Assessment of Narrow-band Canopy Spectral Reflectance and Turfgrass Performance under Drought Stress

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Abstract. **Canopy reflectance has the potential to determine turfgrass shoot status under drought stress conditions. The objective of this study was to describe the relationship of turf quality and leaf firing versus narrow-band canopy spectral reflectance within 400 to 1100 nm for different turfgrass species and cultivars under drought stress. Sods of four bermudagrasses (*Cynodon dactylon* L. × *C. transvaalensis*), three seashore paspalums (*Paspalum vaginatum* Swartz), zoysiagrass (*Zoysia japonica*), and st. augustinegrass (*Stenotaphrum secundatum*), and three seeded tall fescues (*Festuca arundinacea*) were used. Turf quality decreased 12% to 27% and leaf firing increased 12% to 55% in 12 grasses in response to drought stress imposed over three dry-down cycles. The peak correlations occurred at 673 to 693 nm and 667 to 687 nm for turf quality and leaf firing in bermudagrasses, respectively. All three tall fescues had the strongest correlation at 671 nm for both turf quality and leaf firing. The highest correlations in the near-infrared at 750, 775, or 870 nm were found in three seashore paspalums, while at 687 to 693 nm in Zoysiagrass and st. augustinegrass. Although all grasses exhibited some correlations between canopy reflectance and turf quality or leaf firing, significant correlation coefficients (*r*) were only observed in five grasses. Multiple linear regression models based on selected wavelengths for turf quality and leaf firing were observed for 7 (turf quality) and 9 (leaf firing) grasses. Wavelengths in the photosynthetic region at 658 to 700 nm or/and near-infrared from 700 to 800 nm predominated in models of most grasses. Turf quality and leaf firing could be well predicted in tall fescue by using models, evidenced by a coefficient of determination (R^2) above 0.50. The results indicated that correlations of canopy reflectance versus turf quality and leaf firing varied with turfgrass species and cultivars, and the photosynthetic regions specifically from 664 to 687 nm were relatively important in determining turf quality and leaf firing in selected bermudagrass, tall fescue, zoysiagrass and st. augustinegrass under drought stress.**

Drought stress is a major environmental stress influencing turfgrass growth. Common symptoms of drought injury in turfgrasses include leaf wilting, onset of a blue-green color, chlorosis, and eventually necrosis of tissues. These symptoms can be visually rated as a basis of turfgrass drought resistance, but accurate and rapid detection of early symptoms are often difficult and quantitative measurements would be preferred over visual rating. Remote sensing with broad-band spectral reflectance has been used for evaluation of turfgrass performance under drought stress (Fenstermaker-Shaulis et al., 1997; Jiang et al., 2004) and traffic stress (Jiang et al., 2003; Trenholm et al., 1999). This technology provides a rapid, non-destructive estimate of turf quality and could be a possible screening tool for identification of turfgrass stress tolerance.

Spectral reflectance is the percentage of reflected light from the plant leaf or canopy relative to incoming light. A low reflectance in

visible spectral regions (400 to 700 nm) and a relatively high reflectance in the near-infrared (700 to 1300 nm) are normally observed in a healthy plant leaf (Knipling, 1970). Reflectance in visible wavelengths is correlated with chlorophyll content (Blackburn, 1998; Carter and Spiering, 2002; Datt, 1999; Filella et al., 1995; Gitelson, et al., 1996) and reflectance in the near-infrared is a leaf water content indicator (Bowman, 1989; Curcio and Petty, 1951; Penuelas et al., 1993; Rollin and Milton, 1998). Therefore, changes in leaf or canopy reflectance induced by environmental stresses can be detected and used as an indicator of plant physiological status.

A dense turfgrass canopy provides a good vegetation structure for research of spectral reflectance due to its relatively uniform surface. Early identification of drought stress symptoms may be possible by development of an adequate turf quality model based on alterations of reflectance for a given species or cultivar, and the findings would be beneficial for turfgrass water management. Fenstermaker-Shaulis et al. (1997) reported that biomass and tissue moisture content were predicted by using broad wavelength reflectance from 450 to 700 nm and 800 to 1400 nm in tall fescue under drought. Jiang et al. (2004) identified turf quality models against canopy reflectance for 4 species and

12 grasses by using 8 selected broad-bands from 660 to 1480 nm (10 to 15 nm width). They found that models varied with turfgrass species and cultivars under drought stress, but wavelengths in the photosynthetic region near 710 nm and near-infrared region at 900 to 950 and 1200 nm were most important in determining turf quality and reflectance relationships. These results provided valuable information for monitoring drought stress and aiding irrigation management in turfgrasses.

Narrow-band reflectance (e.g., 3 nm interval) collection would be an alternative approach and possibly provide more detailed information of turfgrass responses to drought stress, since many more wavelengths are involved in correlations between reflectance and turf canopy variables. Leaf firing (i.e., chlorosis, tan-brown color) is an indictor of drought tolerance in turfgrass (Carrow and Duncan, 2003). But to date, research using narrow-band reflectance under drought stress has not been conducted to analyze the detailed correlations of turf quality and leaf firing versus reflectance in the photosynthetic region at 400 to 700 nm and near-infrared at 700 to 1100 nm, nor have models for different grass types been developed. Bermudagrass, seashore paspalum, zoysiagrass and st. augustinegrass are widely used warm-season turfgrasses, and tall fescue is a popular cool-season turfgrass grown in the northern, transitional, and upper to midsouthern U.S. climates. Therefore, the objective of this study was to describe the relationships of turf quality and leaf firing versus narrow-band spectral reflectance within 400 to 1100 nm for different turfgrass species and cultivars under drought stress.

Materials and Methods

Plant materials. Sods were collected from field plots at the University of Georgia Experiment Station in Griffin, including bermudagrass ('TifSport', 'TifEagle', 'Tifway', and 2000-7), seashore paspalum ('Sea Isle 1', 'Sea Isle 2000', and 'Temple'), Zoysiagrass ('Meyer'), and st. augustinegrass ('Palmetto'), and seeded tall fescue ('Plantation', 'Greystone', and 'Tulsa II'). Grasses were established on 24 Apr. 2001 and grown in barrels in a field. The barrels were filled with Profile (Profile Products LLC, Buffalo Grove, Ill.), a calcined illite clay and amorphous silica material. All soil was removed from sods, and the grasses then were sprigged into the barrels. For seeded grasses, the quantity of seed was 10 gram per barrel. The barrel was 0.65 m dia. by 0.90 m depth with surface area of 0.24 m^2 and a volume of 206 L. All grasses were mowed twice weekly using a hand clipper with clippings removed by using a portable vacuum. Bermudagrass, seashore paspalum, and zoysiagrass were mowed at 2.5 cm, st. augustinegrass at 3.8 cm, and tall fescue at 5.1 cm, respectively. Granular fertilizer (N–P–K) applied to the barrels (in terms of kg·ha⁻¹) was 97.6 N on 2 Apr. (6–2–0), 48.8 N on 28 Apr. (15–5–15), 24.4 N on 9 May (15–5–15), 24.4 N on 16 May (15–5–15), 48.8 N on 25 May (6–2–0), and 24.4 N on 31 May (13–0–13).

Irrigation was applied as necessary to maintain healthy turfgrass.

Drought stress and spectral reflectance. Drought stress was initiated after bringing all containers to field capacity and then withholding water during dry-down periods. Field capacity was determined by using Diviner 2000 portable soil moisture monitoring system (Sentek Sensor Technology, Austral.). A large, removable, sensor-controlled rainout shelter facility (12.8 × 30.5 m) was used to maintain dry-down conditions. The rainout shelter was placed in its original position and was able to move automatically to cover all barrels when it rained and to move back after raining. The study consisted of three dry-downs with each period from 11 to 15 d. After each dry-down, turf quality was allowed to fully recover to a non-stress level before the next dry-down started. The first dry-down was initiated on 10 July 2001 and finished on 25 July 2001. The second dry-down started on 20 Aug. 2001 and finished on 31 Aug. 2001, and the third dry-down started on 10 Sept. 2001 and ended on 21 Sept. 2001. The duration of each dry-down was determined by how rapidly turf quality declined in response to drought stress, which allowed a range of drought stress symptom occurring among different grasses for collection of turf quality and canopy spectral reflectance data.

Turf quality was rated visually on a daily basis and was based on color, shoot density and uniformity, where 1 = brown, dead turf and 9 = ideal dark-green, density and uniformity for the species. Leaf firing refers to leaf chlorosis starting at leaf tips and margins. Initial injury is a yellowing but often progresses into a tan-brown color with death of the tan-brown areas. Leaf firing rating was based on percentage leaves exhibiting the above symptoms (Carrow and Duncan, 2003).

Canopy spectral reflectance measurements were collected with a Unispec Spectral Analysis System (PP systems, Haverhill, Mass.) between 400 nm and 1100 nm wavelengths at 3-nm intervals. Reflectance foreoptics were bifurcated fiberoptics, and ambient full sunlight illuminated the canopy during measurement. The fiberoptics probe was held 15 cm directly above ground and canopy reflectance was measured immediately after a white standard reference was scanned. Canopy reflectance was calculated by comparing the sample reflectance to a standard reference scan. The reflectance readings were taken at 1300 h to maximally reduce background noise. All measurements were taken daily during each dry-down period.

Experiment design and statistical analysis. The experiment was a randomized completely block design with repeated dry-down cycles. In total, 12 grasses (including 5 species) was used with each individual grass replicated 3 times (3 barrels) within each single dry-down. Data of turf quality, leaf firing and canopy spectral reflectance within each treatment day were averaged for a single grass across the three replicates, and the averaged data were combined across three dry-downs and used for correlation analysis and model develop-

ment for each individual grass. Turf quality and leaf firing models against reflectance were generated by using stepwise multiple simple regression procedures (SAS Institute Inc., Cary, N.C.). Ten wavelengths within 400 to 1100 nm that had best correlations of reflectance with turf quality and leaf firing were used to run models and the optimum models were then summarized for each individual grass. Data collected in overcast or heavy cloudy days were not included in the analysis since canopy reflectance was limited under such weather conditions.

Results and Discussion

Turf quality and leaf firing. Turf quality decreased after 8 to 12 d drought stress for all 12 grasses (Table 1). 'TifSport' and 'Tifway' bermudagrass, 'Sea Isle 2000' and 'Temple' seashore paspalum, and 'Palmetto' st. augustinegrass exhibited acceptable turf quality ratings of 6.0 or above at the end of drought stress. 'TifEagle' bermudagrass, 'Sea Isle 1' seashore paspalum, 'Plantation' and 'Tulsa' tall fescue, and 'Meyer' zoysiagrass exhibited >20% loss of turf quality under drought stress. An earlier onset of drought stress symptoms was observed in tall fescue relative to the other

species although these cultivars were drought resistant (Carrow and Duncan, 2002).

Leaf firing increased after 8 to 12 d drought stress for 12 grasses (Table 1). TifSport, Tifway, and 'Temple' exhibited less than 20% leaf firing, while 'TifEagle', 'Sea Isle 1', 'Plantation', 'Greystone', 'Tulsa II', and 'Meyer' had >38% leaf firing by the end of drought stress. The most severe leaf firing was noted in 'Tulsa II' , which exceeded 55%. Leaf firing is an indicator of overall drought resistance under field conditions in turfgrass (Carrow and Duncan, 2003). The occurrence of leaf firing was consistent with patterns of turf quality, demonstrating differences in drought resistance among turfgrass species and cultivars. Variations in leaf firing for all grasses provided a range of responses for spectral reflectance measurements under drought conditions.

All grasses exhibited similar ratings of turf quality and leaf firing before drought stress was imposed except for 'Tulsa II' tall fescue, which had the significant lower turf quality compared to some of the other grasses (Table 2). Large differences in turf quality and leaf firing were observed between grasses after drought stress. 'Temple' seashore paspalum showed the highest turf quality and the least

Table 1. Changes in turf quality and leaf firing within each grass averaged across drought stress periods.

Grasses	Turf quality		Leaf firing (%)		Drought
	Before[z]	End[y]	Before	End	duration (d)
TifSport (B)[x]	7.2 a[w]	6.3 b	2.1 b	18.1 a	10–12
TifEagle (B)	7.1 a	5.4 b	2.0 b	44.4 a	10–12
Tifway (B)	7.4 a	6.3 b	2.6 b	19.8 a	10–12
2000-7 (B)	7.0 a	5.9 b	2.7 b	23.9 a	10–12
Sea Isle 1 (SP)	7.0 a	5.3 b	2.3 b	39.7 a	10–13
Sea Isle 2000 (SP)	7.4 a	6.6 b	4.4 b	22.8 a	10–12
Temple (SP)	7.7 a	6.8 b	1.8 b	12.3 a	10–12
Plantation (TF)	7.4 a	5.8 b	1.2 b	38.6 a	9–11
Greystone (TF)	7.1 a	5.9 b	1.1 b	39.6 a	9–10
Tulsa II (TF)	6.7 a	4.9 b	1.9 b	55.2 a	8–9
Meyer (ZS)	7.0 a	5.6 b	1.0 b	39.9 a	9–12
Palmetto (SA)	7.4 a	6.2 b	2.8 b	21.0 a	9–12

[z]Before = before drought stress, where turf quality of 9.0 = ideal and 1.0 = brown, dead turf.
[y]End = end of drought stress.
[x]B = bermudagrass; SP = seashore paspalum; TF = tall fescue; ZS = zoysiagrass; SA = st. augustinegrass.
[w]Means followed by the same letters within a row at a given grass for turf quality and leaf firing were not significantly different at *P* < 0.05.

Table 2. Turf quality and leaf firing among 12 grasses averaged across drought stress periods.

Grasses	Turf quality		Leaf firing (%)	
	Before[z]	End[y]	Before	End
Temple (SP)[x]	7.7 a[w]	6.8 a	1.8 a	12.3 d
Sea Isle 2000 (SP)	7.4 a	6.6 ab	4.4 a	22.8 bcd
Tifway (B)	7.4 a	6.3 abc	2.6 a	19.8 dc
Palmetto (SA)	7.4 ab	6.2 abc	2.8 a	21.0 bcd
Plantation (TF)	7.4 a	5.8 a–d	1.2 a	38.6 abc
TifSport (B)	7.2 a	6.3 abc	2.1 a	18.1 d
TifEagle (B)	7.1 a	5.4 dc	2.0 a	44.4 a
Greystone (TF)	7.1 a	5.9 a–d	1.1 a	39.6 ab
Meyer (ZS)	7.0 ab	5.6 b–d	1.0 a	39.9 ab
2000-7 (B)	7.0 ab	5.9 a–d	2.7 a	23.9 bcd
Sea Isle 1 (SP)	7.0 ab	5.3 dc	2.3 a	39.7 ab
Tulsa II (TF)	6.7 b	4.9 d	1.9 a	55.2 a

[z]Before = before drought stress, where turf quality of 9.0 = ideal; 1.0 = brown, dead turf.
[y]End = end of drought stress.
[x]B = bermudagrass; SP = seashore paspalum; TF = tall fescue; ZS = zoysiagrass; SA = st. augustinegrass.
[w]Means followed by the same letters within a column for turf quality and leaf firing were not significantly different at *P* < 0.05.

leaf firing by the end of drought treatment, while 'Tulsa II' tall fescue had the least turf quality and the highest leaf firing. The relative comparisons of drought tolerance between grasses provided additional information for better understanding alterations of spectral reflectance for each grass.

Correlations for turf quality and leaf firing. In the range of 400 to 1100 nm, all 12 grasses exhibited some correlations between canopy reflectance and turf quality, but significant correlation coefficients ($r = -0.41 \sim -0.60$) were observed only in 5 grasses (Table 3). Significant r values for turf quality occurred within the photosynthetic regions specifically from 651 to 693 nm in 'TifEagle' and from 664 to 687 nm in 'Meyer', respectively. Reflectance at 664 to 680 nm and near-infrared regions from 768 to 810 nm were significantly correlated with turf quality in 'Sea Isle 1'. Two tall fescues, 'Plantation' and 'Tulsa II', demonstrated high correlations of reflectance at 640 to 690 nm and 740 to 890 nm with turf quality. Although these correlations varied with grasses, the result indicated that reflectance at 664 to 687 nm were well correlated with turf quality in all 5 grasses, including 'TifEagle', 'Sea Isle 1', 'Plantation', 'Tulsa II', and 'Meyer}.

Significant correlations between canopy reflectance and leaf firing were also observed in 5 grasses (Table 3). Reflectance at 572 to 700 nm and 645 to 693 nm were mainly correlated with leaf firing in 'TifSport' and 'Meyer', respectively; while leaf firing was correlated only in near-infrared regions from 765 to 814 nm in 'Sea Isle 1'. Significant r values occurred at both 645 to 690 nm and 736 to 900 nm in 'Plantation} and 'Tulsa II' tall fescues. These results demonstrated that reflectance at 645 to 693 nm were generally correlated with leaf firing in 'TifSport', 'Sea Isle 1', 'Plantation', 'Tulsa II', and 'Meyer'.

Leaf reflectance in the visible wavelengths is correlated with concentration of leaf pigments, and reflectance near 675 nm, 680 nm, or 700 nm is highly correlated with chlorophyll concentration (Blackburn, 1998; Carter and Spiering, 2002; Datt, 1999; Gitelson, et al., 1996). Changes of spectral reflectance under environmental stress can be a reliable indicator of plant growth and physiological status (Carter, 1993; Gitelson and Merzlyak, 1994). A relationship between canopy reflectance with both turf quality and leaf firing was found in 664 to 687 nm in five grasses, suggesting that reflectance near this particular photosynthetic region was relatively important in determining drought resistance in turfgrasses, which may be associated with changes in chlorophyll content under drought stress.

Peak correlations. The narrow-band reflectance wavelength with the highest r values for turf quality ranged from 671 to 870 nm and from 671 to 875 nm for leaf firing in all 12 grasses (Table 4). Most grasses exhibited peak correlations for turf quality at 670 to 693 nm, except for three seashore paspalums, which demonstrated the highest r values in the near-infrared region above 700 nm. Similar to the patterns of turf quality, peak correlations for leaf firing were observed within 667 to 693

nm for most grasses except for 'Sea Isle 1' and 'Sea Isle 2000'. These results indicated that reflectance at near-infrared 750, 775, and 870 nm was more effective for monitoring canopy status under drought stress in seashore paspalums compared to photosynthetic wavelengths. All three tall fescues had the strongest correlation at 671nm for both turf quality and leaf firing, suggesting a consistent response of tall fescue cultivars to drought stress. Leaf firing has been used as one indictor for assessment of improved drought resistance and persistence in turf-type tall fescue (Carrow and Duncan, 2003).

Unlike other grasses, reflectance at near-

infrared 750, 775, and 870 nm other than photosynthetic wavelengths was associated with canopy status under drought stress in seashore paspalums. In the NIR region (700-1300 nm), typical healthy leaves do not show strong absorption features, and the magnitude of reflectance is controlled by the structural discontinuities (Penuelas and Filella, 1998). The typical increased reflectance in the NIR region is due to internal scattering of light within the leaf that results in greater reflective surfaces (Gupta and Woolley, 1971; Knipling, 1970). Leaf surface of seashore paspalum appears more smooth and shinning compared to other warm-season turfgrasses, and this unique char-

Table 3. Grasses with significant correlation coefficient (*r*) of turf quality and leaf firing versus canopy reflectance at wavelengths from 400 to 1100 nm under drought stress.

Grasses	Turf quality		Leaf firing	
	Wavelength (nm)	*r*	Wavelength (nm)	*r*
TifSport (B)[z]	---	---	572~618	0.46*~0.57*
	---	---	623~693	0.58**~0.62**
	---	---	697~707	0.47*~0.57*
TifEagle (B)	651~693	−0.41*~−0.48*	---	---
Sea Isle1 (SP)	664~680	−0.45*~−0.46*	765~814	-0.46*~−0.47*
	768~810	−0.46*~−0.48*		
Plantation (TF)	641~690	-0.47*~−0.59*	645~690	0.47*~0.55*
	746~817	−0.47*~−0.51*	742~904	−0.47*~−0.54*
	827~891	−0.47*~−0.50*		
Tulsa II (TF)	641~664	−0.48*~−0.57*	615~641	0.47*~0.55*
	667, 671	−0.59**~−0.60**	645~690	0.60**~0.67**
	674~690	−0.52*~−0.58*	693	0.52*
	733~898	0.47*~0.58*	736~930	−0.42*~−0.59*
Meyer (ZS)	664~687	−0.47*~−0.49*	645~693	0.47*~0.54*

[z]B = bermudagrass; SP = seashore paspalum; TF = tall fescue; ZS = zoysiagrass; SA = st. augustine-grass.
*,**Significant at $P < 0.05$, 0.01, respectively.

Table 4. Wavelength positions with the peak (highest) correlation coefficient (*r*) between turf quality, leaf firing and canopy reflectance from 400 to 1100 nm for turfgrasses under drought stress.

Grasses	Turf quality		Leaf firing	
	Wavelength (nm)	*r*	Wavelength (nm)	*r*
TifSport (B)[z]	687	−0.42	687	0.62**
TifEagle (B)	673	−0.48*	677	0.38
Tifway (B)	687	−0.26	667	0.32
2000-7 (B)	693	−0.15	687	0.45
Sea Isle1 (SP)	775	0.48*	775	−0.47*
Sea Isle 2000 (SP)	869	0.15	875	−0.40
Temple (SP)	752	0.26	687	0.32
Plantation (TF)	671	−0.59*	671	0.55*
Greystone (TF)	671	−0.39	671	0.44
Tulsa II (TF)	671	−0.60*	671	0.67**
Meyer (ZS)	687	−0.49*	687	0.54*
Palmetto (SA)	687	−0.23	693	0.23

[z]B = bermudagrass; SP = seashore paspalum; TF = tall fescue; ZS = zoysiagrass; SA = st. augustine-grass.
*,**Significant at $P < 0.05$ or 0.01, respectively.

Table 5. Multiple linear regression models for turf quality and leaf firing against canopy reflectance for turfgrasses under drought stress.

Grasses	Turf quality	R^{2z}	Leaf firing	R^2
TifSport (B)[y]	R687, R690	0.32*	R658, R687, R667, R684	0.65**
TifEagle (B)	R658, R674	0.33*	R671, R677	0.36*
2000-7 (B)	---		R684, R687, R697	0.40*
Sea Isle 1 (SP)	R784, R801	0.49**	R772, R775	0.33*
Sea Isle 2000 (SP)	---		R856, R875	0.27
Plantation (TF)	R772, R778, R784	0.50*	R674, R784, R789	0.64**
Greystone (TF)	R661, R671, R677	0.60**	R661, R671, R677	0.61**
Tulsa II (TF)	R671, R677, R755	0.70***	R671, R658	0.60**
Meyer (ZS)	R661, R687	0.42**	R684, R687, R690	0.71***

[z]R^2 = coefficient of determination.
[y]B = bermudagrass; SP = seashore paspalum; TF = tall fescue; ZS = zoysiagrass; SA = st. augustine-grass.
*,**,***Significant at $P < 0.05$, 0.01, or 0.001, respectively.

acteristic of canopy structure would be a factor influencing reflectance of seashore paspalum. Jiang et al. (2003) found that reflectance from 756 to 804 nm were highly correlated with turf quality of seashore paspalum under wear stress. Trenholm at al. (2000) reported that reduced leaf total cell wall content was the major mechanisms of wear tolerance in seashore paspalum. Further investigation needs to be performed to elucidate relationship between leaf surface, leaf cell and canopy structure and spectral reflectance in turfgrasses under stress conditions.

Canopy characteristics, soil background, or weather conditions at sampling could be factors influencing reflectance and cause variations in correlations of canopy variables. The first derivative of reflectance data can eliminate background effects and could estimate a range of canopy structures (Danson et al., 1992; Malthus and Maderia, 1993). The first derivative of canopy reflectance increased the significance of peak correlations between reflectance and turf canopy variables such as quality and canopy temperature in a traffic stress study (Jiang et al., 2003). In the traffic study, treatments often resulted in exposure of the soil surface and substantial changes in the nature of the turf canopy. Smoothing of curves or better correlations of canopy reflectance versus turf quality and leaf firing were not observed by using the first derivative of reflectance in this study (data not shown). These results indicate that the original spectral data assessed drought responses of turfgrasses better than the first derivative, possibly due to a uniform, dense canopy within each grass barrel and no soil background exposure. Data collected under overcast weather conditions were blocked and not used for analysis, which might also reduce background noise for the correlation processes.

Models for turf quality and leaf firing. Multiple linear regression models were developed for turf quality and leaf firing against canopy reflectance based on 10 selected wavelengths with the highest correlations (Table 5). Turf quality models were not detected for five grasses, including 'Tifway' and 2000-7 bermudagrasses, 'Sea Isle 2000' and 'Temple' seashore paspalum, Palmetto st. augustinegrass; while 'Tifway', 'Temple', and 'Palmetto' did not exhibit adequate models for leaf firing. Turf quality and leaf firing models for most grasses contained photosynthetic wavelengths from 658 to 700 nm except for 'Sea Isle 1} and 'Sea Isle 2000' seashore paspalum, and 'Plantation' and 'Tulsa II' tall fescue, which included near-infrared wavelengths from 772 to 875 nm. Turf quality and leaf firing could be well predicted in the three tall fescue cultivars by using multiple linear regression models at 661 to 677 nm or/and 772 to 789 nm, as evidenced by a coefficient of determination (R^2) above 0.50. Regression models based on radiometry data with R^2 around 0.50 or above were used in predicting tallgrass prairie

biomass (Olson and Cochran, 1998), and tall fescue biomass was predicted at R^2 of 0.21 to 0.41 in other study (Fenstermaker-Shaulis et al, 1997). Jiang et al. (2004) reported that broad-band reflectance near 660 and 900 nm predominated in turf quality models of 'Tifway' and 2000-7, respectively, and reflectance near 710 nm mainly accounted for seashore paspalum models under drought stress. Similar results were not found by using narrow-band approaches in this study. The use of different instruments generating broad-band and narrow-band spectra may contribute to variations in model development in turfgrasses.

Interestingly, Jiang et al. (2004) reported broad-band spectral models for turf quality that were significant for all 12 grasses with $R^2 > 0.50$ except for two grasses (Temple and Sea Isle 1). Broad-band spectral reflectance integrates reflectance across 10 to 15 adjacent wavelengths, and these results suggested that for spectral monitoring of drought stress on turfgrasses, a broad-band approach may be more appropriate than a narrow-band of only 1 to 3 nm intervals.

In summary, narrow-band canopy reflectance could be used to determine drought resistance in some turfgrass species. Correlations of canopy reflectance versus turf quality and leaf firing varied with grass species and cultivars, however, reflectance at the photosynthetic regions from 664 to 687 nm were relatively important in determining turf quality and leaf firing in selected bermudagrass, tall fescue, zoysiagrass and st. augustinegrass. Leaf firing under drought stress could be predicted by using multiple linear regression models for most grasses. But, each grass exhibited a different model, suggesting that species and cultivar differences in reflectance should be considered in using reflectance models. These results are valuable for providing techniques for rapid screening drought tolerant cultivars or ecotypes, field mapping of drought stress, managing turf plots under drought stress, and improving irrigation scheduling of turfgrasses.

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