RESEARCH

Relationships between Normalized Difference Vegetation Index and Visual Quality in Cool-Season Turfgrass: II. Factors Affecting NDVI and its Component Reflectances

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ABSTRACT

Normalized difference vegetation index (NDVI, computed as [near infrared (NIR) – Red)]/[NIR + Red]) may provide an objective means to evaluate visual quality of turfgrass. The NDVI is influenced by red (visible) and NIR reflectance (invisible), but each may respond differently to environmental factors; basic information is lacking about the two components in relation to turf quality. In this 3-yr study near Manhattan, KS, we examined relationships of NDVI and its component reflectances along with 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'). Percentage green cover was measured with digital image analysis and shoot density was estimated visually to evaluate their impacts on turf quality and reflectance. Differences in NDVI and red and NIR reflectances were observed among turfgrasses at each level of quality. Across the range of turf quality, NDVI was influenced more strongly by red than NIR reflectance. Red reflectance was strongly affected by density (r = 0.85) and green cover (r = 0.86); NIR reflectance was affected by density (r = 0.63) but negligibly by green cover. Results suggest other fundamental factors that are poorly understood may be affecting NIR reflectance and, hence, NDVI in turf. These factors may confound relationships between NDVI and turf quality and require further study.

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

The normalized difference vegetation index (NDVI) is a common vegetation index from which we can exploit the striking differences in spectral reflectance between the red and near-infrared (NIR) wavelengths. Recently, NDVI has been proposed as an objective alternative to the more traditional, subjective method of visually estimating turfgrass quality (Bell et al., 2002; Keskin et al., 2008). This is because significant correlations have been observed between NDVI and turfgrass visual quality in a number of studies (Trenholm et al., 1999; Bell et al., 2002; Fitz-Rodriguez and Choi, 2002; Jiang and Carrow, 2005, 2007; Lee et al., 2011).

Although significant correlations have been reported between NDVI and visual quality, little fundamental research has been conducted in turfgrass to evaluate reflectance in each of the components of NDVI (i.e., red and NIR). Red reflectance is affected primarily by chlorophyll absorption and, thus, by chlorophyll content (Knipling, 1970; Gausman, 1977). Reflectance in the NIR, however, is affected primarily by light scattering within leaf cells. Although related (e.g., absorption of red light affects cell production, which in turn affects reflectance in the NIR), reflectance in the red and NIR are distinct biophysical phenomena that

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may respond differently to environmental factors such as water stress (Goodin and Henebry, 1998).

Because red reflectance is visible, it is likely that visual estimates of turfgrass quality are closely related to red reflectance. Conversely, NIR reflectance is not visible and therefore may not be accounted for by visual ratings of turf quality. Therefore, to better understand NDVI's relationship to visual turfgrass quality, it is important to understand the parameters that affect reflectance in both the red and NIR.

Penuelas et al. (1993) reported that reflectance in the NIR is an indicator of plant water status. Discontinuities among membranes, cell walls, and protoplasts in leaves, which may be affected by plant water status, result in significant NIR light scattering (Gausman, 1973). Furthermore, leaf components such as stomata, nuclei, cell wall constituents, and cytoplasm also contribute to reflectance in the NIR (Gausman, 1977). Any of these factors, which may not be visible and could vary among turfgrass species or cultivars, could nevertheless affect NIR and, hence, NDVI (Fu and Huang, 2004; Brosnan et al., 2005). Presumably, this could result in turfgrass species or cultivars with similar visual quality but different NDVI or vice versa.

Previous research has indicated that canopy factors such as color, percent live cover, shoot density, and shoot injury affect both NDVI and visual quality in turfgrasses (Trenholm et al., 1999; Bell et al., 2002). In those studies, subjective evaluations of the turfgrass canopies were compared with NDVI. However, Karcher and Richardson (2003) developed a technique to quantify turfgrass color using digital images, which presents an opportunity to make objective comparisons between turfgrass color and NDVI.

In a companion paper (Part I), we reported significant differences among four cool-season turfgrasses in their relationships between NDVI and visual quality. In that paper, the focus was an evaluation of prediction models of turf quality from NDVI among grasses over 3 yr. In this study, our objective was to better understand the relative contributions of red and NIR reflectance to NDVI among the same four cool season turfgrasses. A second objective was to clarify the effect of percentage green cover, using the method of Karcher and Richardson (2003), and canopy density on NDVI and its component reflectances. The overarching goal is to gain a more fundamental understanding of factors that affect NDVI in turfgrass so that greater accuracy can be obtained in predicting visual quality from NDVI.

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. The soil at the site was a Chase silt loam (fine, smectitic, mesic Aquertic Argiudoll).

Thirty-two plots (1.36 by 1.76 m) were established with Kentucky bluegrass (*Poa pratensis L.*, 'Apollo'), two Kentucky × Texas bluegrass (*Poa arachnifera* Torr.) hybrids ('Thermal Blue' and 'Reveille'), and tall fescue (*Festuca arundinacea* Schreb., 'Dynasty'). 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. 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 requirements, 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 twice a week at 7.6 cm with a walk-behind rotary mower.

Measurements of Visual Quality, Spectral Reflectance, Percentage Green Cover, and Density

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, CropScan, Inc. 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. The NDVI was computed as (R935 – R661)/(R935 + R661), where R661 and R935 denote reflectance at 661 and 935 nm, respectively; R661 corresponds to red reflectance and R935 to NIR reflectance (Trenholm et al., 1999). 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. To reduce variation, 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. Further details about plot establishment, maintenance, and the above measurements are included in the companion paper (Part I) and in Su et al. (2008), who conducted their research concurrently with this project on the same plots.

In 2005 and 2006, percentage green cover images were taken with a First Growth Digital Canopy Camera (Decagon Devices, Inc., Pullman, WA). Data from all plots were collected on six measurement dates in 2005 (28 July, 3 Aug., 11 Aug., 18 Aug., 1 Sept., and 30 Sept.) and nine in 2006 (26 April, 25 May, 16 June, 22 June, 30 June, 6 July, 12 July, 19 July, and 28 July), concurrently with multispectral radiometer measurements; digital image data were not collected in 2004 because the camera was not available. All images were taken from 1 m above ground level, which was the same height as the multispectral radiometer. The color, digital images were then analyzed for percentage green cover with software (SPSS, 1998) using the method of Karcher and Richardson (2003, 2005). To our knowledge, no other research in the peer-reviewed literature has reported objective comparisons between NDVI and percentage green cover in turfgrass using digital imagery.

In 2006, shoot density ratings were evaluated by the same researcher who estimated visual quality ratings on the same day visual quality was rated and NDVI and percentage green cover was measured. Similar to visual quality, the density scale consisted of ratings from 1 to 9 but were based only on shoot density (1 = no grass, 6 = minimally acceptable condition, or about 60% density, and 9 = dense grass) (Trenholm et al., 1999). Density estimates were added in 2006 to help differentiate relative contributions of shoot density from percentage green cover, as measured with digital images, to NDVI and its reflectance components.

Statistical Design and Data Analysis

Plots were arranged in a randomized complete block design with four replications for each treatment (grass × irrigation combination). Comparisons among grasses of visual quality ratings, NDVI and its component reflectances, percentage green cover, and density were analyzed with the general linear model and correlation (Pearson's) procedures of SAS (SAS Institute, 2008). Differences between means were separated by Fisher's protected least significant difference ($p = 0.05$).

RESULTS AND DISCUSSION

In the first section that follows, the full dataset from a 3-yr study presented in a companion paper (Part I) was utilized to illustrate that in all turfgrass plots rated at the same high level of visual quality, there were differences in NDVI and its component reflectances among grasses. In subsequent sections, however, all data are from a subset of dates in the second and third years in which percentage green cover was measured concurrently with NDVI and visual quality. This provided objective evaluations of the impacts of percentage green cover on visual quality and NDVI and its component reflectances. In the third year of the study, visual estimates of shoot density were also collected on the same dates to evaluate the impact of density on NDVI and its component reflectances.

Differences among Grasses in NDVI and its Component Reflectances in Plots Rated at a High Visual Quality Level across Three Years

Among all turfgrass plots rated at a visual quality of 7, which is considered high quality turfgrass, there were significant differences in NDVI among grasses in each year (Fig. 1). In tall fescue, NDVI was greatest among grasses in 2004 and 2005 and greater than the hybrid bluegrasses in 2006, which may be due to greater density in tall fescue among the grasses (Trenholm et al., 1999). This is supported by visual evaluations of turfgrass density in 2006 (Table 1) and by Lee (2008), who physically measured green leaf area index and aboveground biomass in these same plots in 2006 and reported greater green leaf area and biomass in tall fescue than in any of the bluegrasses. In this study, NDVI was similar between the hybrid bluegrasses across all 3 yr (Fig. 1). Kentucky bluegrass was similar to both hybrid bluegrasses in 2004 and to Reveille in 2005 but was greater than both hybrids and equal to tall fescue in 2006.

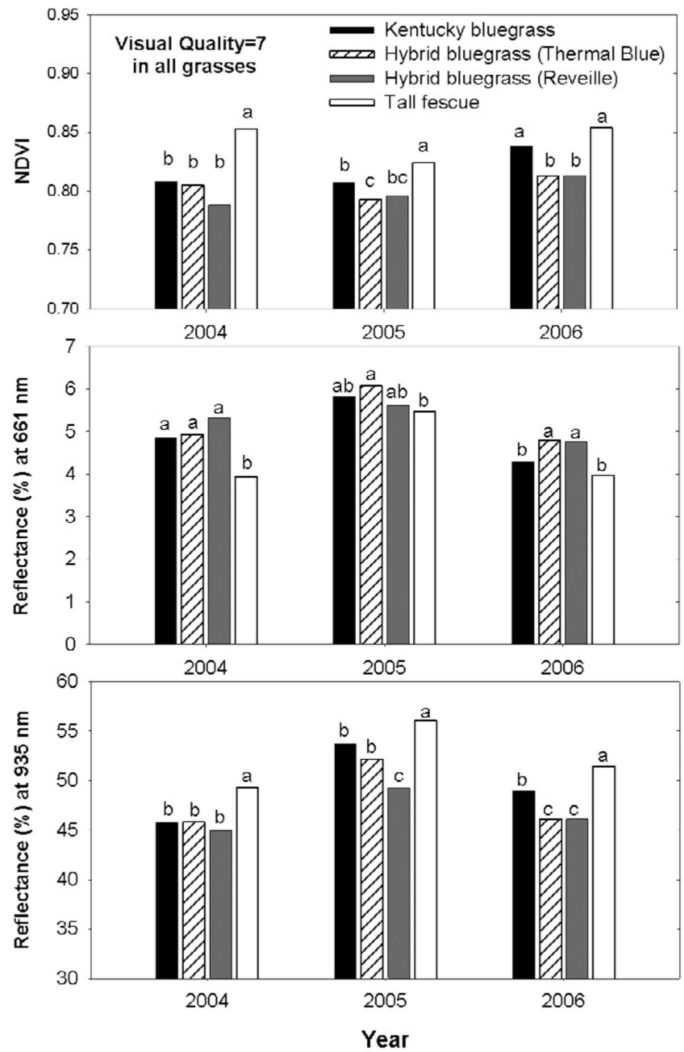

Figure 1. Mean normalized difference vegetation index (NDVI) (top), reflectance at 661 nm (middle), and reflectance at 935 nm (bottom) among turfgrasses rated at visual quality of 7, on a 1 to 9 scale with 9 the greatest quality, in 2004, 2005, and 2006. Grasses included Kentucky bluegrass, two hybrid bluegrasses ('Thermal Blue' and 'Reveille'), and tall fescue. Means with the same letter within each year by reflectance group (i.e., NDVI, reflectance at 661 nm [R661], and reflectance at 935 nm [R935]) are not significantly different ($p = 0.05$).

Red reflectance (i.e., at 661 nm), which is in the visible portion of the spectrum, closely mirrored the patterns of NDVI among grasses in plots rated with a visual quality of 7 (Fig. 1). For example, red reflectance was consistently

Table 1. Average differences among grasses in visual quality, normalized difference vegetation index (NDVI), reflectance at 661 nm (R661) and at 935 nm (R935), percentage green cover (% green), and canopy density (p = 0.05) for a subset of measurement dates in 2005 (n = 48 per grass) and 2006 (n = 72 per grass). Two hybrid bluegrasses include 'Thermal Blue' and 'Reveille'.

	2005					2006					
	Visual quality	NDVI	R661	R935	% green	Visual quality	NDVI	R661	R935	% green	Density
Kentucky bluegrass	5.8C[†]	0.70D	9.6B	54.3B	47C	5.6C	0.74C	6.4A	44.0B	63D	5.9D
Hybrid bluegrass (Thermal Blue)	5.6C	0.67C	10.7A	53.0BC	53C	6.7B	0.79B	5.4B	45.0B	75B	7.0B
Hybrid bluegrass (Reveille)	6.4B	0.73B	7.9C	52.0C	63B	6.5B	0.78B	5.6B	45.1B	67C	6.7C
Tall fescue	7.1A	0.81A	6.3D	59.2A	71A	7.4A	0.87A	3.6C	53.2A	83A	8.0A

[†]Means followed by the same letter within a column were not significantly different (p = 0.05).

low in tall fescue across years, indicating a generally greater absorption of red light in tall fescue among grasses. Greater absorption of red light was likely a result of higher chlorophyll content in tall fescue because of its greater density than the bluegrasses as discussed above; greater absorption of red light also resulted in greater NDVI in tall fescue (Knipling, 1970; Gausman, 1977; Daughtry et al., 1992; Stiegler et al., 2005; Jensen, 2007; Jones et al., 2007). Conversely, reflectance at 661 nm was greatest in all three bluegrasses in 2004, in Thermal Blue in 2005, and in both hybrid bluegrasses in 2006, indicating less absorption of red light in those grasses. There were no differences in reflectance at 661 nm between the hybrid bluegrasses in any year, which is the same as the pattern of NDVI. Lower reflectance in Kentucky bluegrass in 2006 suggests that it had greater chlorophyll content than either of the hybrid bluegrasses even when the quality of all three grasses was high.

Reflectance in the NIR (i.e., at 935 nm) also closely resembled the patterns of NDVI although underlying mechanisms may be less evident (Fig. 1). Near-infrared reflectance is not visible and arises primarily from light scattering within leaf cells (Knipling, 1970; Gausman, 1977). Given that all the plots in Fig. 1 were rated with a high quality of 7, there was no significant senescence or firing of leaves among plots. It is possible that greater reflectance at 935 nm in tall fescue may have been caused by its greater density (Table 1), which could result in greater leaf additive reflectance (i.e., greater reflectance because of more leaves) (Knipling, 1970; Jensen, 2007). However, additional factors such as differences in shadows among the turfgrasses may also have affected reflectance at 935 nm (Knipling, 1970). Further research is needed to evaluate fundamental mechanisms affecting (invisible) NIR reflectance among turfgrass species and cultivars. Such information may help to refine prediction models of turfgrass quality from measurements of NDVI (e.g., the models presented in the companion paper, Part I).

Relationships of NDVI and its Component Reflectances with Visual Quality, Green Cover, and Density

In the subset of dates in which ancillary measurements of percentage green cover and density estimates were collected, visual quality was strongly correlated with NDVI in both years among grasses (Table 2). This is the same trend that was reported in the companion paper (Part I) and by others (Trenholm et al., 1999; Bell et al., 2002; Fitz-Rodriguez and Choi, 2002; Keskin et al., 2008; Lee et al., 2011).

Clear patterns of NDVI and reflectance at 661 and 935 nm emerged when viewed incrementally across visual quality ratings, as illustrated in 2005 (Fig. 2). For example, NDVI increased with visual quality, with significant differences among grasses at every quality rating from 5 to 8. The increase in NDVI with quality was likely caused in large part by increased percentage of green cover and density of the canopies, which were also both strongly, positively correlated with NDVI (Fig. 3 and 4). Our results are also supported by others who have reported that NDVI

Table 2. Correlations (r) between visual quality and normalized difference vegetation index (NDVI) and its component reflectances, percentage green cover (% green), and density. Two hybrid bluegrasses include 'Thermal Blue' and 'Reveille'.

	2005				2006				
	NDVI	R661[†]	R935	% green	NDVI	R661	R935	% green	Density[‡]
Kentucky bluegrass	0.95[¶]	−0.83	0.38[¶]	0.92	0.79	−0.72	0.78	0.62	0.85
Hybrid bluegrass (Thermal Blue)	0.91	−0.83	0.40[¶]	0.94	0.72	−0.68	0.36[¶]	0.62	0.75
Hybrid bluegrass (Reveille)	0.92	−0.81	0.57	0.89	0.82	−0.78	0.70	0.76	0.83
Tall fescue	0.82	−0.75	NS[#]	0.81	0.40[††]	−0.42[††]	NS	0.36[¶]	0.68

[†]R661, reflectance at 661 nm; R935, reflectance at 935 nm.

[‡]Density was not evaluated in 2005.

[§]All probability values < 0.0001 unless otherwise denoted.

[¶]$0.001 < p < 0.01$.

[#]NS, not significant at p = 0.05.

[††]$0.0001 < p < 0.001$.

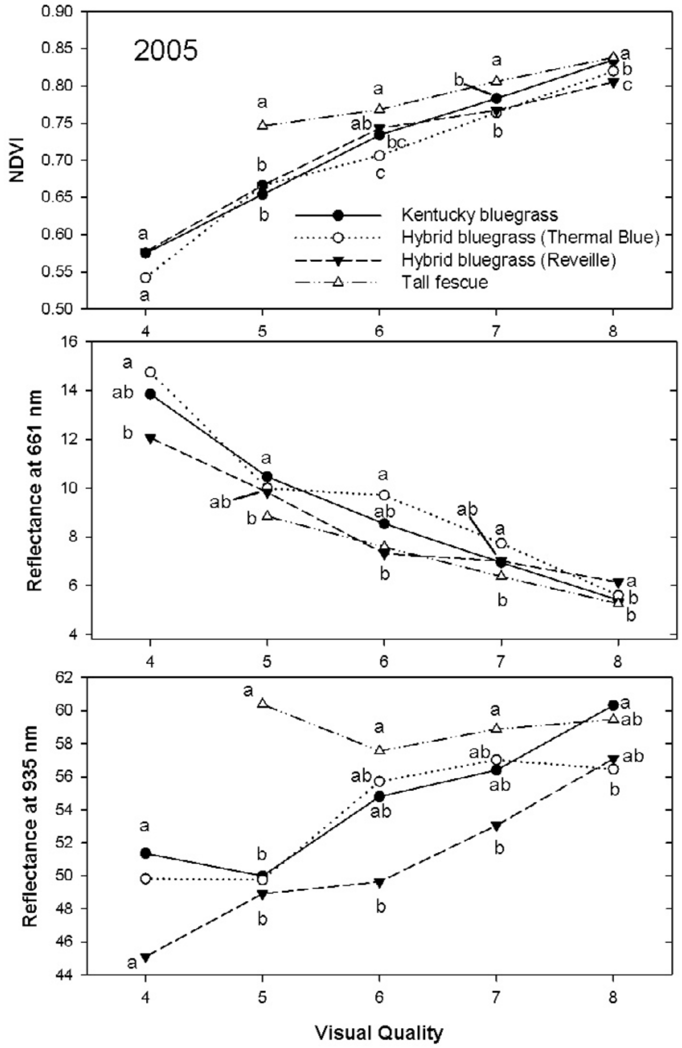

Figure 2. In 2005, mean normalized difference vegetation index (NDVI) (top), reflectance at 661 nm (middle), and reflectance at 935 nm (bottom) among grasses at each visual quality rating from 4 to 8 with 8 the greatest quality. Grasses included Kentucky bluegrass, two hybrid bluegrasses ('Thermal Blue' and 'Reveille'), and tall fescue (n = 48 per grass). Means with the same letters at each visual quality rating (i.e., compare vertically) within each reflectance group (i.e., NDVI, reflectance at 661 nm [R661], and reflectance at 935 nm [R935]) are not significantly different (p = 0.05).

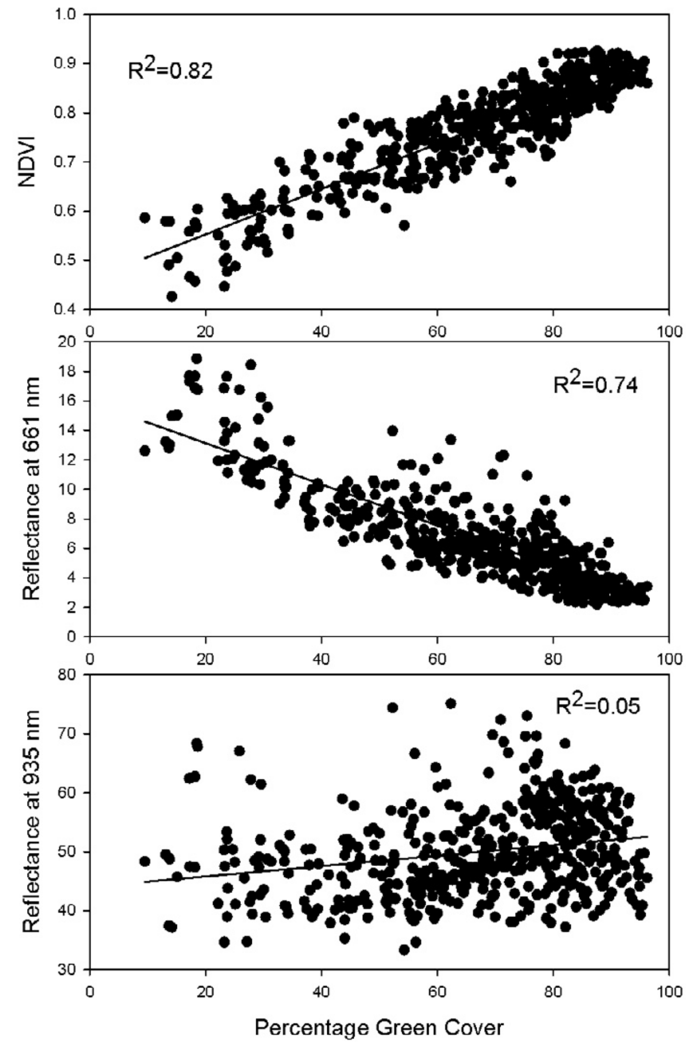

Figure 3. Relationships between percentage green cover and normalized difference vegetation index (NDVI) (top), reflectance at 661 nm (middle), and reflectance at 935 nm (bottom). Data are pooled among grasses from 2005 and 2006.

is correlated closely with color, density, and percent live cover of the turf canopy (Trenholm et al., 1999; Bell et al., 2002). The increases in green cover and density with quality were probably indicative of an increase in live aboveground biomass, which has also been positively correlated with NDVI in a number of grassland studies (Vescovo et al., 2004; Maskova et al., 2008; Fan et al., 2009).

Among grasses, correlations between NDVI and percentage green cover and density were also strong (p < 0.0001) and were also consistently greatest in the three bluegrasses and least in tall fescue (Tables 3 and 4). For example, correlations between NDVI and green cover and density in the bluegrasses ranged from r = 0.87 to 0.95 but in tall fescue only from r = 0.73 to 0.78 for green cover and r = 0.53 for density. Greater correlations in the bluegrasses were a result of wider ranges in green cover and density than in tall fescue. The greater correlations between NDVI and percentage green cover and density in the bluegrasses also indicate why the models developed to predict quality from NDVI had narrower confidence intervals in the bluegrasses than in tall fescue, as presented in the companion paper (Part I).

The differences in NDVI between the bluegrasses and tall fescue are illustrated by the average spectral signatures of the four grasses in well-watered and water-deficit plots during a 3-wk period with the greatest drought stress in 2005 (3 Aug., 8 Aug., and 11 Aug.) (Fig. 5). Significant differences in the spectral signatures were observed between irrigation treatments in the bluegrasses, in which substantial browning of leaves had occurred. Conversely, differences in spectral signatures were negligible between irrigation treatments in tall fescue, which exhibited little senescence of leaves under water deficit. These data clearly illustrate the differences in spectral signatures between

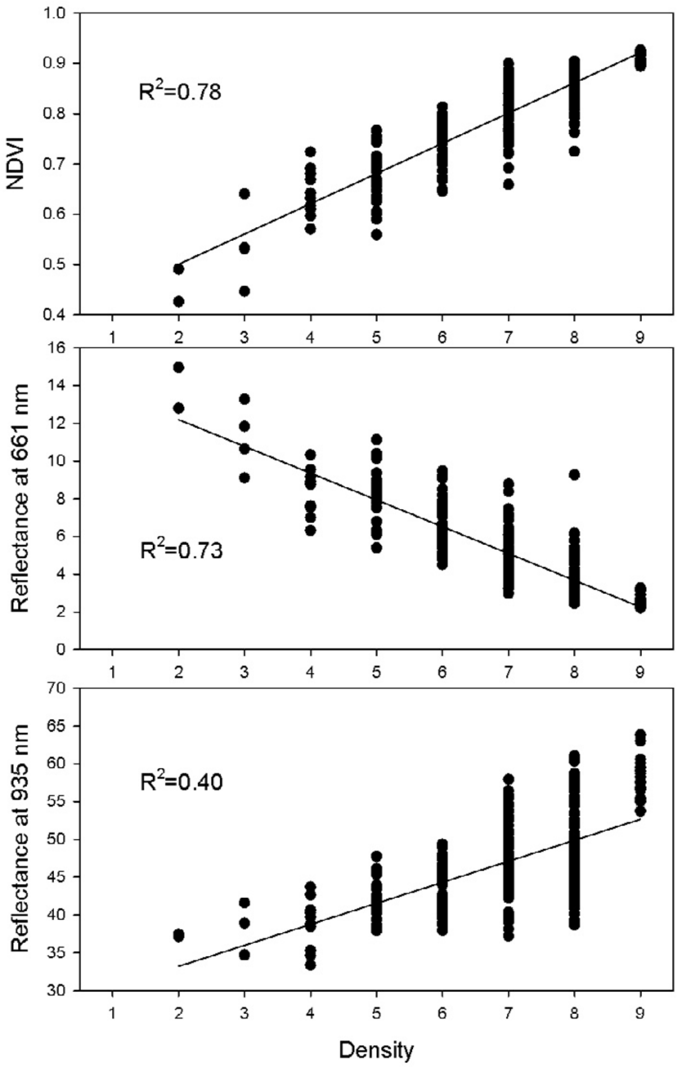

Figure 4. Relationships between shoot density and normalized difference vegetation index (NDVI) (top), reflectance at 661 nm (middle), and reflectance at 935 nm (bottom). Data are pooled among grasses from 2006.

healthy and senescing vegetation and the effects on the component reflectances that determine NDVI.

Reflectance at 661 nm decreased as visual quality increased (Fig. 2). In general, the patterns of differences in R661 among grasses were mirrored with NDVI at each increment of visual quality. For example, red reflectance at a visual quality of 5 was low in tall fescue, which corresponded with greater NDVI in tall fescue among grasses. At visual quality of 8, red reflectance was greatest in Reveille, which corresponded with lower NDVI in Reveille among grasses. In general, the reduction in red reflectance with increasing turf quality illustrates the strong relationship between visual quality and reflectance in the visible (red) wavelengths.

The decline in red reflectance observed in Fig. 2 indicates an increase in red light absorption (hence, less reflected light) as quality improves and suggests a corresponding increase in chlorophyll content (Knipling, 1970; Gausman, 1977). This is supported by strong, positive

Table 3. Correlations (*r*) between percentage green cover and normalized difference vegetation index (NDVI) and reflectance at 661 nm (R611) and at 935 nm (R935). Two hybrid bluegrasses include 'Thermal Blue' and 'Reveille'.

	2005			2006		
	NDVI	R661	R935	NDVI	R661	R935
Kentucky bluegrass	0.92†	−0.80	0.41‡	0.88	−0.91	0.47
Hybrid bluegrass (Thermal Blue)	0.95	−0.88	0.39‡	0.89	−0.88	0.24§
Hybrid bluegrass (Reveille)	0.91	−0.78	0.63	0.87	−0.85	0.62
Tall fescue	0.78	−0.65	NS¶	0.73	−0.51	0.64

†All probability values < 0.0001 unless otherwise denoted.
‡0.0001 < p < 0.01.
§p = 0.04.
¶NS, not significant at p = 0.05.

Table 4. Correlations between canopy density and normalized difference vegetation index (NDVI) and reflectance at 661 nm (R661) and at 935 nm (R935) in 2006. Two hybrid bluegrasses include 'Thermal Blue' and 'Reveille'.

	NDVI	R661	R935
Kentucky bluegrass	0.90†	−0.88	0.67
Hybrid bluegrass (Thermal Blue)	0.87	−0.87	0.23‡
Hybrid bluegrass (Reveille)	0.87	−0.83	0.67
Tall fescue	0.53	−0.45	0.46

†All probability values < 0.0001 unless otherwise denoted.
‡p = 0.05.

correlations between visual quality and percentage green cover and by corresponding negative correlations between percentage green cover and R661 (Tables 2 and 3; Fig. 3). Canopy density was also positively correlated with visual quality and negatively correlated with R661 (Tables 2 and 4; Fig. 4), which also indicates that chlorophyll content increased with density. The strong effects of percentage green cover and canopy density on red reflectance, which is visible, illustrates why these mechanisms that are important components in visual quality also strongly influence NDVI.

Reflectance at 935 increased with quality in the three bluegrasses but not in tall fescue (Fig. 2). The increase in reflectance with quality in the bluegrasses was probably caused by decreasing amounts of brown, senesced leaves as turf quality improved, as illustrated in the spectral signatures between well-watered and water-deficit plots (Fig. 5); reflectance in the NIR is typically lower from senesced leaves than from photosynthesizing, green leaves (Knipling, 1970; Jensen, 2007). Reflectance at 935 remained relatively steady in tall fescue as quality increased from 5 to 8, probably because of its higher density and it was not as severely stressed as the bluegrasses. In addition, it is documented that NIR reflectance remains steady or even increases in the early stages of leaf dehydration and leaf yellowing (Knipling, 1970; Jensen, 2007). Therefore, it is possible that even at a quality rating of 5 in tall fescue most leaves had not deteriorated sufficiently to reduce NIR reflectance.

The R935 increased slightly with percentage green cover but the relationship between the two factors was weak (Fig. 3). The slight increase in R935 with percentage

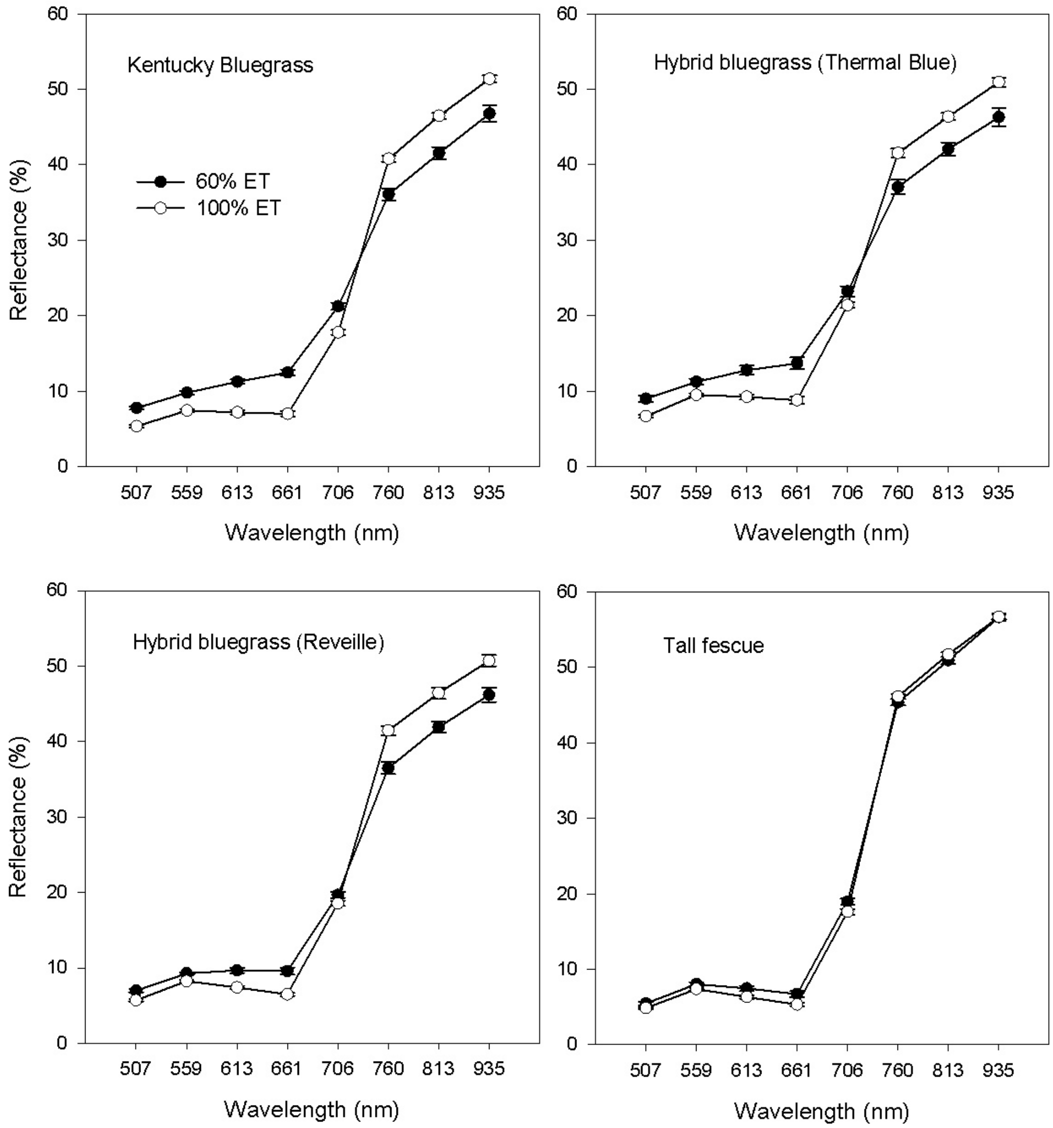

Figure 5. Average reflectance spectrum in well-watered (100% evapotranspiration [ET]) and irrigation-deficit (60% ET) plots during a 3-wk period in 2005 with significant drought and heat stress (n = 12 per grass per irrigation treatment). Error bars denote standard error, which are smaller than symbols in some instances.

green cover was probably caused by a corresponding decrease in brown, senesced leaves, as illustrated by the spectral signatures in water-deficit and well-watered plots (Fig. 5). However, it is important to note that in Fig. 5, data are restricted to a 3-wk period with the greatest drought stress, while data in Fig. 3 includes all data from the 2 yr including less-stressed periods. It is likely that outside of the 3-wk stressful period, there was less senescence in bluegrass plots, although perhaps some yellowing of leaves. Jensen (2007) reported that NIR reflectance is similar between green and yellowing leaves, which probably explain the overall insensitivity of NIR reflectance to percentage green in this study. Reflectance at 935 nm increased with shoot density, but correlations were weaker than between density and NDVI and R661 (Fig. 4).

In general, correlations of R935 were weaker than corresponding correlations of NDVI and R661 with visual quality, percentage green color, and density (Tables 2, 3, and 4). Not surprisingly, this indicates a lesser influence of NIR reflectance, which is not visible, than red reflectance on relationships between visual quality and NDVI. Nevertheless, the increase in R935 with quality in the bluegrasses (Fig. 2) indicates an important contribution of R935 to NDVI, possibly because of improved plant water status at higher quality ratings (Penuelas et al., 1993). Correlations of visual quality with NDVI were also greater than with R661 alone, probably because NDVI is a ratio that normalizes factors such as atmospheric conditions, canopy shadows, illumination effects, etc. (Jensen, 2007). Nevertheless, greater correlations of visual quality with NDVI than with R661 alone suggest an important contribution of R935 to NDVI. The different patterns between the bluegrasses and tall fescue of NIR reflectance across quality ratings (Fig. 2) may partially explain the differences in prediction models among grasses, as was reported in the companion paper (Part I).

While it is apparent from our data that changes in R935 were caused by corresponding changes in density and perhaps by leaf firing, it is possible that other factors not visible to the eye were influencing R935 (e.g., changes in spongy mesophyll cells, shadows in the canopy). Further research may help clarify whether other less evident physiological or biophysical characteristics of the turf canopy are affecting R935 but not R661, which could confound relationships between NDVI and visual quality.

Differences among Grasses in Seasonal Averages of NDVI and its Component Reflectances, Green Cover, and Density

The relationships among visual quality, NDVI and its component reflectances, percentage green cover, and density are illustrated well by the seasonal means of each variable (Table 1). For example, in 2006, the pattern of visual quality and NDVI were identical among grasses with tall fescue the greatest, Kentucky bluegrass the least, and no differences between the hybrid bluegrasses. The latter is consistent with the results reported in the companion paper (Part I), in which negligible differences were found between the hybrid bluegrasses in their models of NDVI and quality in 2004 and 2006. The seasonal means of percentage green cover and density were also greatest in tall fescue and least in Kentucky bluegrass in 2006 although there were differences between the hybrid bluegrasses. Red reflectance (R661) was in the exact reverse order of NDVI among grasses in 2006, which demonstrates the effects of red reflectance on NDVI and its close relationship with visual quality in turfgrass. In 2005, visual quality, NDVI, and percentage green cover were greatest in tall fescue and least in Kentucky bluegrass and Thermal Blue; R661 was lowest in tall fescue and greatest in Kentucky bluegrass and Thermal Blue. Reflectance at 935 was greatest in tall fescue in both years, but patterns among the three bluegrasses were more variable.

In summary, differences in NDVI were observed among turfgrasses even when all were rated at the same level of quality. The differences in NDVI were caused by corresponding differences in both red (visible) and NIR reflectance (invisible). Differences in red reflectance may have been indicative of differences in green leaf density among grasses, which probably would have affected chlorophyll content per unit ground area. The causes for differences in NIR reflectance were possibly related to differences in density among grasses, but other less evident factors may also have been involved (e.g., plant water status, leaf cell constituents, shadows in the canopies). Across the range of turfgrass visual quality, red reflectance generally responded more strongly than NIR reflectance. In particular, NIR reflectance was not appreciably affected by percentage green cover. However, different patterns of NIR reflectance across quality ratings, particularly between the bluegrasses and tall fescue, had significant impacts on NDVI. This suggests that NIR reflectance contributed to the differences in prediction models among grasses as reported in the companion paper (Part I).

Further research is needed to evaluate specific effects of biophysical and physiological components of turfgrass canopies on red and, in particular, NIR reflectance. For example, comparing NDVI and its reflectance components to objective measurements of shoot density, various leaf properties (e.g., plant water status, leaf cell constituents, stomatal densities, leaf angles), and shadows in the canopy may elucidate their impacts on NDVI among turfgrass species and cultivars. Such information is imperative if we are to advance the science of using reflectance data to evaluate turfgrass quality, by improving our understanding of fundamental factors of the turf canopy that affect NDVI and are also important to visual quality.

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