kentucky bluegrass. Crop Sci. 45:1917–1926. doi:10.2135/cropsci2004.0511

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. Commun. Soil Sci. Plant Anal. 36:1799–1807. doi:10.1081/CSS-200062449

Fitz-Rodriguez, E., and C.Y. Choi. 2002. Monitoring turfgrass quality using multispectral radiometry. Trans. ASAE 45:865–867.

Fu, J.M., and B.R. Huang. 2004. Leaf characteristics associated with drought resistance in tall fescue cultivars. Acta Hortic. 661:233–239.

Gausman, H.W. 1977. Reflectance of leaf components. Remote Sens. Environ. 6:1–9. doi:10.1016/0034-4257(77)90015-3

Horst, G.L., M.C. Engelke, and W. Meyers. 1984. Assessment of visual evaluation techniques. Agron. J. 76:619–622. doi:10.2134/agronj1984.00021962007600040027x

Jensen, J.R. 2007. Remote sensing of vegetation. p. 355–408. *In* Remote sensing of the environment; an earth resource perspective. 2nd ed.

Pearson Prentice Hall, Upper Saddle River, NJ.
Jiang, Y.W., and R.N. Carrow. 2005. Assessment of narrow-band canopy spectral reflectance and turfgrass performance under drought stress. HortScience 40:242–245.
Jiang, Y., and R.N. Carrow. 2007. Broadband spectral reflectance models of turfgrass species and cultivars to drought stress. Crop Sci. 47:1611–1618. doi:10.2135/cropsci2006.09.0617
Jiang, Y., H. Liu, and V. Cline. 2009. Correlations of leaf relative water content, canopy temperature, and spectral reflectance in perennial ryegrass under water deficit conditions. HortScience 44:459–462.
Keskin, M., Y.J. Han, R.B. Dodd, and A. Khalilian. 2008. Reflectance-based sensor to predict visual quality ratings of turfgrass plots. Appl. Eng. Agric. 24:855–860.
Kutner, M.H., C.J. Nachtsheim, and J. Neter. 2004. Simultaneous inferences and other topics in regression analysis. p. 168–170. *In* Applied linear regression models. 4th ed. McGraw-Hill Irwin, New York, NY.
Lee, H. 2008. Measurement of turfgrass quality, leaf area index, and aboveground biomass with multi-spectral radiometry. M.S. thesis. Kansas State University, Manhattan, KS.
Lee, H., D.J. Bremer, K. Su, and S.J. Keeley. 2011. Relationships between normalized difference vegetation index and visual quality in turfgrasses: Effects of mowing height. Crop Sci. 51:323–332. doi:10.2135/cropsci2010.05.0296
Milliken, G.A., and D.E. Johnson. 2002. Analysis of messy data, Volume III: Analysis of covariance. Chapman & Hall/CRC, Boca Raton, FL.
Penuelas, J., I. Filella, C. Biel, L. Serrano, and R. Save. 1993. The reflectance at the 950–970 nm region is an indicator of plant water stress. Int. J. Remote Sens. 14:1887–1995. doi:10.1080/01431169308954010
Rodriguez, I.R., G.L. Miller, and L.B. McCarty. 2001. Bermudagrass establishment on high sand-content soils using various N-P-K ratios. HortScience 37:208–209.
SAS Institute. 2008. The SAS system for Windows. Release 9.2. SAS Inst., Cary, NC.
Stiegler, J., G. Bell, N. Maness, and M. Smith. 2005. Spectral detection of pigment concentrations in creeping bentgrass golf greens. Int. Turf. Soc. Res. J. 10:818–825.
Su, K., D.J. Bremer, S.J. Keeley, and J.D. Fry. 2008. Rooting characteristics and canopy responses to drought of turfgrasses including hybrid bluegrasses. Agron. J. 100:949–956. doi:10.2134/agronj2007.0292
Trenholm, L.E., R.N. Carrow, and R.R. Duncan. 1999. Relationship of multispectral radiometry data to qualitative data in turfgrass research. Crop Sci. 39:763–769. doi:10.2135/cropsci1999.0011183X003900030025x
Trenholm, L.E., M.J. Schlossberg, G. Lee, and W. Parks. 2000. An evaluation of multi-spectral responses on selected turfgrass species. Int. J. Remote Sens. 21:709–721. doi:10.1080/014311600210524
Turgeon, A. 1991. Turfgrass management. 3rd ed. Prentice Hall, Englewood Cliffs, NJ.