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Relationships between NDVI and visual quality in turfgrasses: Effects of mowing height

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Abbreviations: DOY, day of year; HBG, hybrid bluegrass; KBG, Kentucky bluegrass; LAI, leaf area index; NDVI, normalized difference vegetation index.

Abstract

Canopy spectral reflectance may provide an objective means to evaluate visual quality of turfgrass, but evaluations of quality may be confounded by cultural practices that affect reflectance, such as mowing height. In this two-year study near Manhattan, KS, USA we examined effects of mowing height on relationships between normalized difference vegetation index (NDVI) and visual quality ratings in Kentucky bluegrass (KBG; *Poa pratensis* L., 'Apollo') and in a KBG x Texas bluegrass (*Poa arachnifera* Torr.) hybrid (HBG; 'Thermal Blue'). Mowing heights were 7.62 cm (high) and 3.81 cm (low). The NDVI averaged 4.5 to 7% greater in high- than in low-mown plots. Distinct regression models of visual quality were found at each mowing height and in each species (r^2 from 0.40 to 0.81); separate relationships between NDVI and visual quality were also found between years in the same plots. Correlations between NDVI and visual quality were stronger at high than at low mowing heights, possibly because of greater green biomass at high mowing heights. The 95% confidence intervals surrounding predictions of visual quality from NDVI ranged from ±1.34 to 2.75 (on a 1 to 9 scale). Thus, lack of precision is a concern when using these models for detection of differences between treatments. Results indicate that when using NDVI to evaluate turfgrass quality, evaluations should be limited to plots maintained at the same mowing height and with the same species to reduce variability in NDVI.

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 quick, it is also 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 non-reproducible (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* Swartz) ecotypes and hybrid bermudagrass cultivars (*Cynodon dactylon* L. Pers. x *C. transvaalensis* Burtt-Dacy, '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 different cultural practices (Bell et al., 2002; Fitz-Rodriguez and Choi, 2002; Keskin et al., 2008).

Mowing heights vary in turfgrasses under typical management practices (e.g., residential lawns, golf course greens, fairways and roughs, sports fields), and mowing heights have considerable and varied effects on visual quality. For example, in one study visual quality in tall fescue was greatest at low mowing heights (Richie et al., 2002). Conversely, visual quality was less at low than at high mowing heights in a creeping bentgrass putting green (Salaiz et al., 1995). Su et al. (2009), conducting research concurrently with this project on the same plots, found that visual quality decreased at a lower mowing height in a hybrid bluegrass (Thermal Blue) but increased at a lower mowing height in a Kentucky bluegrass (Apollo). In addition, the type of mower as well as blade sharpness may affect height uniformity, tip shredding or browning and thus, also impact visual quality in turfgrasses (Parish and Fry, 1997).

Mowing of turfgrass removes green leaf area and biomass, which may affect spectral reflectance from the canopies. A number of grassland studies have reported strong correlations between the amount of green leaf area index (LAI), biomass and vegetation indices (e.g., NDVI) obtained from reflectance data (Mutanga and Skidmore, 2004; Vescovo et al., 2004; Gianelle et al., 2009; Maskova et al., 2008; Chen et al., 2009; Fan et al., 2009). In a hybrid bermudagrass, NDVI was greater before than after mowing (Fitz-Rodriguez and Choi, 2002), indicating that removal of green biomass with mowing was detected with NDVI.

Because mowing may affect spectral reflectance, it follows that determination of turfgrass visual quality with reflectance may be confounded by mowing height. Bell et al. (2002) reported greater correlations between turfgrass quality and vegetation indices in turfgrasses mown at high than at low heights, suggesting that differences in biomass quantities affected relationships between reflectance and turfgrass quality. In a number of studies where the feasibility of using reflectance for quality determination was evaluated, the effects of mowing were not explicitly addressed despite the presence of different mowing heights in those studies (Bell et al., 2002; Fitz-Rodríguez and Choi, 2002; Jiang and Carrow, 2005, 2007). Keskin et al. (2008) developed an optical sensor to predict visual quality in turfgrass from reflectance measurements but acknowledged that different mowing heights may confound the practical application of their sensor.

Additional research is necessary to directly investigate the effects of mowing on canopy spectral reflectance and to evaluate practical implications of mowing on relationships between reflectance and turfgrass visual quality. In this study our objectives were to evaluate relationships between NDVI and visual quality ratings in two cool-season turfgrasses and to closely examine the effects of mowing height on those relationships.

Materials and Methods

Study site

This research was conducted under an automated rainout shelter (12 × 12 m) for two consecutive years from 20 June to 30 Sept. (day of year [DOY] 172 to 274) in 2005 and 26 Apr. to 28 July (DOY 116 to 209) in 2006 at the Rocky Ford Turfgrass Research Center (39^{o}13’53” N, 96^{o}34’51” W) in Manhattan, KS. The rainout shelter shielded turf plots from precipitation and therefore, allowed for precise applications of water. A minimum of 0.25 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

Sixteen plots (1.36 × 1.76 m) of KBG (Apollo) and 16 plots of a HBG (Thermal Blue) were arranged in a randomized complete block design with whole plot treatments of mowing height and irrigation in a two by two factorial (Fig. 1). Species was a split-plot factor. Irrigation was included as a factor to impose wider ranges in turfgrass quality, which provided a broader base for the evaluation of relationships between NDVI and visual quality. The mowing height factor (high mowing =7.62 cm and low mowing =3.81 cm) was randomly assigned to the two rows (whole–plot strips) 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 each block, each of the four combinations of mowing height by irrigation treatments was applied to two plots. The species factor (HBG and KBG) was then randomly assigned to those two plots. Further details of plot establishment and maintenance are available in Su et al. (2009).

Turfgrasses 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 (Allen et al., 1998) using data from an on-site weather station.

Measurements of visual quality, spectral reflectance, and leaf area and biomass

The visual quality of each plot 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) by the same researcher in both years. Spectral reflectance of the canopy was measured in eight wavebands, including 507, 559, 613, 661, 706, 760, 813, and 935 nm, with a hand-held multispectral radiometer (model MSR16, CropScan, Inc. Rochester, MN). 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 then averaged. 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 one day 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.

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 R denotes reflectance at the specified wavelength (Trenholm et al., 1999). Other studies have also reported strong correlations between NDVI and visual quality in turfgrasses (Trenholm et al., 1999; Bell et al., 2002; Fitz-Rodriguez and Choi, 2002; Jiang and Carrow, 2007; Keskin et al., 2008). 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.

We were not able to measure green LAI as the study progressed because it is a destructive procedure that would have deleteriously affected the limited number of plots. However, we measured green LAI and biomass at the end of the study in 2006 to evaluate any differences between mowing heights at that time. To measure green LAI and aboveground biomass, turfgrasses were clipped at ground level from three 45.6 cm^2 subplots (7.62 cm diam.) within three different plots of Kentucky bluegrass and the hybrid bluegrass at each mowing height. 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, Régent Instruments, Quebec City, Canada). Biomass samples were then dried in a forced-air oven for 24 hours at 70 ^{o}C and weighed to determine dry biomass.

Statistical analysis

Data among plots were analyzed with correlation and regression procedures of SAS (SAS Institute Inc., Cary, NC) for comparisons between visual quality ratings and NDVI. Regression data were analyzed by: 1) pooling data from both species, separately by mowing height in each year to determine the overall effect of mowing height on relationships between NDVI and visual quality; and 2) pooling data from both years, separately by species at each mowing height to determine whether relationships between NDVI and visual quality varied between species. Instructive observations about responses to the main effects of mowing and species across years were gained by presenting the data in this way. The general linear model procedure was used to analyze effects of mowing height on individual dates and on green LAI and aboveground biomass in 2006. The general lineal model procedure was also used to conduct analysis of covariance to test for equal slopes and intercepts in regression models among mowing heights, 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).

Results and Discussion

In the first two sections that follow, we separated data by species and by year to: 1) evaluate the effects of mowing on spectral reflectance (including NDVI); and 2) compare coefficients of variation between measurements of NDVI and ratings of visual quality. In these evaluations, we included data only from 100% ET plots because including data from the second irrigation treatment (60% ET) would have confounded the results. However, thereafter we included data from both 100% and 60% ET plots to provide a broader base for the evaluation of relationships between NDVI and visual quality.

Effects of mowing height on spectral reflectance in 100% ET plots

The spectral signatures of each species, averaged over the growing season of each year, were distinct between mowing heights (Fig. 2). In both species, spectral reflectance was generally greater in low-mown than in high-mown plots in both years. In the photosynthetically active radiation, or visible region (507 to 661 nm), light absorption by leaf pigments such as chlorophyll resulted in lower reflectance than in the near infrared region (706 to 935 nm). In the visible region, lower reflectance in high-mown plots suggests greater absorption by chlorophyll and thus, greater chlorophyll content and biomass than in low-mown plots (Daughtry et al., 1992; Jones et al., 2007).

Differences in spectral reflectance between mowing heights were also observed in the near infrared region (Fig. 2), which indicates differences in internal leaf structure (e.g., thickness of the mesophyll cell layer, which affects light scattering and reflectance) (Knipling, 1970; Taiz and Zeiger, 2002). Although reflectance in the near infrared region is not visible, it is used to calculate NDVI. Therefore, differences in NDVI between mowing heights may indicate variability in a number of plant physiological functions or morphology, some of which are visible and some that are not visible.

With the exception of Kentucky bluegrass in 2005, NDVI averaged 4.5 to 7% greater in high- than in low-mown, 100% ET plots in both years (Table 1). In 2006, NDVI was greater in high- than in low-mown plots on four out of nine measurement days in Kentucky bluegrass and seven out of nine days in the hybrid bluegrass (Fig. 3). This is similar to a trend observed in a hybrid bermudagrass where NDVI was greater before than after mowing (Fitz-Rodriguez and Choi, 2002). In grassland studies, greater NDVI has indicated greater green LAI and biomass (Asrar et al., 1984; Maskova et al., 2008; Fan et al., 2009). Therefore, in our study greater NDVI in high-mown plots may indicate greater green LAI or biomass than in low-mown plots.

Indeed, at the end of 2006 green LAI was 50-91% greater at high than at low mowing heights in both species (Fig. 4). Similarly, aboveground biomass was up to 51% greater at the high than the low mowing height. Su et al. (2009), who measured canopy-level photosynthesis in the same plots as this study in 2005, reported reductions of up to 34% in photosynthesis from the high to low mowing height. Greater photosynthesis at the high mowing height in 2005 indicates that green LAI was also greater at the high than at the low mowing height, because the photosynthetic capacity of a canopy increases with green LAI (Loomis and Conner, 1992; Bremer and Ham, 2005, 2010).

In 2006, measurements were collected on three dates prior to initiation of the mowing treatment. Interestingly, NDVI in the hybrid bluegrass was greater on the first two dates in plots that had been mown low in the previous year (2005) than in plots that had been mown high; a similar trend was observed in Kentucky bluegrass although differences were not significant (Fig. 3). Greater early-season NDVI in previously low-mown plots was likely caused by a combination of less dead litter from the previous year and greater amount of exposed green, actively growing biomass than in high-mown plots. After mowing treatments began, however, the trend reversed and NDVI became lower in low- than in high-mown plots. This pattern reveals a strong mowing height effect on NDVI. Visual quality remained similar between mowing treatments during this period, and no changes in visual quality occurred after initiation of the mowing height treatment (data not shown).

In 2005, differences in NDVI diminished between high- and low-mown plots as the season progressed (Fig. 3). This confluence coincided with the late-summer and early fall period when weather becomes more favorable for cool-season turfgrass growth. 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 low mowing may have caused green LAI and biomass to increase with time in low-mown plots. 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. This trend was not as evident in 2006, perhaps because the study ended earlier in the growing season than in 2005. Further research is needed to determine relationships between spectral reflectance and green LAI/biomass in turfgrass.

Variability in NDVI measurements and visual quality ratings in 100% ET plots

Variability in NDVI measurements and visual quality ratings may both contribute towards variability in the relationships between NDVI and visual quality. In our study, coefficients of variation revealed greater variability in visual ratings than in NDVI (Table 2). For example, coefficients of variation ranged from 46% to over two times greater in visual quality ratings than in NDVI measurements. This is similar to results from Bell et al. (2002), who reported more consistent measurements with optical sensors than with visual ratings. Those authors also found that visual ratings by three evaluators reduced overall variability in the relationships between NDVI and visual quality. It is possible that using multiple evaluators may have reduced variability in visual quality ratings in our study as well.

Mowing height effects in 2005 and 2006 in all plots including 60% and 100% ET

When data were pooled across species and analyzed separately by mowing height and year, coefficients of determination (r^2) between NDVI and visual quality ranged from 0.75 to 0.81 in 2005 and 0.40 to 0.66 in 2006 (Table 3). These are similar to results from other studies that have indicated strong relationships between NDVI and visual quality (Trenholm et al., 1999; Bell et al., 2002; Fitz-Rodriguez and Choi, 2002; Keskin et al., 2008). In our study, correlations between NDVI and visual quality were greater in 2005, probably because of greater heat and drought stress than in 2006. Greater stress in 2005 generally expanded the range of turfgrass quality between well watered and irrigation deficit plots and provided a broader base for comparing NDVI with visual quality.

The r^2 between NDVI and visual quality was 8% and 65% greater in 2005 and 2006, respectively, at the high than at the low mowing height (Table 3). This is comparable to results from Bell et al. (2002), who reported greater r^2 between NDVI and visual quality in turfgrasses at a high than at a low mow height. In our study, coefficients of variation for both NDVI and visual quality were also less in high-mown than in low-mown plots (Table 2).

The reason for greater r^2 between NDVI and visual quality at high than at low mowing heights is uncertain (Table 3). However, it suggests that greater amounts of green leaf area and biomass at higher mowing heights strengthens the relationship between NDVI and visual quality, perhaps by providing more consistent measurements of NDVI and visual ratings. Presumably, higher mowing height corresponds with greater overall green leaf area (Fig. 4) and thus, greater chlorophyll content in the canopy. Other researchers have reported that chlorophyll content in a canopy is strongly related to spectral reflectance (Daughtry et al., 1992; Jones et al., 2007), including NDVI (Trenholm et al., 2000; Mangiafico and Guillard, 2005; Stiegler et al., 2005). Saturation of NDVI has been observed in other grasslands with increases in LAI (Vescovo et al., 2004; Gianelle et al., 2009). Therefore, it is possible that NDVI saturation may have occurred in our high-mown plots (Fig. 4). An additional factor that may weaken relationships between NDVI and visual quality at low mowing heights is the presence of exposed soil, because soils have different optical properties than leaves (Avery and Berlin, 1992; Jensen, 2007).

Analyses of covariance indicated distinct relationships (i.e., models) between visual quality and NDVI at each mowing height (Table 3; Fig. 5). The models varied with each mowing height and year. In 2005, there was no interaction between models at the high and low mowing heights but they were significantly distinct from each other (P=0.05; i.e., models had equal slopes but different intercepts). In 2006, however, the models had significant interaction (i.e., different slopes). As illustrated in Fig. 5, models with equal slopes but different intercepts indicate that for the same value of NDVI, mean turf quality will differ between mowing heights and the differences in mean visual quality between mowing heights will remain consistent with changes in NDVI. In models with different slopes, however, the differences in mean visual quality between mowing heights will vary as NDVI changes. In our data, this was most apparent in 2006 at higher NDVI values (Fig. 5).

Models at the same mowing heights also varied between years. Specifically, at the high mowing height, the models had no interaction (i.e., equal slopes) between 2005 and 2006, but different intercepts (Fig. 5). At the low mowing height, there was interaction between models (i.e., different slopes) between years. This inter-annual variability among models may have been related to differences in heat and drought stress between 2005 and 2006, as indicated above. Year-to-year variability in models of NDVI and visual quality on the same plots has also been reported by other researchers (Trenholm, 1999; Jiang et al., 2009). This variability in models among mowing heights and years suggests that separate models may need to be developed at each mowing height and in each year, making NDVI use for turfgrass visual quality determinations more cumbersome.

The 95% confidence intervals surrounding predictions of visual quality from NDVI ranged from ±1.34 to 2.75 (Table 3). Thus, in general the confidence intervals overlapped between high and low mowing heights and between years, which indicates these models are not precise enough for practical detection of differences in quality with NDVI. Further research, perhaps with multiple evaluators, may be required to determine whether the precision of the models could be improved. Nevertheless, the widths of the 95% confidence intervals were 17-30% smaller at high than at low mowing heights, which illustrates that the predictive strength of the models increased with mowing height.

Species effects at each mowing height in all plots including 60% and 100% ET

When data were pooled across years and analyzed separately by mowing height and species, correlations between NDVI and visual quality were slightly greater in the hybrid bluegrass than in Kentucky bluegrass, particularly at the low mowing height (Table 4). Analysis of covariance also revealed separate mathematical models that defined the relationships between NDVI and visual quality between species. There was no interaction in the models between KBG and HBG mowed at the same heights, but the models were distinct between species (i.e., models had similar slopes but different intercepts between species) (Table 4; Fig. 6).

Greater correlations between NDVI and visual quality in HBG than in KBG, and different models between the two turfgrasses mowed at the same heights, both indicated a species effect on reflectance. Other researchers have reported distinct relationships between spectral reflectance and visual quality among different turfgrass cultivars and species (Bell et al., 2002; Jiang and Carrow, 2005, 2007; Keskin et al., 2008), which may be related to differences in canopy architecture, leaf shininess or color, green LAI and biomass, etc., among cultivars or species. In our study, the HBG was generally noticeably lighter in color than the KBG, which may have affected visual quality ratings and NDVI.

Correlations between NDVI and visual quality were greater at high than at low mowing heights in both species (Table 4). This is the same general pattern of greater correlations at high than at low mowing heights that was discussed earlier, and indicates the pattern was consistent across both species. Analysis of covariance also revealed separate relationships between NDVI and visual quality at each mowing height and within each species. In both species there was significant interaction in the models between high and low mowing heights, and the patterns between the models at both mowing heights were similar in each species (Fig. 6; Table 4). Therefore, clear mowing height effects were observed on the relationship between NDVI and visual quality in each species.

The 95% confidence intervals surrounding predictions of visual quality from NDVI ranged from ±1.42 to 2.44 (Table 4). Thus, as was observed earlier when species were combined at each mowing height and compared across years, the overlap in the confidence intervals between KBG and HBG or between mowing heights within each species indicates the models are not precise enough for practical detection of differences in quality with NDVI.

In summary, NDVI was generally greater at the high than at the low mowing height in our study, possibly a reflection of greater green leaf area and biomass at the high mowing height. Other factors that affect NDVI, such as canopy architecture, internal leaf properties, or plant stress, may also have contributed differences in NDVI between mowing heights. Variability was significantly reduced in mathematical models describing relationships between NDVI and visual quality when NDVI and visual quality were measured discriminately among mowing heights and species. This indicates that when using NDVI to evaluate turfgrass quality among plots, all plots should be of the same species and maintained at the same height. Furthermore, relationships between NDVI and visual quality were also different between years for the same treatment combinations. Differences between years may have been caused by greater stress in the first year, which expanded the range of visual quality among plots and provided a broader base for comparing NDVI with visual quality. Nevertheless, it suggests that separate models may need to be developed in each year, making NDVI use for turfgrass quality determinations more cumbersome. The 95% confidence intervals surrounding predictions of visual quality from NDVI ranged from ±1.34 to 2.75 (on a 1 to 9 scale), indicating these models are not precise enough for practical detection of differences between treatments. Further research is needed to investigate specific factors that may confound relationships between spectral reflectance and visual quality at different mowing heights and between cultivars or species, such as differences in green leaf area and biomass, leaf properties, and canopy architecture, and to determine whether precision of models such as those in this study can be improved.

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Table 1. Average normalized difference vegetation index (NDVI) in high- (7.62 cm) and low- (3.81 cm) mown plots of Kentucky bluegrass (Apollo) and a hybrid bluegrass (Thermal Blue) during 2005 (n=48 per species x mowing height) and 2006 (n=36 per species x mowing height); data are from 100% ET plots.

Year	Turfgrass	NDVI		P Value[†]
		High	Low	
2005	Kentucky Bluegrass	0.804	0.790	0.23
	Hybrid Bluegrass	0.760	0.727	0.02
2006	Kentucky Bluegrass	0.795	0.744	0.009
	Hybrid Bluegrass	0.808	0.755	0.0005

[†] Probability value: indicates level of significance of differences between high- and low-mown plots in each turfgrass in each year.

Table 2. Coefficients of variation (CV) in measurements of NDVI and visual ratings of turfgrass quality, in high- (7.62 cm) and low-(3.81 cm) mown plots of Kentucky bluegrass (Apollo) and a hybrid bluegrass (Thermal Blue) during 2005 (n=48 per species x mowing height) and 2006 (n=36 per species x mowing height); data are from 100% ET plots.

Year	Turfgrass	Mow Height	CV		% Difference[†]
			NDVI	Visual Quality	
2005	Kentucky bluegrass	High	0.065	0.102	58
		Low	0.073	0.115	57
		% Difference[‡]	-12	-11	
	Hybrid bluegrass	High	0.075	0.134	80
		Low	0.105	0.153	46
		% Difference	-29	-12	
2006	Kentucky Bluegrass	High	0.099	0.209	112
		Low	0.112	0.236	110
		%Difference	-12	-12	
	Hybrid Bluegrass	High	0.072	0.110	54
		Low	0.087	0.127	46
		% Difference	-18	-13	

† Differences in CV between NDVI, measured with MSR, and turfgrass quality, rated visually (100*($CV_{VisualQuality}$-CV_{NDVI})/CV_{NDVI}).
‡ Differences in CV between mowing heights of NDVI and visual quality (100*(CV_{High}-CV_{Low})/CV_{Low}).

Table 3. Pooled models from Kentucky bluegrass (KBG; Apollo) and a hybrid bluegrass (HBG; Thermal Blue) at each mowing height in 2005 (n=96 per mowing height) and 2006 (n=72 per mowing height), 95% confidence intervals (CI) of models in predicting visual quality (VQ) from normalized difference vegetation index (NDVI), coefficients of determination (r^2) between VQ and NDVI in plots at high and low mowing heights (MH) in 2005 and 2006, and probability (P) values.

	Mowing Height	Pooled Models KBG and HBG	CI: Predicting VQ From NDVI	r^2[†]	P Value[‡]	
					By MH	By Yr
2005	Low	NDVI=0.063*VQ+0.337	±1.66	0.75	0.05[§]	
	High	NDVI=0.068*VQ+0.316	±1.34	0.81		
2006	Low	NDVI=0.051*VQ+0.437	±2.75	0.40	0.04[¶]	0.02[#]
	High	NDVI=0.064*VQ+0.380	±1.81	0.66		<.0001[††]

[†] All r^2 were significant at $P < .0001$.

[‡] Determined with analysis of covariance; indicate level of significance of differences between models, either in slope or intercept.

[§] In 2005, equal slopes, but different intercepts between mowing heights.

[¶] In 2006, different slopes between mowing heights.

[#] At low mowing height, different slopes between years.

[††] At high mowing height, equal slopes, different intercepts between years.

Table 4. Pooled models from 2005 and 2006 at each mowing height in each turfgrass (n=84 per species x mowing height), 95% confidence intervals (CI) in predicting visual quality (VQ) from normalized difference vegetation index (NDVI), coefficients of determination (r^2) between VQ and NDVI in high and low-mown plots in Kentucky bluegrass (KBG) and a hybrid bluegrass (HBG), and probability (P) values.

	Mowing Height	Pooled Model 2005-2006	CI: Predicting VQ From NDVI	r^2 [†]	P Value[‡]	
					By MH	By Yr
KBG	Low	NDVI=0.055*VQ+0.413	±2.44	0.56	0.03[§]	
	High	NDVI=0.065*VQ+0.363	±1.72	0.73		
HBG	Low	NDVI=0.062*VQ+0.345	±1.72	0.67	0.04[¶]	<.0001[#]
	High	NDVI=0.071*VQ+0.302	±1.42	0.75		<.0001[††]

[†] All r^2 were significant at $P < .0001$.
[‡] Determined with analysis of covariance; indicate level of significance of differences between models, either in slope or intercept.
[§] In KBG, different slopes between mowing heights.
[¶] In HBG, different slopes between mowing heights.
[#] At low mowing height, equal slopes but different intercepts between species.
[††] At high mowing height, equal slopes but different intercepts between species.

List of Figures

Figure 1. Schematic of plot area including whole-plot strip treatments of mowing height (rows) and irrigation level (columns within a block). The split-plot factor of species is denoted by HBG (hybrid bluegrass) and KBG (Kentucky bluegrass). Mowing heights are 3.81 cm and 7.62 cm and irrigation level is 60% and 100% evapotranspiration (ET) replacement.

Figure 2. Average reflectance spectrums at high and low mowing heights in well-watered plots of a Kentucky bluegrass and hybrid bluegrass in 2005 (n=48 per species per mowing height) and 2006 (n=36 per species per mowing height). Error bars denote standard error, which are smaller than symbols in some instances. In Kentucky bluegrass, error bars overlapped only at 507 nm in 2005, while in hybrid bluegrass error bars overlapped at 813 and 935 nm in both years and at 760 nm in 2006.

Figure 3. Normalized difference vegetation index (NDVI) in high- (7.62 cm) and low-(3.81 cm) mown plots of Kentucky bluegrass (KBG; Apollo) and a hybrid bluegrass (HBG; Thermal Blue) during 2005 (left) and 2006 (right); data are from 100% ET plots. Significant differences between mowing treatments on a given date are denoted along the abscissa by "+" ($p<0.05$) or "×" ($p<0.1$). Dashed line on DOY 142 in 2006 indicates beginning of low mowing treatment.

Figure 4. Green leaf area index (LAI; left) and biomass (right) in high- (7.62 cm) and low- (3.81 cm) mown plots of Kentucky bluegrass (KBG; Apollo) and a hybrid bluegrass (HBG; Thermal Blue). Probability (P) values above paired bars of LAI and biomass indicate level of significance of differences between high and low mowing heights in 2006.

Figure 5. Relationships between normalized difference vegetation index (NDVI) and visual quality on a one to nine scale with nine the greatest quality. Models are presented for high-

and low-mown treatments in 2005 (n=192) and 2006 (n=144). Data are pooled between turfgrasses at each mowing height and in each year.

Figure 6. Relationships between normalized difference vegetation index (NDVI) and visual quality on a one to nine scale with nine the greatest quality. Models are presented for high- and low-mown treatments in Kentucky bluegrass (Apollo) and a hybrid bluegrass (Thermal Blue). Data are pooled between 2005 and 2006 at each mowing height and in each turfgrass (n=168).

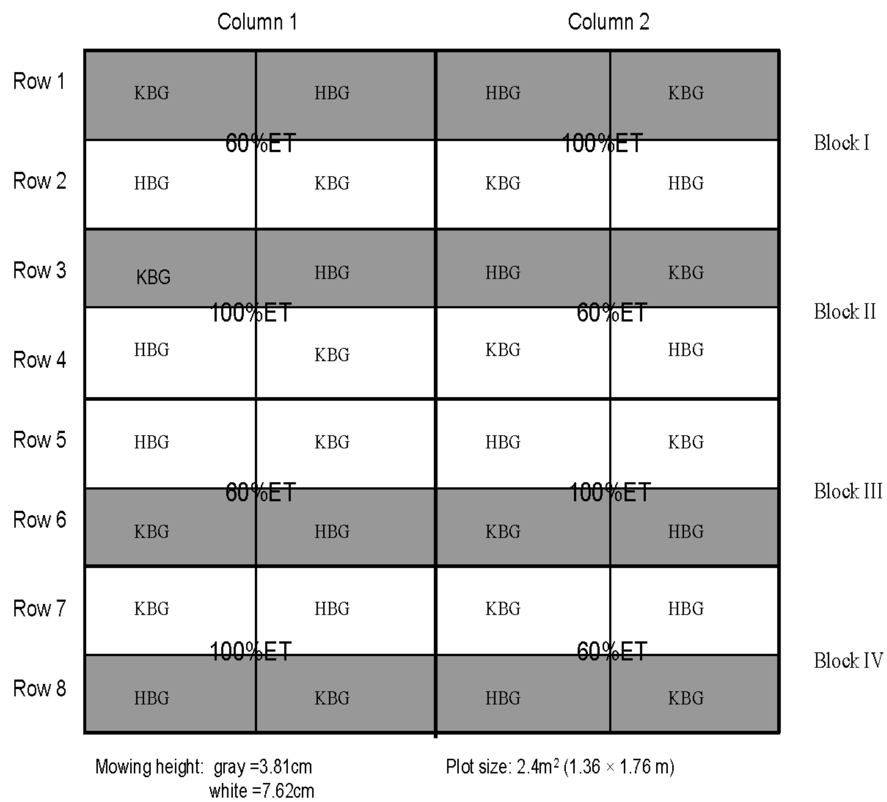
Column 1
Column 2
Row 1
KBG
HBG
HBG
KBG
60%ET
100%ET
Block I
Row 2
HBG
KBG
KBG
HBG
Row 3
KBG
HBG
HBG
KBG
100%ET
60%ET
Block II
Row 4
HBG
KBG
KBG
HBG
Row 5
HBG
KBG
HBG
KBG
60%ET
100%ET
Block III
Row 6
KBG
HBG
KBG
HBG
Row 7
KBG
HBG
KBG
HBG
100%ET
60%ET
Block IV
Row 8
HBG
KBG
HBG
KBG
Mowing height: gray =3.81cm
white =7.62cm
Plot size: 2.4m2 (1.36 × 1.76 m)

Figure 1

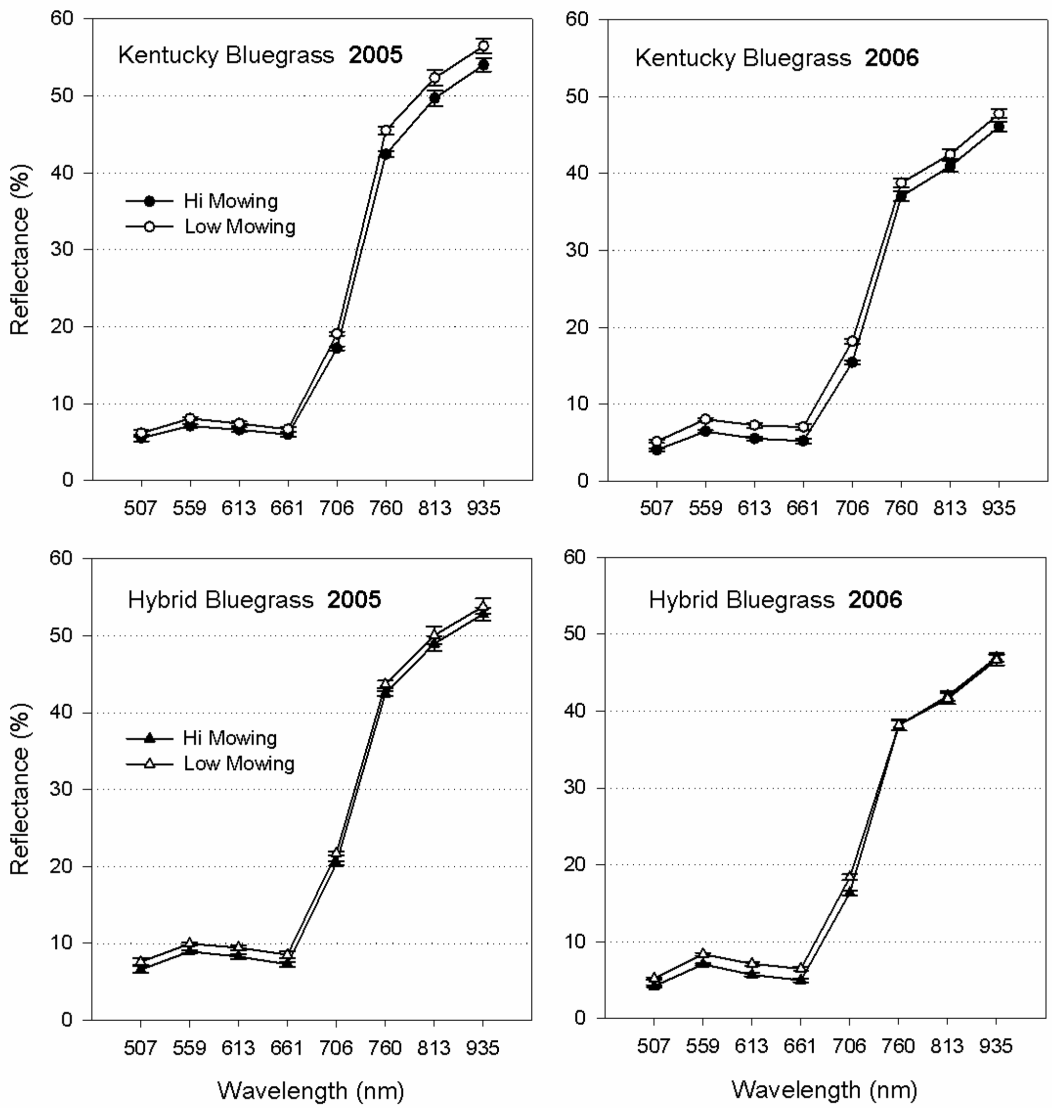
Kentucky Bluegrass 2005
Kentucky Bluegrass 2006
Hybrid Bluegrass 2005
Hybrid Bluegrass 2006
Hi Mowing
Low Mowing
Reflectance (%)
Wavelength (nm)
0
10
20
30
40
50
60
507
559
613
661
706
760
813
935

Figure 2

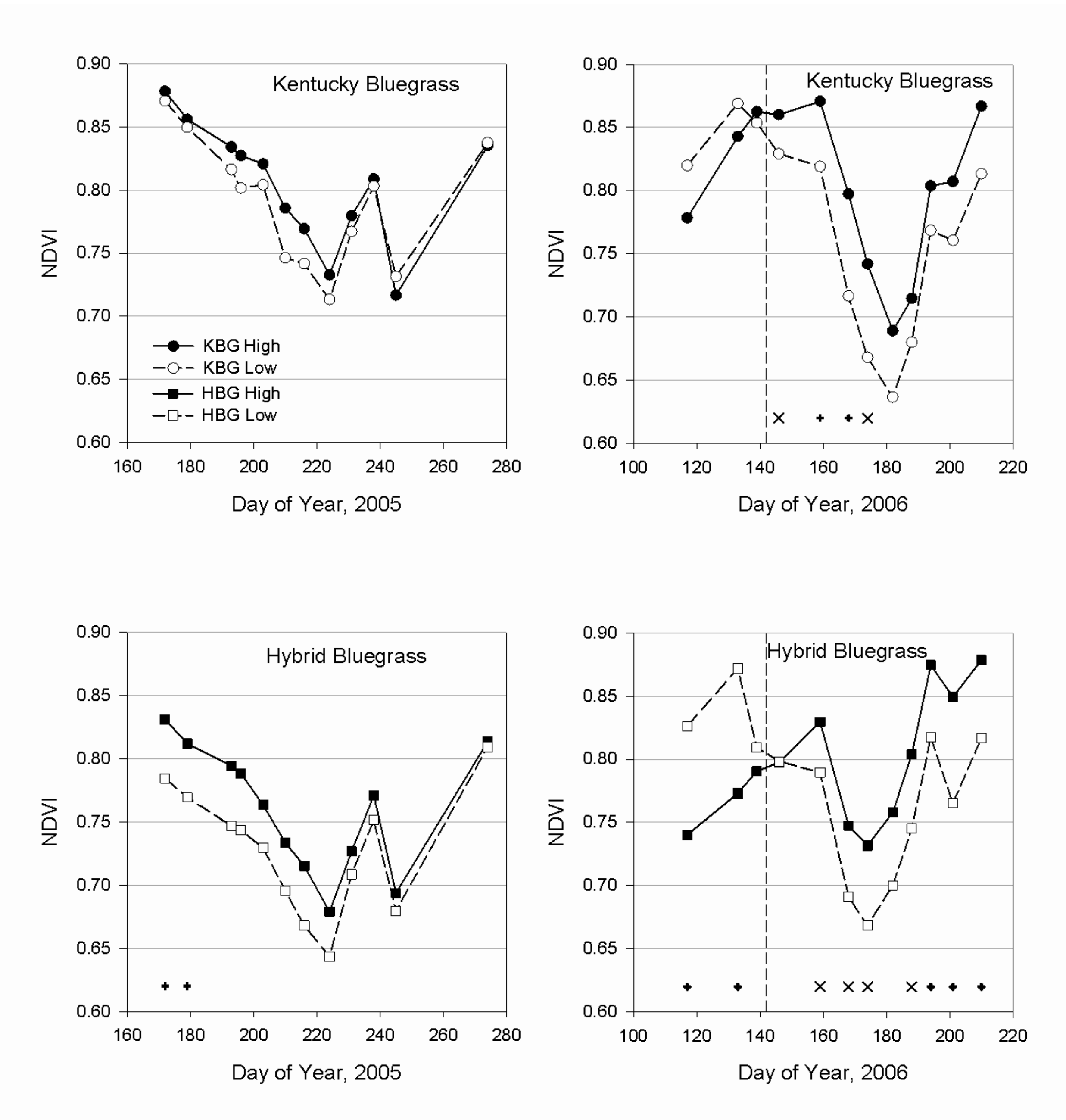
Kentucky Bluegrass
Kentucky Bluegrass
Hybrid Bluegrass
Hybrid Bluegrass
KBG High
KBG Low
HBG High
HBG Low
NDVI
Day of Year, 2005
Day of Year, 2006
0.60
0.65
0.70
0.75
0.80
0.85
0.90
160
180
200
220
240
260
280
100
120
140
160
180
200
220

Figure 3

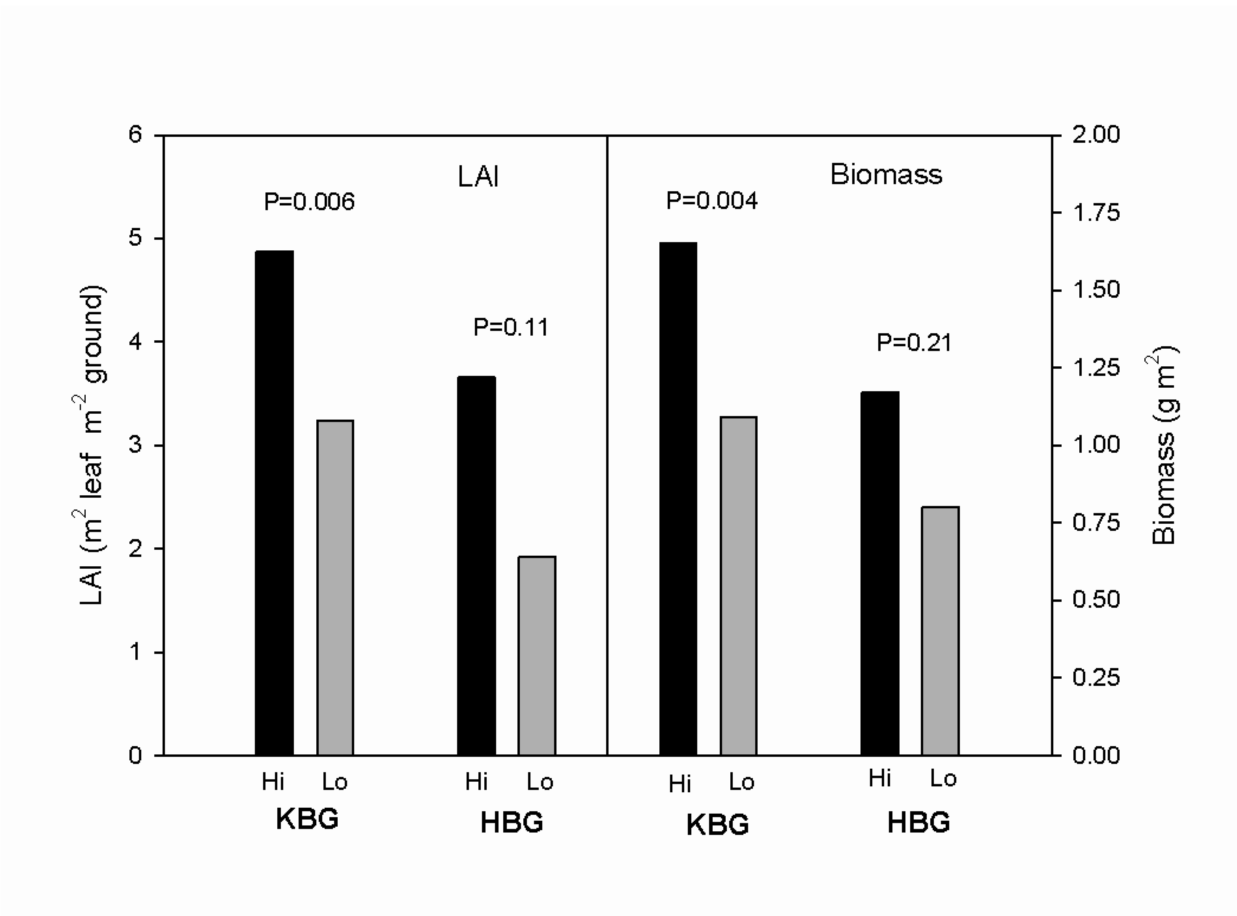
LAI
Biomass
P=0.006
P=0.11
P=0.004
P=0.21
LAI (m2 leaf m-2 ground)
Biomass (g m2)
0
1
2
3
4
5
6
0.00
0.25
0.50
0.75
1.00
1.25
1.50
1.75
2.00
Hi Lo
KBG
Hi Lo
HBG
Hi Lo
KBG
Hi Lo
HBG

Figure 4

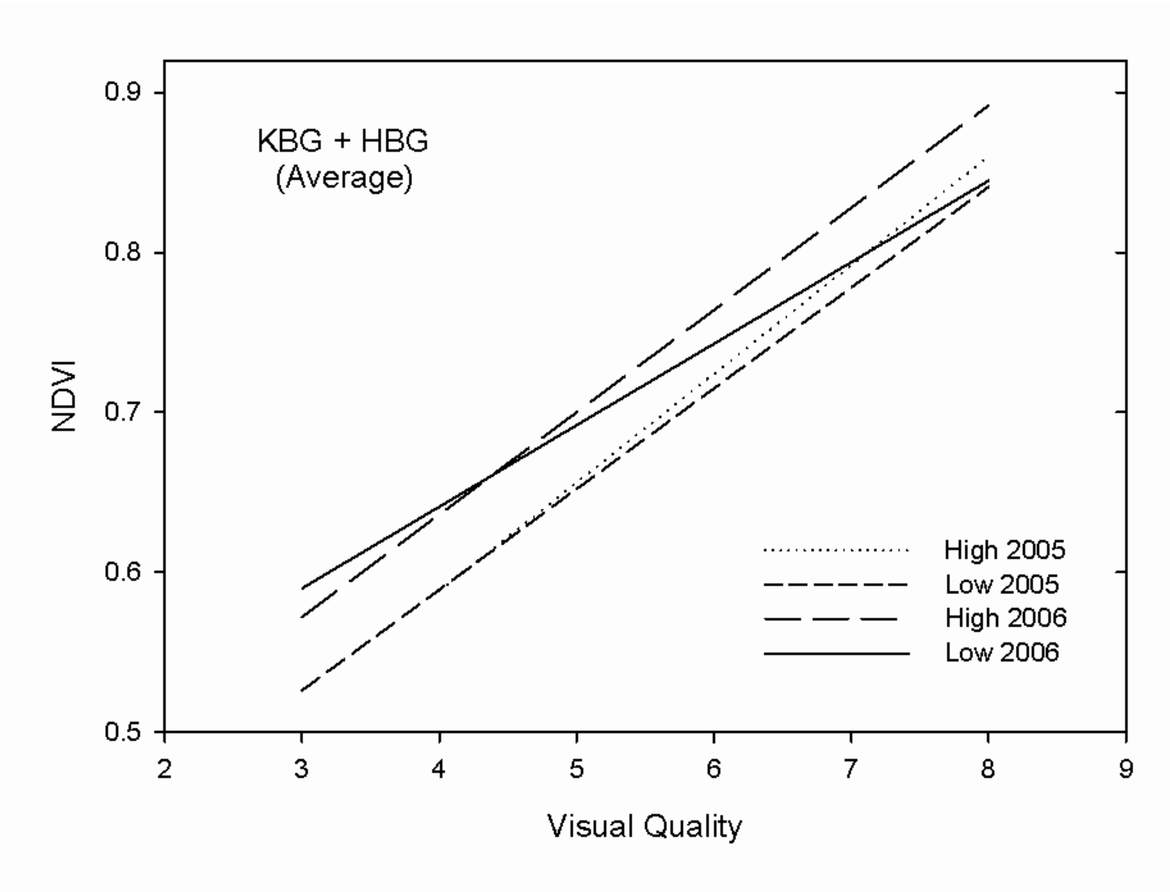
KBG + HBG
(Average)
NDVI
0.5
0.6
0.7
0.8
0.9
2
3
4
5
6
7
8
9
Visual Quality
High 2005
Low 2005
High 2006
Low 2006

Figure 5

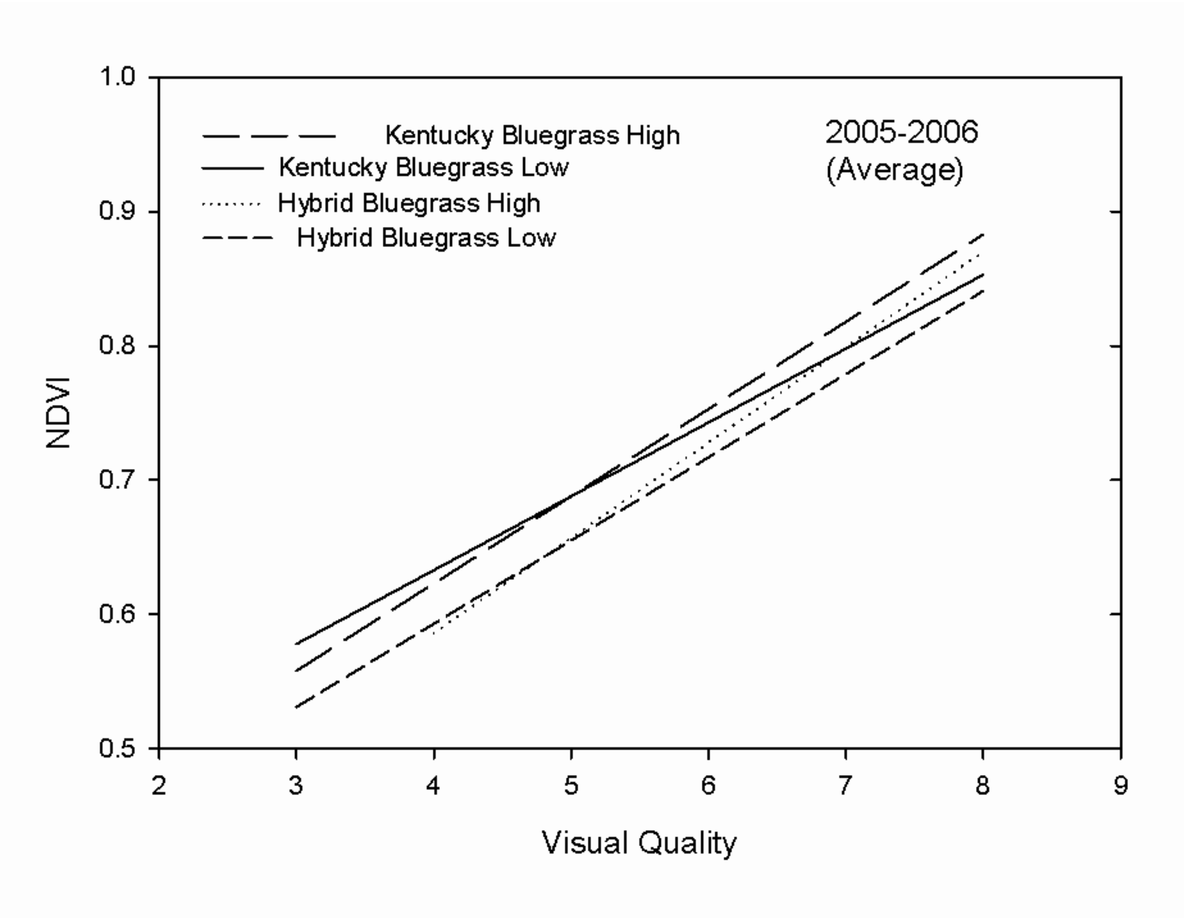
Kentucky Bluegrass High
Kentucky Bluegrass Low
Hybrid Bluegrass High
Hybrid Bluegrass Low
2005-2006
(Average)
NDVI
1.0
0.9
0.8
0.7
0.6
0.5
2
3
4
5
6
7
8
9
Visual Quality

Figure 6