Multispectral Radiometer Signatures for Stress Evaluation in Compacted Bermudagrass Turf

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Abstract. A 3-year study was conducted in Auburn, Ala., on an established hybrid bermudagrass [*Cynodon dactylon* (L.) Pers. × *C. transvaalensis* Burt-Davy ‘Tifway’] stand maintained at a 2.54-cm mowing height. Treatments were level of soil traffic applied via a weighted golf cart to produce turf and soil that received varying amounts of traffic. Dormant bermudagrass was overseeded with perennial ryegrass (*Lolium perenne* L.) each October, which remained until May of each year. Spectral data were collected monthly using a multispectral radiometer. Percent reflectance data were acquired over 512 discrete wavelengths in visible (VIS) and near-infrared (NIR) ranges. Quarterly data collection included soil penetrometer and bulk density measurements to a depth of 15 cm. After 2 years of traffic, both soil penetrometer and bulk density data indicated statistically significant increases in soil compaction. In general, as traffic increased there were also increases in percent reflectance in the VIS range. Data were subject to temporal variation, however, as values changed with the date of sample collection. The NIR reflectance data provided little consistent correlation to measurements of soil compaction. Use of NIR and VIS radiometry to evaluate turf stress showed some potential, but temporal variation must be considered.

It is well documented that soil compaction has adverse effects on vegetation. Negative agronomic effects of soil compaction include decreased yield (Al-Adawi and Reeder, 1996; Oussible et al., 1992), decreased root growth and length density (Kasper et al., 1995; Rechel et al., 1990), and decreased uptake of N, P, and K (Dolan et al., 1992; Lowery and Schuler, 1991).

In turfgrass, the visual quality, percent turf cover, and total nonstructural carbohydrates of perennial ryegrass, Kentucky bluegrass (*Poa pratensis* L.), and tall fescue (*Festuca arundinacea* Schreb.) all decreased as compaction increased (Carrow, 1980). In a greenhouse study, decreased N use, evapotranspiration, and root growth of perennial ryegrass were observed in compacted soils (Sills and Carrow, 1983). Soil compaction also reduced the visual quality of perennial ryegrass, and rooting was reduced in the 10- to 25-cm soil zone (O’Neil and Carrow, 1983). In comparison, compaction of a Kentucky bluegrass stand had no effect on root weight or distribution. However, visual quality, shoot density, and percent total cover were all reduced in the compacted plots (O’Neil and Carrow, 1982). Compaction of a loamy sand soil putting green increased soil strength and reduced field water infiltration (Murphy et al., 1993). In summary, compaction of turf soils has been shown to increase turfgrass stress via reductions in water use, rooting depth, and soil aeration.

Many studies have investigated stress effects on the spectral reflectance of vegetation (Carter, 1993; Chapin, 1991; Save et al., 1995). Changes in spectral reflectance of vegetation have been attributed to changes in leaf pigments, especially chlorophyll (Carter, 1993; Carter et al., 1996). Increased spectral reflectance in the visible (VIS) region, which was caused by decreased absorption by pigments, was correlated with stress in six vascular plant species (Carter, 1993). Save et al. (1995) found increased spectral reflectance in the VIS and near-infrared (NIR) for leaves with decreased water potentials. Chapin (1991) offered the hypothesis that most physiological response is similar in stressed plants; thus, similar signatures in reflectance would likely occur.

In turfgrass, multispectral radiometry has been used to assess plant light reflectance at various wavelengths (Fenstermaker-Shaulis et al., 1997; Trenholm et al., 1999a, 1999b). Radiometry data in the Trenholm study (1999a) was highly correlated with qualitative data, such as turf color, turf quality, and uniformity. Although radiometry data were strongly associated with the qualitative variables, such as visual turf quality and shoot injury, they were not related to quantitative shoot growth data (Trenholm et al., 1999a).

Because spectral reflectance has been shown to successfully identify stressed (Fenstermaker-Shaulis et al., 1997; Trenholm et al., 1999a) from non-stressed turfgrass, the method may offer a rapid way to quantify and calibrate the degree of turfgrass stress. Since multispectral radiometry has been shown to correlate well with qualitative measures of turfgrass stress from wear (Trenholm et al., 1999a), it was our objective to determine how well multispectral

radiometry would correlate with quantitative measures from compaction of turf. Since turf wear is often a secondary effect of turf compaction, and compaction causes stress in turf, we chose readily available quantitative measures of soil compaction. Soil resistance (Murphy et al., 1993) and soil bulk density (Carrow, 1980) are variables often used to quantify the severity of compaction in turf soils. We evaluated the impact of levels of soil traffic on multispectral radiometry, soil resistance, and bulk density, and examined correlations between those measured variables.

Materials and Methods

Five replications of trafficked plots were established at the Turfgrass Research Unit (Auburn, Ala.) in Feb. 1997. Soil at the site is a Marvyn fine sandy loam, classified as a fine-loamy, kaolinitic, thermic, Typic Kanhapludult. Turf was a 5-year-old stand of ‘Tifway’ hybrid bermudagrass maintained at a mowing height of 2.54 cm with clippings not removed. Plots were mowed every other day. In October of each year, the plots were overseeded with perennial ryegrass at a rate of 440 kg·ha⁻¹. The overseed was not chemically removed, and naturally transitioned back to bermudagrass in early May of each year. Standard and recommended fertilizer and pest control practices were used to maintain the plots (Higgins, 1998), including monthly applications of N at 3.0 g·m⁻². Irrigation was supplied as needed to supply a total of 2.5 cm of water per week. Overseeded plots received the same mowing and irrigation practices as bermudagrass.

The study consisted of five levels of traffic to create different degrees of soil compaction and turf wear, with each traffic level replicated five times. The experiment was arranged as a randomized complete-block design. Each plot was 3.2 × 3.2 m, with a 3.2-m alley surrounding each plot to accommodate application of traffic treatments. Traffic treatments were applied via a two-person golf cart weighted to simulate the average load of two golfers and their clubs (≈200 kg). Traffic was applied 3 d per week (Monday, Wednesday, and Friday) beginning in Feb. 1997, and continued throughout the length of the study, until Sept. 2000. The period from Feb. until June 1997 was used to create levels of soil compaction, and no data were collected during this time. Traffic was applied by driving the golf cart randomly across designated plots a total of zero, 10, 20, 30, or 40 times per day. All turns were made in plot alleys, with the cart driven directly across treatment plots. Since not every pass of the golf cart went across the exact same area of each plot, levels of traffic are not quantified as a total number of passes. Instead, treatments will be referred to as “Zero Traffic” (ZT), “Slight Traffic” (ST), “Moderate Traffic” (MT), “Heavy Traffic” (HT), and “Extreme Traffic” (ET) for the rest of this paper.

Data collection started in June 1997 and ended in Aug. 2000. At approximately monthly intervals during periods of active bermudagrass growth, the following data were collected randomly from within each plot: multispectral radiometer readings (aver-

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age of 10 per plot at a 30-cm height) and soil penetrometer readings (to a depth of 150 mm) [American Society of Agricultural Engineers (ASAE), 2000]. Soil bulk density (0–15 cm) measurements were collected in June 1997, Apr. 1998, Apr. 1999, and June 2000 (Blake and Hartge, 1986). Radiometer data were recorded for 512 discrete bands in the UV, VIS, and NIR regions (wavelengths 310–1050 nm). A portable spectroradiometer equipped with an 8° FOV foreoptic and a silicon array sensor was used to measure radiance ($\text{W} \cdot \text{cm}^{-2} \cdot \text{nm} \cdot \text{sr} \times 10^{-10}$) (GER Corp., Millbrook, N.Y.). Radiance was converted to percent reflectance using a Spectralon panel (GER Corp.). Radiometer data were collected between the hours 11:00 AM and 2:00 PM, after the plots were mowed, and were always collected 1 week after N applications had been made to the turf.

ARimik CP-20 manual soil cone penetrometer (Agridry Rimik Pty. Ltd., Toowoomba, Queensland, Australia) was used to measure soil resistance. Soil resistance is defined as the force required to push the soil cone penetrometer into the soil divided by the cross-sectional area of the base of the cone (ASAE, 2000). The penetrometer was equipped with a cone having a base area of 130 mm². Resistance was measured at 15-mm increments continuously throughout the soil profile to a depth of 150 mm. Five insertions were performed within each plot. Data were collected when soils were at or near field capacity (-10 kPa), with irrigation applied as needed to obtain this water content.

Soil bulk density cores were collected using the technique of Blake and Hartge (1986). Three undisturbed cores (4.1-cm diameter $\times$ 15.2 cm deep) were removed from each plot using a Giddings hydraulic soil probe (Giddings Machine, Ft. Collins, Colo.). Averages of three cores from each plot were reported as the bulk density.

Linear regression was performed on bulk density data using SAS (SAS, 1989), with the number of daily cart passes (0, 10, 20, 30, or 40) used as the regressor. Correlations between bulk density, soil penetrometer resistance, and radiometer data were also calculated using SAS.

Results and Discussion

Results of compaction treatment application. Bulk density and penetrometer measurements taken on 28 June 1997 revealed that traffic applied from Feb. to June 1997 was successful in achieving different compaction levels (Figs. 1 and 2). Bulk density increased as traffic increased ($P = 0.006$), and penetrometer readings increased as the number of traffic passes increased ($P = 0.09$). Greatest differences in penetrometer resistance were observed between plots that had not received traffic and those that received the highest level of traffic (Fig. 2). Significant differences in soil resistance were observed at every increment of depth, except at the final depth of 150 mm (Fig. 2).

After 2 years of compaction treatments, soil bulk density increased as traffic increased

Fig. 1. Soil bulk density at 0–15 cm depth at three sampling dates as affected by the relative level of traffic, June 1997.

(Fig. 1). Within treatments, bulk density did not increase dramatically over 2 years of compaction. For example, in June 1997, plots receiving the highest traffic treatment had an average bulk density of 1.54 g·cm⁻³, and in Apr. 1999 those same plots had an average bulk density of 1.55 g·cm⁻³. Soil bulk density response to traffic treatments was the same in June 1997 and Apr. 1999, as illustrated by similar slope and intercept coefficients for regression lines fit to the data (Fig. 1).

In June 1999, significant differences in soil resistance due to compaction treatments existed ($P = 0.001$) (Fig. 2). Differences were less apparent in the 0–15 mm depth, but

strong differences in soil resistance existed in the underlying depths. Typically, there were significant differences in soil resistance when uncompacted plots (ZT) were compared to those receiving ST or MT, but differences in soil resistance between the two highest compaction treatments (HT and ET) were less obvious.

After 3 years of soil compaction, bulk density had increased in all plots, and there was no longer a linear increase between bulk density and increasing compaction (Fig. 1). A general overall increase in bulk density was likely a result of the lack of 3 years of aerification. Yearly core aerification of bermudagrass

Fig. 2. Soil penetrometer resistance by soil depth as affected by the relative level of traffic, at three sampling dates. Horizontal bars around each marker represent standard error.

is a recommended practice, and traffic from maintenance (sprayers, fertilizer spreaders, mowers) would compact the entire soil area over the 4 years of the study. At this sampling, soil bulk density did not increase with additional traffic beyond the HT (30) treatment. The first derivative of the regression equation revealed that soil bulk density was maximized at 29 daily cart passes/plot.

Soil penetrometer data collected in July 2000 revealed that 3 years of continuous traffic treatments had created differences in soil compaction (Fig. 2). The only depths that did

not exhibit significant differences due to traffic were at the surface (0–15 mm) and at the lowest (135–150 mm) sampling depth. Lack of significant differences at the surface is likely due to root, shoot, and thatch development, which would lessen the impact of compaction immediately at the surface.

Wavelength selection. Previous research found that wavelengths in the 535- to 640-nm range, and wavelengths in the 685- to 700-nm range best correlated with evaluations of plant stress (Carter, 1993). Reflectance at specific wavelengths of 661, 706, 760, 813, and 935

Fig. 3. Temporal variability in percent reflectance of hybrid bermudagrass, as measured by multispectral radiometry at 661 and 935 nm.

nm was also shown to be highly correlated with visual turf quality, shoot density, and shoot injury (Trenholm et al., 1999b). Disease data has been assessed at wavelengths of 460, 600, and 800–810 nm (Green et al., 1998; Nutter et al., 1990, 1993; Raikes and Burpee, 1998). Because these wavelengths have been shown to correlate with qualitative measures of turf stress, we chose to evaluate similar wavelengths in this study. Selected wavelengths for this project were 507 (green), 559 (green), 661 (red), 706 (red), 760 (NIR), 813 (NIR), and 935 (NIR) nm.

Table 1. Results of the regression of percent reflectance of bermudagrass turf against traffic level, as affected by sampling date.

Wavelength (nm)	Date					
	25 June 1999	6 July 1999	30 Aug. 1999	16 May 2000	6 July 2000	4 Aug. 2000
507	L** (0.79) ^z	L** (0.76)	NS (0.47)	Q*** (0.96)	NS (0.18)	L*** (0.95)
559	NS (0.53)	L* (0.68)	NS (0.54)	Q*** (0.98)	NS (0.21)	L*** (0.91)
661	L*** (0.91)	Q** (0.70)	NS (0.34)	Q** (0.88)	NS (0.24)	NS (0.34)
706	L** (0.76)	L** (0.73)	NS (0.47)	Q*** (0.97)	NS (0.42)	L*** (0.93)
760	NS (0.16)	L** (0.78)	Q*** (0.87)	L*** (0.99)	L* (0.69)	NS (0.55)
813	NS (0.16)	L* (0.78)	Q*** (0.86)	L*** (0.99)	L** (0.74)	L* (0.58)
935	NS (0.08)	L* (0.69)	Q** (0.78)	L*** (0.97)	NS (0.52)	NS (0.17)

^z r^2 for the regression equation between percent bermudagrass reflectance at that wavelength and date, and traffic level.

ns, *, **, ***Nonsignificant or significant at $P \leq 0.05$, 0.001, or 0.0001, respectively; linear (L), quadratic (Q).

The normalized difference vegetation index (NDVI) and the NIR reflectance divided by red reflectance (IR/R), were also calculated from the reflectance data. NDVI is calculated as:

$$R_{935} - R_{661}, \text{ divided by } R_{935} + R_{661},$$

where "R" is the percent reflectance at the NIR (935) and red (661) wavelengths. The NDVI has been shown to correlate well with photosynthetically active tissue (Asrar et al., 1984; Raikes and Burpee, 1998; Trenholm et al., 1999a). Reflectance in the NIR range divided by reflectance in the red range (661 nm) (IR/R) has been correlated with shoot biomass (Daughtry et al., 1992).

Relationship of radiometer data to measured soil physical properties. Figure 3 illustrates percent reflectance of the bermudagrass surface as a function of golf cart traffic at six sampling dates. Due to space limitations, temporal variations for two wavelengths (661 and 935 nm) are illustrated; regressions between percent reflectance and compaction for all seven wavelengths are provided in Table 1. Temporal variation in percent bermudagrass reflectance was evident at the seven sampling dates (Fig. 3). Bermudagrass reflectance varied by 2% to 4% in the VIS range (507, 559, 661, and 706 nm), and by 10% to 17% in the NIR range (760, 813, and 935 nm). Given that the bermudagrass plots were maintained consistently throughout May–Aug. of 1999 and 2000, and that radiometer data were collected on cloudless days between the hours of 11:00 AM and 2:00 PM, variation in percent reflectance was likely not related to some consistent change, such as a decrease in turf

cover or increase in soil compaction. Many other factors could create temporal variation in percent reflectance, including variation in turf color due to mowing practices, presence of undetected disease, leaf age, or variation in chlorophyll content (Green et al., 1998; Gupta and Woolley, 1971). Although every effort was made to obtain plot readings when the turf was at optimum color, quality, and moisture status, temporal variation over the 3 years of data collection was expected.

Temporal variation in radiometer data has been studied previously, often within the topic of disease assessment. When multispectral radiometry was used to assess dollar spot (*Sclerotinia homoeocarpa*) infestation, data collected at 600-nm agreed well ($R^2 > 0.83$) with visual dollar spot ratings (Nutter et al., 1993). When the radiometer data were collected a second time, after 24 h, this second data set correlated well with the first data set (slope = 1.0) (Nutter et al., 1993). In a different study, when radiometer data were collected over an entire disease (*Rhizoctonia solani*) epidemic of 20 d, less than 50% of the variability was explained by the linear regression between disease severity and percent reflectance (Raikes and Burpee, 1998). The authors hypothesized that when data are analyzed over an entire epidemic, environmental or plant variability may significantly affect reflectance (Raikes and Burpee, 1998).

In some cases as traffic increased, percent reflectance of the bermudagrass increased (Fig. 3). This often occurred within the VIS wavelengths, a response also found in earlier work (Carter, 1993; Nutter et al., 1993). In our

study, best fit of reflectance data occurred on 16 May 2000, when there was always a significant linear or quadratic increase in bermudagrass reflectance as traffic increased, at every wavelength analyzed (r^2 values > 0.88) (Table 1). In other cases, however, the reflectance response (VIS or NIR) to increasing traffic was highly variable, and percent reflectance was either unaffected, or decreased as traffic increased. Some studies have shown NIR reflectance may be unresponsive to stress (Carter, 1993), or may decrease as stress increases (Nutter et al., 1993; Raikes and Burpee, 1998).

In other research, NDVI has been shown to correlate well with plant parameters such as photosynthesis (Asrar et al., 1984; Gallo et al., 1985) or leaf area index (Daughtry et al., 1992). In our study NDVI did not correlate appreciably better with soil resistance or soil bulk density than any of the other studied wavelengths (Tables 2 and 3). Similar results were observed for IR/R. Lack of significant correlation in this study may be due to the stress treatment applied, as soil compaction would create turf stress via a combination of factors, including turf wear, low soil oxygen, and high soil bulk density. Such "multi-stresses" may not correlate with spectral data as well as a single stress, such as nitrogen deficiency, or an individual disease.

Within each wavelength, there was little consistency in response among sampling dates as traffic increased. Table 1 illustrates the variation in regression equation fit to the data, and the wide range of r^2 values describing the suitability of fit. Four of the six sampling dates produced a significant regression response between percent reflectance at a given wavelength and traffic level. Although the 813-nm wavelength had five of six sampling dates with significant regression relationships, these were not consistently increasing or decreasing. The linear relationships of July 1999 and May 2000 indicated that percent reflectance increased as traffic increased, while in July and Aug. 2000 reflectance decreased as traffic increased. From year to year, no one sampling month produced similar results. For example, Aug. 1999 data only had significant relationships within the NIR wavelengths, while in Aug. 2000 only the 813-nm wavelength within the NIR wavelengths was significantly related to traffic level ($r^2 = 0.58$).

Table 2. Coefficients of determination for the relationship between percent reflectance of bermudagrass turf and soil penetrometer readings (0–15 cm depth average).

Wavelength (nm)	Date			
	25 June 1999	6 July 1999	16 May 2000	6 July 2000
	r^2			
507	0.56	0.91	0.53	0.21
559	0.22	0.89	0.58	0.24
661	0.69	0.86	0.33	0.26
706	0.52	0.89	0.51	0.42
760	0.27	0.55	0.71	0.55
813	0.35	0.57	0.69	0.62
935	0.23	0.79	0.64	0.43
NDVI ^z	0.94	0.46	0.22	0.47
IR/R ^y	0.95	0.59	0.23	0.42

$$^z\text{NDVI} = R_{935} - R_{661} / R_{935} + R_{661}.$$

$$^y\text{IR/R} = R_{935} / R_{661}.$$

Table 3. Coefficients of determination for the relationship between percent reflectance of bermudagrass turf and soil bulk density.

Wavelength (nm)	Date			
	25 June 1999	6 July 1999	16 May 2000	6 July 2000
	r^2			
507	0.44	0.88	0.89	0.02
559	0.33	0.52	0.90	0.07
661	0.37	0.95	0.74	0.03
706	0.55	0.84	0.83	0.19
760	0.03	0.09	0.75	0.55
813	0.007	0.09	0.70	0.55
935	0.19	0.89	0.63	0.39
NDVI ^z	0.30	0.85	0.0004	0.12
IR/R ^y	0.19	0.89	0.0006	0.10

$$^z\text{NDVI} = R_{935} - R_{661} / R_{935} + R_{661}.$$

$$^y\text{IR/R} = R_{935} / R_{661}.$$

Because it has been previously shown that it is difficult to separate the source of stress in radiometer measurements (Chapin, 1991; Green et al., 1998; Raikes and Burpee, 1998), an objective was to correlate radiometer data with quantitative measurements of soil compaction (bulk density and penetrometer resistance). Although our treatments had created differences in soil bulk density (Fig. 1) and soil resistance (Fig. 2), correlations between radiometer data and soil resistance (Table 2) or bulk density (Table 3) were not consistent over sampling date or wavelength.

Best correlations between reflectance and soil resistance were observed in the VIS wavelengths, with lower r^2 within the NIR range (Table 2). There was no unique wavelength that provided a strong correlation between reflectance and soil resistance across all sampling dates. Typically, if a wavelength in the VIS range had a high r^2 , other visible wavelengths did as well. This was observed in July 1999.

Strong regression relationships between reflectance and traffic level did not always create a high correlation between reflectance and soil resistance. For example, regressions between reflectance and traffic level were highly significant on the 16 May 2000 sampling, yet correlations between reflectance and soil resistance on that same date never exceeded an r^2 of 0.71, and most were much lower. At the July 1999 sampling, however, significant regression responses between reflectance and traffic were mirrored by high correlations between reflectance and soil resistance.

Correlations between reflectance and soil bulk density followed the same trends as with the soil resistance data (Table 3). If high r^2 values existed between the data sets, it occurred for almost all the studied wavelengths (July 1999 and May 2000); thus, no unique wavelength was better correlated with reflectance than another.

The application of golf cart traffic increased both soil resistance and soil bulk density during 3 years of measurement. Average soil bulk density increased 14% from June 1997 to Apr. 2000. In general, percent reflectance in the VIS range increased as traffic increased, and reflectance in the NIR range was variable. These general responses, however, were prone to temporal variability, and regression equations of the relationships between traffic and

reflectance varied across sampling date. Correlations between bermudagrass reflectance and soil resistance and bulk density were variable. There was not any one wavelength across all sampling dates that produced high correlations between reflectance and soil resistance or bulk density data. Although multispectral radiometers sense stress in turfgrass, the exact cause of the stress may be difficult to ascertain, and temporal variability is likely. Additional research that studies spectral reflectance and direct measures of turfgrass stress is warranted.

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