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Digital Image Analysis and Spectral Reflectance to Determine Turfgrass Quality

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ABSTRACT

The limitations of the conventional visual rating system used to assess turfgrass quality include its subjective nature and the need for properly trained observers who can discern differences among treatments or turfgrass varieties. The objective of our study was to investigate if digital image analysis (DIA) and spectral reflectance [normalized difference vegetative index (NDVI)] can be used to evaluate turfgrass varieties. Trials were established at New Mexico State University and visual quality ratings, digital images, and NDVI were collected monthly on three warm-season and three cool-season variety trials and on one cool-season and one warm-season mixed species trial. Correlations among quality, NDVI, dark green color index (DGCI) and percent green cover (PCov) were computed. Multiple regression was used to determine if combining NDVI and DIA improved the association between visual turfgrass quality and other variables. Quality was most strongly associated with NDVI (R^2 ranging from 0.37 to 0.65) for most datasets. Additionally, multiple linear regressions identified NDVI as the variable affecting a higher change in R^2 when entered to the model than either DGCI or PCov. Visual quality had a weaker association with sampling date than did NDVI or DGCI, which indicates that NDVI may track quality changes more reliably over time. However, a stronger association between variety and visual quality than between variety and NDVI or DGCI indicates that a visual assessment detects varietal differences better. Therefore, it is questionable whether visual assessments can be replaced by NDVI or DIA to characterize the aesthetic appeal of turfgrasses accurately.

Turfgrass quality is a term that was first introduced by Beard (1973) to numerically describe the degree to which a turfgrass conforms to an agreed standard. The visual rating system from 1 (worst) to 9 (best) has since been used by researchers and turfgrass managers worldwide to evaluate turfgrasses. It incorporates density, uniformity, leaf texture, smoothness, growth habit, and color (Krans and Morris, 2007) and is based on the evaluator's judgment. Although the term "quality" has been the accepted standard for decades in turfgrass research and breeding, data collection based on a visual assessment has been criticized because of its subjective nature and because it requires properly trained observers who can effectively discern differences among varieties. Horst et al. (1984) and Trenholm et al. (1999) reported that visual ratings are inconsistent over time and among evaluators, and the reproducibility of such data has been questioned. Krans and Morris (2007) also noted that criteria for visual turfgrass quality ratings are not well defined and that protocols and standards used in variety trials need to be normalized among researchers engaged in the visual assessment of turfgrasses.

Digital image analysis and spectral reflectance have been suggested as alternatives to visual ratings as they provide measurements rather than subjective assessments. Quantifying a parameter of interest on a digital image by means of appropriate software has been used as a research tool across several agricultural disciplines (Karcher and Richardson, 2013). Specifically, DIA has been successfully used by researchers to assess turfgrass color (expressed as DGCI) and PCov (Karcher and Richardson, 2003; Richardson et al., 2001) since it was documented that such an analysis provides an accurate estimation of both parameters. Moreover, DIA has been shown to accurately quantify turfgrass establishment (e.g., Shaver et al., 2006; Schiavon et al., 2012) and physiological stress caused by traffic (e.g., Sorochan et al., 2006), disease (e.g., Horvath and Vargas, 2005), or drought (e.g., Carrow and Duncan, 2003). Bunderson et al. (2009) used DIA and quality ratings to assess 20 different species and species mixtures of native and well-adapted turfgrasses. A detailed summary of the use of DIA in turfgrass research has been published by Karcher and Richardson (2013). However, DIA has been mostly limited to research seeking to quantify changes of green cover and color. Although green cover and color are two parameters among a suite of criteria used to assess turf quality visually, there is still a

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Abbreviations: DGCI, dark green color index; DIA, digital image analysis; EC, electrical conductivity; NDVI, normalized difference vegetative index; NTEP, National Turfgrass Evaluation Program; PCov, percent green cover.

lack of consensus and published reports about the utility of DIA in measuring overall turfgrass quality.

Spectral reflectance using optical sensors to determine irradiance from turfgrass covers has also been proposed as an objective measurement of the visual appearance of turfgrass (e.g., Bell et al., 2002; Bremer et al., 2011; Trenholm et al., 1999). Multispectral radiometry has been used by researchers to estimate turfgrass parameters such as color and cover and for evaluating turfgrass stress (e.g., moisture and traffic), and has been suggested as a tool for precision turfgrass management (Carrow et al., 2010). A detailed overview on the evolution and applicability of spectral sensing in turfgrass management has been provided by Bell et al. (2013). Despite the large number of published reports on the use of various remote sensing measurements to document changes in turfgrass appearance, the few that have investigated the suitability of remote sensing as a replacement for visual quality assessments have produced mixed results.

Using multispectral radiometry to investigate stressed and non-stressed cultivars of hybrid bermudagrasses (*Cynodon dactylon* L. × *Cynodon transvaalensis* Burtt-Davy) and seashore paspalum (*Paspalum vaginatum* Sw.), Trenholm et al. (1999) found that reflectance at several wavelengths in the visible and near-infrared spectrum, including the NDVI ratio, were highly correlated with visual turf quality. The authors reported in two separate studies that linear regression between NDVI and turf quality produced r^2 values of 0.59 and 0.81 (Trenholm et al., 1999). Similarly, Fitz-Rodriguez and Choi (2002) reported that NDVI correlated well ($R^2 = 0.73$) with bermudagrass quality. Keskin et al. (2008) observed that the two wavelength bands most important in predicting the quality of bermudagrass and rough bluegrass (*Poa trivialis* L.) were 680 and 780 nm. Bell et al. (2009) compared readings from a hand-held NDVI sensor to visual quality ratings of bermudagrass, buffalograss (*Buchloe dactyloides* Nutt.), and zoysiagrass (*Zoysia* spp.) variety trials planned and organized by the National Turfgrass Evaluation Program (NTEP). The authors reported that the sensor reduced the time required to complete data collection and correlation coefficients between NDVI readings and quality ratings (separately for each month) ranged from as low as 0.17 (not significant) ($R^2 = 0.03$) to as high as 0.94 ($R^2 = 0.88$). However, when data were averaged over the entire research period, coefficients were all significant and ranged from 0.59 ($R^2 = 0.35$) for buffalograss and 0.80 ($R^2 = 0.64$) for bermudagrass. Although most studies investigating the relationship between spectral reflectance and visual quality rating reported significant associations between the two parameters, they used separate models for different species or analyzed them separately (e.g., Bell et al., 2009; Bremer et al., 2011; Jiang and Carrow, 2007). Only Trenholm et al. (1999), Keskin et al. (2008), and Schiavon et al. (2011) compared values across different species. Schiavon et al. (2011) investigated a blend of three bermudagrass cultivars and a total of 10 cultivars of six warm-season turfgrass species. The authors compared data collected during a 3-yr period and found a significant correlation ($r = 0.54$) ($R^2 = 0.29$) between NDVI measurements and visual ratings.

Despite the abundance of studies that examined the relationship between spectral reflectance and visual appearance, information is still needed to resolve if DIA can be used instead of visual assessment to determine overall turfgrass quality. More information is also needed to determine if NDVI can accurately measure turfgrass quality across a wide range of turfgrass species and cultivars in mixed trials. Additionally, studies are needed to assess whether combining DIA and NDVI might improve the degree of association between visual turfgrass quality and these remote sensing technologies. The objective of our study was to explore associations among visual turfgrass quality, DIA, and NDVI in several turfgrass species and varieties. Our second objective was to determine if the coefficients of determination between visual turfgrass quality and these technologies could be improved by combining both NDVI and DIA and also to examine the variability uniquely attributable to these variables.

MATERIALS AND METHODS

Studies were conducted from 2008 to 2012 at the New Mexico State Turfgrass Salinity Research Center and at the Fabian Garcia Horticultural Research Center located in Las Cruces, NM. Visual ratings, NDVI measurements, and digital images were taken monthly during the data collection period of each year (Table 1). The NTEP's variety trials, which included warm-season bermudagrass, zoysiagrass, seashore paspalum, and cool-season Kentucky bluegrass (*Poa pratensis* L.) and two sets of tall fescue (*Festuca arundinacea* Schreb.) trials, were established in triplicate plots arranged in a randomized complete block. Individual plot size for bermudagrasses, zoysiagrasses, and seashore paspalum was 1.8 by 1.8 m but was 1.5 by 1.5 m for all other trials. A detailed list of all varieties included in the trials can be found at the NTEP's website (www.ntep.org). All warm-season grasses, Kentucky bluegrass, and one tall fescue trial were irrigated with saline water [electrical conductivity (EC) = 2.2 dS m^{-1}]. The second tall fescue trial was irrigated with potable water (EC = 0.6 dS m^{-1}). Warm-season grasses were mown with a walk-behind reel mower at 2 cm with the clippings removed and the cool-season grasses were mown with a rotary mower at 7.5 cm with the clippings returned. Data were also collected on a reduced irrigation trial at the Fabian Garcia Research Center in 2008 and 2009. This trial comprised a total of 19 cool-season and 22 warm-season grasses that were mown at 7.5 and 2.5 cm, respectively, and the clippings were returned. Cool-season grasses included alkaligrass [*Puccinellia distans* (Jacq.) Parl.] 'Fults'; Canada bluegrass (*Poa compressa* L.) 'Barpressa'; Chewing's fescue (*Festuca rubra* L. ssp. *commutata* Gaudin) 'Jamestown IV'; hard fescue (*Festuca longifolia* Thuill.) 'Hardtop'; hybrid bluegrass (*Poa pratensis* L. × *Poa arachnifera* Torr.) 'HB 130', 'HB 328', and 'Longhorn'; Kentucky bluegrass 'Baron' and 'Full Moon'; prairie Junegrass [*Koeleria macrantha* (Ledeb.) Schult.] 'Barleria'; slender creeping red fescue (*Festuca rubra* L.) 'Dawson'; perennial ryegrass (*Lolium perenne* L.) 'Brightstar SLT'; and tall fescue 'Barlexas II', 'Endeavor', 'Justice', 'Silverado II', 'Turf Saver', 'Water Saver', and 'Water Saver New', which were irrigated at either 55, 70, or 85% of reference evapotranspiration (Allen et al., 2005). Warm-season grasses included bermudagrass 'Barbados', 'Celebration', 'LaPaloma', 'NuMex Sahara', 'Princess 77', 'Riviera', 'Savannah', 'Sunbird', 'Tifsport', 'Transcontinental', and 'Yukon'; buffalograss 'SWI 2000', 'Prestige', and 'Turffalo'; centipedegrass [*Eremochloa ophiuroides* (Munro) Hack.] 'TifBlair'; an unknown variety of inland saltgrass [*Distichlis spicata* (L.) Greene]; seashore paspalum 'SeaIsle 2000', 'Sea Spray', and 'Supreme'; and zoysiagrass (*Zoysia*

Table 1. Turfgrass trials, number of entries in each trial, number of observations, specific maintenance (mowing height, irrigation amounts, and irrigation water quality), and data collection periods for each trial included in the study.

	Trial	Number of entries†	Observations (N)	Mowing height	Irrigation‡	Data collection
1	NTEP§ bermudagrass	41 (31 + 10)	4253	2 cm	Saline water, 90% ETo¶	July–Nov. 2008; Apr.–Oct. 2009 and 2010; Apr.–Nov. 2011, 2012
2	NTEP seashore paspalum	12 (6 + 6)	1255	2 cm	Saline water, 90% ETo	July–Nov. 2008; Apr.–Oct. 2009 and 2010; Apr.–Nov. 2011, 2012
3	NTEP zoysiagrass	12 (11 + 1)	971	2 cm	Saline water, 90% ETo	July–Oct. 2009; Apr.–Oct. 2010; Apr.–Nov. 2011, 2012
4	NTEP tall fescue	113	8027	7.5 cm	Saline water, 100% ETo	July–Nov. 2008; Mar.–Nov. 2009; Mar.–Nov 2010; Mar.–June 2011
5	NTEP tall fescue	114 (113 + 1)	8427	7.5 cm	Potable water, 100% ETo	July–Nov. 2008; Mar.–Nov. 2009; Mar.–Nov. 2010; Mar.–June 2011
6	NTEP Kentucky bluegrass	114 (110 + 4)	9490	7.5 cm	Saline water, 120% ETo	July–Nov. 2008; Mar.–Nov. 2009; Mar.–Nov. 2010; Apr.–Oct. 2011
7	Cool-season reduced irrigation trial	19 varieties from 10 species	2394	7.5 cm	Potable water at 55%, 70%, and 85% ETo	May–Nov. 2008; Mar.–Oct. 2009
8	Warm-season reduced irrigation trial	22 varieties from 6 species	2766	2 cm	Potable water at 50%, 60%, and 80% ETo	May–Nov. 2008; Mar.–Oct. 2009

† The first number in brackets indicates official NTEP entries; the second number denotes additional entries.

‡ Irrigation amount indicates an average across the entire study period but varied between seasons in each year.

§ National Turfgrass Evaluation Program.

¶ Reference evapotranspiration.

japonica Steud.) 'Companion', 'Empire', and 'Zenith'. Warm-season grasses were irrigated at either 50, 60, or 80% of reference evapotranspiration. Table 1 summarizes the number of entries for each trial, mowing heights, plot sizes, and periods of data collection. The soil at the Turfgrass Salinity Research Center consisted of Bluepoint loamy sand, a mixed thermic Typic Torriorthent. The soil at the Horticultural Research Center consisted of a Glendale loam, a fine-silty mixed (calcareous) thermic typic Torrifluvents . Generally, all plots were fertilized to prevent nutrient stress and were kept weed- and insect free.

Digital image analysis to determine DGCI and PCov was conducted on two photographs taken randomly per plot. Each digital image covered an area of 0.9 by 1.1 m and measurements were averaged between the two photographs. A 92 cm (length) by 61 cm (width) by 61 cm (height) metal box equipped on the inside with four 9-W lamps was used to provide uniform lighting conditions for all the digital images taken (Ikemura, 2003; Karcher and Richardson, 2013). A Canon A570is (Canon Inc. Tokyo, Japan) camera was set to a shutter speed of 1/60, an aperture of f/2.6, ISO 200, and a focal lens of 32 mm. Percent green coverage was determined using SigmaScan Pro 5 software package (Systat Software Inc., San Jose, CA) following the methods described by Richardson et al. (2001). Dark green color index was calculated using the entire picture frame without excluding bare spots (Karcher and Richardson, 2003, 2005). Normalized difference vegetation indices were determined with a GreenSeeker Hand Held Optical Sensor Unit Model 505 (NTech, Ukiah, CA) attached to a shoulder strap and held approximately 80 cm above the canopy. The unit was operated at walking speed (approx. 4 km h^{-1}), thereby scanning a 100-cm wide area perpendicular to the direction of walking (Bell et al., 2009). Between 20 and 30 readings per plot were collected and values were computed as NDVIs from two reflectance readings (ρ) taken at 770 nm (near-infrared) and at 660 nm (red):

$$\mathrm{NDVI} = (\rho_{770\mathrm{nm}} - \rho_{660\mathrm{nm}}) \times [(\rho_{770\mathrm{nm}} + \rho_{660\mathrm{nm}})^{-1}]$$

Values were subsequently stored on a personal digital assistant, from which they were downloaded onto a personal computer for further analysis. Visual quality ratings were taken by an experienced turfgrass scientist (e.g., Bremer et al., 2011; Bunderson et al., 2009; Fitz-Rodriguez and Choi, 2002; Keskin et al., 2008; Trenholm et al., 1999) using a scale of 1 to 9. Ratings incorporated density, uniformity, texture, smoothness, growth habit, and genetic color (Morris and Shearman, 2014). A rating of 1 represented extremely poor, completely dormant, dead, or no turf and 9 indicated a perfect, exceptional green and uniform plot. A rating of 6 was considered minimally acceptable. Digital images, NDVI measurements, and visual quality ratings were all taken within 3 d of one another.

The aim of this article is not to present and discuss variety or other treatment differences within or among the individual trials. The general performance of turfgrasses under reduced irrigation will be published in a separate paper. The turfgrass qualities of each NTEP trial have been submitted and are published on the NTEP website (www.ntep.org, accessed 4 July 2014). This report will discuss results only as they relate to a general comparison among NDVI, DIA, and visual turfgrass quality.

Statistical analyses were performed using SAS (version 9.3; SAS Institute, Cary, NC). Within each dataset, correlations among visual quality, NDVI, DGCI, and PCov were computed and, as an assessment of simple association, the corresponding coefficient of determination values ($r^2 = R^2$) are reported. In addition, simple associations for quality, NDVI, and DGCI with day and variety as qualitative independent variables are also summarized using R^2 values from one-way ANOVA. To determine if combining NDVI and DIA improved the association between visual turfgrass quality and these technologies, a multiple regression of quality on NDVI, DGCI, and PCov was conducted and the change in R^2 uniquely attributable to each variable was computed based on Type II sums of squares (which for main effects only models are equivalent to Type III sums of squares). Similar analyses which added day, variety, and the day × variety interaction

Table 2. Coefficients of determination (R^2) of linear models to predict visual quality, normalized difference vegetation index (NDVI), and dark green color index (DGCI) from NDVI, DGCI, percent coverage (PCov), sampling day (Day), and variety. Values are listed for Kentucky bluegrass (41 varieties), tall fescue [irrigated with either saline (113 varieties) or potable water (114 varieties)], bermudagrass (41 varieties), seashore paspalum (12 varieties), and zoysiagrass (12 varieties) and for two reduced irrigation trials (19 cool-season and 22 warm-season grasses).

Variables		Kentucky bluegrass	Tall fescue		Bermudagrass	Seashore paspalum	Zoysiagrass	Reduced irrigation	
			Potable water	Saline water				Cool-season	Warm-season
Quality	NDVI	0.37	0.51	0.53	0.45	0.56	0.53	0.48	0.65
Quality	DGCI	0.31	0.54	0.46	0.47	0.37	0.41	0.23	0.47
Quality	PCov	0.34	0.46	0.41	0.44	0.45	0.50	0.32	0.48
Quality	Day	0.12	0.29	0.58	0.30	0.63	0.22	0.13	0.57
Quality	Variety	0.15	0.18	0.06	0.22	0.06	0.30	0.33	0.09
NDVI	DGCI	0.38	0.67	0.47	0.59	0.60	0.67	0.51	0.62
NDVI	PCov	0.59	0.61	0.53	0.62	0.78	0.75	0.55	0.65
NDVI	Day	0.45	0.53	0.69	0.69	0.86	0.55	0.32	0.65
NDVI	Variety	0.09	0.10	0.04	0.08	0.02	0.21	0.18	0.03
DGCI	PCov	0.44	0.77	0.56	0.64	0.78	0.76	0.82	0.87
DGCI	Day	0.32	0.39	0.46	0.58	0.72	0.34	0.60	0.73
DGCI	Variety	0.11	0.12	0.05	0.10	0.02	0.25	0.06	0.02

as classification variables to the model were also performed. For the initial regression using only quantitative factors, variance inflation factors were calculated and used to diagnose for collinearity. A similar set of analyses for each NDVI and DGCI was conducted but with only two quantitative explanatory variables.

RESULTS AND DISCUSSION

Simple Associations among Quality, NDVI, and DIA

The highest coefficient of determination (R^2) for quality was with NDVI (0.37 for Kentucky bluegrass and 0.65 for the warm-season reduced irrigation trial) for most datasets (Table 2). Associations between turf quality and DGCI and between quality and PCov were generally weaker, as evidenced by lower R^2 values (Table 2). The degrees of association between NDVI and turfgrass quality observed in this study fell within the range of values reported by others (Bell et al., 2009; Bremer et al., 2011; Keskin et al., 2008; Trenholm et al., 1999). However, our study included a much larger dataset, with trials consisting of 12 to 120 varieties and our data collection was conducted over a longer time period. Furthermore, both Bell et al. (2009) and Bremer et al. (2011) reported time periods during which there was no significant correlation between quality and NDVI readings for some grasses, a finding we did not observe for all but one of our trials (associations by date are not presented). Only for seashore paspalum did NDVI not correlate with visual quality in June, August, September, and October of 2010 or in March of 2011 and 2012. When data were combined throughout the entire study period, the correlation coefficients for all trials were significant and values indicated that both NDVI and DGCI could potentially be used to assess turfgrass quality even in large variety trials.

Coefficients of determination between NDVI and DGCI, between NDVI and PCov, and between DGCI and PCov were generally higher than those between turf quality and either NDVI, DGCI, or PCov (Table 2). This is not surprising, as both spectral reflectance and DIA are similar measurements based on changes in green color or PCov, whereas visual turf quality is based on an assessment of six parameters (density, uniformity, leaf texture, smoothness, growth habit, and green color) of which only two (density or green coverage and color) relate to green color. However, the number of sampling dates for which there was no significant correlation between DGCI and visual quality was much greater than dates for which there was no significant correlation between NDVI with turf quality. Particularly for zoysiagrass (May 2010 and 2011; March, August, September 2012) and seashore paspalum (June, August, September 2010; March 2011 and 2012), DGCI did not correlate with quality during several months (data not presented). Our findings are consistent with those of Bunderson et al. (2009), who concluded that DIA only correlated well with visual quality assessments for some species. However, the insignificant correlations may be caused by sampling error alone or may be a mathematical artifact of using datasets with smaller ranges of values. Analyses for the zoysiagrass and seashore paspalum datasets, which were conducted separately for each date, computed correlations based on only 36 observations. All other datasets used more than 100 observations per date. Additionally, correlations on some dates may be smaller than in the combined datasets; in particular, when the range of values on a specific date is compressed to a subrange, the correlation may be smaller because the degree of the trend relative to the scatter is smaller. More research may be needed to investigate whether some species exhibit wider ranges in the strength of association between quality and DGCI. The overall R^2 values (based on combining data over all sampling months) appear to indicate a stronger association between NDVI and DGCI than between visual quality and NDVI or visual quality and DGCI (Table 2). Consequently, sampling error alone would be expected to lead to more insignificant correlations between visual quality and DGCI than between visual quality and NDVI.

Sampling day tended to have a higher association with NDVI ($0.32 < R^2 < 0.86$) and DGCI ($0.32 < R^2 < 0.73$) than with visual quality ($0.12 < R^2 < 0.63$) (Table 2). This suggests that visual quality had greater within-day variability (error) relative to day-to-day (or between-day) variability than did NDVI or DGCI. These findings indicate that NDVI or DGCI may assess changes through time more reliably.

Table 3. Coefficients of determination (R^2) and df for multiple linear regression models to determine visual turfgrass quality from normalized difference vegetation index (NDVI), dark green color index (DGCI), and percent cover (PCov) (Model 1) for bermudagrass, seashore paspalum, zoysiagrass, and warm-season mixed species. Variance inflation factors (VIF) are listed to indicate collinearity between the main effects. Sampling day and variety and the sampling day × variety interaction were added as additional classification variables in Model 2 and Model 3.

		Bermudagrass			Seashore paspalum			Zoysiagrass			Mixed species (warm-season grasses)		
Model	Variable	df	R^2†	VIF	df	R^2†	VIF	df	R^2†	VIF	df	R^2†	VIF
1	Intercept	1		0	1		0	1		0	1		0
1	NDVI	1	0.03	3.11	1	0.11	4.55	1	0.05	4.22	1	0.17	2.97
1	DGCI	1	0.03	3.24	1	0.00	4.57	1	0.00	4.55	1	0.00	8.14
1	PCov	1	0.01	3.50	1	0.00	8.36	1	0.02	5.88	1	0.00	8.87
1	Model R^2		0.53			0.56			0.55			0.65	
2	NDVI	1	0.03	–	1	0.02	–	1	0.05	–	1	0.06	–
2	DGCI	1	0.01	–	1	0.00	–	1	0.00	–	1	0.00	–
2	PCov	1	0.00	–	1	0.00	–	1	0.01	–	1	0.00	–
2	Day	34	0.15	–	34	0.20	–	26	0.14	–	13	0.13	–
2	Variety	40	0.04	–	11	0.02	–	11	0.02	–	21	0.05	–
2	Model R^2		0.76			0.78			0.76			0.83	
3	NDVI	1	0.02	–	1	0.01	–	1	0.02	–	1	0.04	–
3	DGCI	1	0.01	–	1	0.00	–	1	0.00	–	1	0.00	–
3	PCov	1	0.00	–	1	0.00	–	1	0.01	–	1	0.00	–
3	Day	34	0.15	–	34	0.20	–	26	0.14	–	13	0.13	–
3	Variety	40	0.04	–	11	0.02	–	11	0.02	–	21	0.05	–
3	Day × variety	1360	0.08	–	374	0.08	–	286	0.10	–	273	0.05	–
3	Model R^2		0.84			0.86			0.86			0.88	

† The last number in a column (separately for each model) denotes model R^2; all other values indicate a change in R^2 after the output variable is added to the model.

Table 4. Coefficients of determination (R^2) and df for multiple linear regression models to determine visual turfgrass quality in Kentucky bluegrass, tall fescue (irrigated with either potable or saline water), and cool-season grasses in a reduced irrigation trial from normalized difference vegetation index (NDVI), dark green color index (DGCI), and percent cover (PCov) (Model 1). Variance inflation factors (VIF) are listed to indicate collinearity between the main effects. Sampling day and variety and the sampling day × variety interaction were added as additional classification variables in Model 2 and Model 3.

		Kentucky bluegrass			Tall fescue (potable irrigation)			Tall fescue (saline irrigation)			Mixed species (cool-season grasses)		
Model	Variable	df	R^2†	VIF	df	R^2†	VIF	df	R^2†	VIF	df	R^2†	VIF
1	Intercept	1		0	1		0	1		0	1		0
1	NDVI	1	0.04	2.56	1	0.03	3.17	1	0.1	2.33	1	0.18	2.27
1	DGCI	1	0.03	1.9	1	0.03	5.4	1	0.04	2.53	1	0.02	5.75
1	PCov	1	0.01	2.84	1	0.00	4.65	1	0	2.85	1	0.02	6.19
1	Model R^2		0.43			0.58			0.6			0.5	
2	NDVI	1	0.03	–	1	0.02	–	1	0.02	–	1	0.06	–
2	DGCI	1	0	–	1	0.01	–	1	0.01	–	1	0	–
2	PCov	1	0	–	1	0.00	–	1	0	–	1	0	–
2	Day	28	0.07	–	25	0.12	–	25	0.14	–	13	0.04	–
2	Variety	113	0.04	–	113	0.04	–	112	0.02	–	18	0.1	–
2	Model R^2		0.55			0.75			0.76			0.66	
3	NDVI	1	0.03	–	1	0.01	–	1	0.01	–	1	0.05	–
3	DGCI	1	0	–	1	0.00	–	1	0.01	–	1	0	–
3	PCov	1	0	–	1	0.00	–	1	0	–	1	0	–
3	Day	28	0.07	–	25	0.12	–	25	0.14	–	13	0.04	–
3	Variety	113	0.04	–	113	0.04	–	112	0.02	–	18	0.1	–
3	Day × variety	3163	0.16	–	2820	0.08	–	2797	0.09	–	234	0.07	–
3	Model R^2		0.70			0.83			0.84			0.72	

† The last number in a column (separately for each model) denotes model $R^{2;}$ all other values indicate a change in R^2 after the output variable is added to the model.

Less variability with time but more variability within each sampling date relative to total variability are both types of rater inconsistencies but one decreases the day-to-day variability and the other increases the error (or unexplained variability).

A possible explanation for the greater variability (error) within each sampling or measurement day is "rater fatigue." A lack of consistency in visual assessment not only among evaluators but also among assessments taken by the same evaluator over time (called rater fatigue) has been suggested by other authors (Horst et al., 1984; Trenholm et al., 1999). Rater fatigue may explain the greater variability of turfgrass quality ratings within a particular sampling day (each rating occasion) when a large number of varieties (e.g., variety trials with a total of 360 plots) need to be assessed.

An explanation for the reduced variation over time could be because daily calibrations that are normally done when using visual assessments may differ from a given day to the next. Such a redefining of the rating range might lead to a

Table 5. Coefficients of determination (R^2) and df for multiple linear regression models to determine normalized difference vegetation index (NDVI) from dark green color index (DGCI) and percent cover (PCov) (Model 1) for bermudagrass, seashore paspalum, zoysiagrass, and warm-season mixed species. Variance inflation factors (VIF) are listed to indicate collinearity between the main effects. Sampling day and variety and the sampling day × variety interaction were added as additional classification variables in Model 2 and Model 3.

		Bermudagrass			Seashore paspalum			Zoysiagrass			Mixed species (warm-season grasses)		
Model	Variable	df	R^2†	VIF	df	R^2†	VIF	df	R^2	VIF	df	R^2†	VIF
1	Intercept	1		0	1		0	1		0	1		0
1	DGCI	1	0.05	2.78	1	0	4.56	1	0.02	4.24	1	0.01	7.93
1	PCov	1	0.08	2.78	1	0.18	4.56	1	0.09	4.24	1	0.04	7.93
1	Model R^2		0.68			0.78			0.76			0.66	
2	DGCI	1	0.02	–	1	0.01	–	1	0	–	1	0	–
2	PCov	1	0.01	–	1	0	–	1	0.04	–	1	0.03	–
2	Day	34	0.23	–	34	0.16	–	26	0.15	–	13	0.17	–
2	Variety	40	0.01	–	11	0.01	–	11	0.02	–	21	0.01	–
2	Model R^2		0.92			0.94			0.92			0.84	
3	DGCI	1	0.01	–	1	0	–	1	0	–	1	0	–
3	PCov	1	0	–	1	0	–	1	0.02	–	1	0.03	–
3	Day	34	0.23	–	34	0.16	–	26	0.15	–	13	0.17	–
3	Variety	40	0.01	–	11	0.01	–	11	0.02	–	21	0.01	–
3	Day × variety	1360	0.03	–	374	0.02	–	286	0.04	–	273	0.03	–
3	Model R^2		0.95			0.97			0.96			0.87	

† The last number in a column (separately for each model) denotes model R^2; all other values indicate a change in R^2 after the output variable is added to the model.

Table 6. Coefficients of determination (R^2) and df for multiple linear regression models to determine normalized difference vegetation index (NDVI) from dark green color index (DGCI) and percent cover (PCov) (Model 1) for Kentucky bluegrass, tall fescue (irrigated with either potable or saline water), and cool-season grasses in a reduced irrigation trial. Variance inflation factors (VIF) are listed to indicate collinearity between the main effects. Sampling day and variety and the sampling day × variety interaction were added as additional classification variables in Model 2 and Model 3.

		Kentucky bluegrass			Tall fescue (potable irrigation)			Tall fescue (saline irrigation)			Mixed species (cool-season grasses)		
Model	Variable	df	R^2†	VIF	df	R^2†	VIF	df	R^2†	VIF	df	R^2†	VIF
1	Intercept	1		0	1		0	1		0	1		0
1	DGCI	1	0.02	1.8	1	0.07	4.39	1	0.04	2.3	1	0.01	7.93
1	PCov	1	0.23	1.8	1	0.02	4.39	1	0.1	2.3	1	0.05	7.93
1	Model R^2		0.61			0.68			0.57			0.56	
2	DGCI	1	0.01	–	1	0.02	–	1	0.02	–	1	0	–
2	PCov	1	0.04	–	1	0	–	1	0.02	–	1	0.02	–
2	Day	28	0.24	–	25	0.20	–	25	0.30	–	13	0.11	–
2	Variety	113	0.01	–	113	0.01	–	112	0.01	–	18	0.06	–
2	Model R^2		0.86			0.89			0.88			0.73	
3	DGCI	1	0.01	–	1	0.01	–	1	0.01	–	1	0	–
3	PCov	1	0.02	–	1	0	–	1	0.02	–	1	0.01	–
3	Day	28	0.24	–	25	0.20	–	25	0.30	–	13	0.11	–
3	Variety	113	0.01	–	113	0.01	–	112	0.01	–	18	0.06	–
3	Day × variety	3163	0.04	–	2820	0.03	–	2797	0.04	–	234	0.06	–
3	Model R^2		0.90			0.93			0.92			0.78	

† The last number in a column (separately for each model) denotes model R^2; all other values indicate a change in R^2 after the output variable is added to the model.

"recalibration" for each sampling date and measurement occasion. For example, if an evaluator mostly assigns ratings between 3 and 8 on one rating date and uses the same range on a second rating date but, on the second occasion, assigns values of 8 to plots that would have been given a 7 on the first occasion and 7 to plots that would have been given a rating of 6, etc., the day-to-day variability would be reduced or even eliminated. The NTEP turfgrass evaluation guidelines (Morris and Shearman, 2014) suggest that the evaluator should identify the range of quality ratings on each sampling date. Ranges that are too similar from one date to another might arise when day-to-day differences are being muted by raters unconsciously recalibrating on each measurement day. Spectral reflectance and DIA are inherently not affected by such errors, unless the measurement technology weakens or fails over time.

The six parameters that are used collectively to describe turfgrass quality visually appear to detect greater differences between varieties than using NDVI or DGCI alone. When variety is regressed against quality, it has a higher association with quality (although the association by itself is never strong) than it does with NDVI or DGCI in every dataset, as evidenced by the greater R^2 values. These findings suggest that a visual assessment is better suited to detecting differences between varieties than NDVI or DGCI. However, NDVI or DGCI may be better suited to detect quality changes through time.

Table 7. Coefficients of determination (R^2) and df for multiple linear regression models to determine dark green color index (DGCI) from normalized difference vegetation index (NDVI) and percent cover (PCov) (Model 1) for bermudagrass, seashore paspalum, zoysiagrass, and warm-season mixed species. Variance inflation factors (VIF) are listed to indicate collinearity between the main effects. Sampling day and variety and the sampling day × variety interaction were added as additional classification variables in Model 2 and Model 3.

		Bermudagrass			Seashore paspalum			Zoysiagrass			Mixed species (warm-season grasses)		
Model	Variable	df	R^2†	VIF	df	R^2†	VIF	df	R^2†	VIF	df	R^2†	VIF
1	Intercept	1		0	1		0	1		0	1		0
1	NDVI	1	0.05	2.66	1	0	4.55	1	0.02	3.93	1	0	2.9
1	PCov	1	0.1	2.66	1	0.18	4.55	1	0.11	3.93	1	0.25	2.9
1	Model R^2		0.69			0.78			0.78			0.88	
2	NDVI	1	0.02	–	1	0.01	–	1	0.01	–	1	0	–
2	PCov	1	0.04	–	1	0.07	–	1	0.06	–	1	0.1	–
2	Day	34	0.21	–	34	0.15	–	26	0.07	–	13	0.07	–
2	Variety	40	0.01	–	11	0.01	–	11	0.01	–	21	0.01	–
2	Model R^2		0.91			0.94			0.87			0.95	
3	NDVI	1	0.01	–	1	0	–	1	0	–	1	0	–
3	PCov	1	0.03	–	1	0.05	–	1	0.04	–	1	0.08	–
3	Day	34	0.21	–	34	0.15	–	26	0.07	–	13	0.07	–
3	Variety	40	0.01	–	11	0.01	–	11	0.01	–	21	0.01	–
3	Day × variety	1360	0.04	–	374	0.02	–	286	0.05	–	273	0.01	–
3	Model R^2		0.95			0.96			0.92			0.96	

† The last number in a column (separately for each model) denotes model R^2; all other values indicate change in R^2 after the output variable is added to the model.

Table 8. Coefficients of determination (R^2) and df for multiple linear regression models to determine dark green color index (DGCI) from normalized difference vegetation index (NDVI) and percent cover (PCov) (Model 1) for Kentucky bluegrass, tall fescue (irrigated with either potable or saline water), and cool-season grasses in a reduced irrigation trial. Variance inflation factors (VIF) are listed to indicate collinearity between the main effects. Sampling day and variety and the sampling day × variety interaction were added as additional classification variables in Model 2 and Model 3.

		Kentucky bluegrass			Tall fescue (potable irrigation)			Tall fescue (saline irrigation)			Mixed species (cool-season grasses)		
Model	Variable	df	R^2†	VIF	df	R^2†	VIF	df	R^2†	VIF	df	R^2†	VIF
1	Intercept	1		0	1		0	1		0	1		0
1	NDVI	1	0.03	2.43	1	0.04	2.57	1	0.04	2.12	1	0.01	2.21
1	PCov	1	0.09	2.43	1	0.15	2.57	1	0.14	2.12	1	0.31	2.21
1	Model R^2		0.47			0.81			0.60			0.83	
2	NDVI	1	0.01	–	1	0.01	–	1	0.03	–	1	0	–
2	PCov	1	0.07	–	1	0.09	–	1	0.06	–	1	0.15	–
2	Day	28	0.32	–	25	0.11	–	25	0.11	–	13	0.12	–
2	Variety	113	0.06	–	113	0.01	–	112	0.01	–	18	0.01	–
2	Model R^2		0.85			0.94			0.94			0.95	
3	NDVI	1	0.01	–	1	0.01	–	1	0.02	–	1	0	–
3	PCov	1	0.05	–	1	0.06	–	1	0.04	–	1	0.12	–
3	Day	28	0.32	–	25	0.11	–	25	0.17	–	13	0.12	–
3	Variety	113	0.06	–	113	0.01	–	112	0.02	–	18	0.01	–
3	Day × variety	3163	0.06	–	2820	0.02	–	2797	0.07	–	234	0.01	–
3	Model R^2		0.92			0.96			0.87			0.97	

† The last number in a column (separately for each model) denotes model R^2; all other values indicate a change in R^2 after the output variable is added to the model.

Multiple Linear Regressions among Quality, NDVI, and DIA

Multiple linear regressions performed using NDVI, DGCI, and PCov to predict quality identified NDVI as the variable causing a higher change in R^2 when entered to the model than either DGCI or PCov (Table 3 and Table 4). These regressions resulted in only slightly higher R^2 values than the simple regressions with NDVI as the only explanatory variable and confirmed simple association findings that NDVI is more strongly associated with visual quality than measurements derived from DIA. This relationship persists when sampling day and variety are added to the model, despite the fact that sampling day and variety increase R^2 more than NDVI on an absolute value basis (Table 3 and Table 4). However, day and variety are factors with multiple df. If the variability uniquely associated with either of these factors is considered on a per df basis (R^2 divided by df), NDVI accounts for more of the variability than day or variety. Therefore, NDVI appears to be more accurate than DGCI or PCov in describing the aesthetic appearance of a turf plot.

Variation inflation factors for several regressions suggest that the portion of variability in green cover (PCov) that can be explained by NDVI and DGCI is quite high. Also, if either NDVI or DGCI is regressed against other DIA variables or spectral reflectance, the first regression points to PCov as uniquely explaining more variability than DGCI or NDVI. It appears that PCov is most important in modeling both NDVI and DGCI (Tables 5–8). This can be partly explained by the fact that NDVI and all measurements derived from DIA reflect changes in green color and subsequently green cover. Therefore NDVI and DIA track changes in green color most closely. However, visual quality is intended to be a measure of aesthetics, which includes a total of six parameters, only two of which are related to green color.

Results of the analysis using the model that included the most factors (Model 3 in Tables 3–8) indicated that despite the inclusion of one more explanatory variable (Table 3 and Table 4), visual quality was associated to a lesser degree ($0.70 < R^2 < 0.88$) with explanatory variables than was NDVI ($0.78 < R^2 < 0.97$) or DGCI ($0.87 < R^2 < 0.97$). This suggests that quality has either a greater measurement error than the remote sensing technologies or that it includes parameters that are not covered by NDVI or DIA.

CONCLUSIONS

The aesthetic appearance of a turfgrass is largely but not entirely defined in terms of the degree of dark green color and the percentage of ground cover. Several other factors such as uniformity, texture, smoothness, and growth habit contribute to visual aesthetics and it is unknown if or how well these factors can be measured using NDVI or DIA. No published studies have investigated the ability of remote sensing instruments to measure quality parameters other than color or green cover. In the large datasets considered here, a stronger association between quality and NDVI than between quality and DGCI or PCov was nearly always observed. The stronger association observed between NDVI and day than that between quality and day suggests that NDVI can characterize changes over time better than quality. However, the stronger association observed between variety and visual quality than that between variety and NDVI or DGCI supports our conclusion that visual assessments can better detect varietal differences. We recognize that there is still a considerable degree of variability and subjectivity in a visual assessment.

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