NOTE

Seasonal Dynamics of Hyperspectral Reflectance Patterns Influencing Detection of Imported Fire Ant (Hymenoptera: Formicidae) Mound Features in Turfgrass[1]

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Imported fire ants (*Solenopsis* spp.) impact soil quality and turfgrass nutrient management affecting an estimated 8.1 million ha in sod production, recreational, and residential settings in the southeastern U.S. Using a ground-based hyperspectral sensor, we seasonally monitored reflectance characteristics of imported fire ant mound features. This information is a prerequisite for either designing vehicle-mounted or airborne sensor arrays with appropriate band-pass filters to maximize mound detection as well as optimize the timing of field- to landscape-scale surveys to improve management efforts. The objectives of this pilot study were 3-fold: (1) assess seasonally-acquired hyperspectral reflectance patterns for ant-affected versus undisturbed turfgrass and soils (inceptisols, entisols, alfisols, and vertisols) for a widely-used turfgrass cultivar, Tifway 419 (*Cynodon dactylon* x *C. transvaalensis*); (2) identify wavebands (50 nm in width) that enhance the detection of imported fire ant mound features across seasons in heavily-managed production and recreational environments, and; (3) summarize and interpret key physicochemical spectral features resulting from non-native *Solenopsis* spp. mound-building activities across seasons. In addition, emphasis was placed on both simplifying post-processing procedures for hyperspectral datasets (thus, minimizing distortions to these complex ant pedoturbation-plant signatures) as well as conserving signal strength needed for cost-effective sensor design. Detailing imported fire ant modifications to soils and turfgrass at key stages in their annual life cycle (i.e., peak biomass and brood minimum) may reveal avenues for the development of better integrated biological-geochemical control techniques for the management of these ants in intensive industries such as turfgrass, an industry that generated total output (revenue) impacts of $62.2 billion in the U.S., expressed in 2005 US dollars (Haydu et al. 2006, http://edis.ifas.ufl.edu/pdffiles/FE/FE63200.pdf).

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Reflectance data (n = 3,800 spectra) were collected from August through December 2006 from field sites with hybrid bermudagrass (Cultivar Tifway 419) in the North Central Hills and Delta physiographic regions of Mississippi. These sites had moderate imported fire ant infestations (50 - 75 mounds ha^{-1}) with low-profile mounds (typically <5 cm) embedded in the turf; however, soil properties and vegetation coverage among imported fire ant mounds varied widely. Hyperspectral scans were acquired from 4 target types (i.e., mound soil, undisturbed bare soil, ant-affected turfgrass at the mound perimeter, and unaffected turfgrass approx. 2 m from the mound perimeter) using a full-range spectroradiometer (350 - 2500 nm; FieldSpec Pro, Analytical Spectral Devices, Inc., Boulder, CO). The device was equipped with a 1° foreoptic; reflectance readings were collected from a height of 1.00 m providing a 0.017-m diam field of view at nadir. For calibration, a square Spectralon panel (Labsphere, North Sutton, NH) was placed in the field of view at 1.00 m from the optics, leveled, and measured before and after each target acquisition. All spectra were collected under cloudless skies, and acquired within ± 2 h of solar noon. Reflectance factors were calculated (Robinson and Biehl 1979, Proc. Soc. Photo-Opt. Instrum. Eng. 196:16 - 26).

Turfgrass care and maintenance factors at the study sites were similar; sites were mowed 2 - 3 times per week and received a minimum of 25.4 mm of irrigation on a weekly basis. Compared with the 30-yr averages (1971 - 2000), precipitation at the North Central Hills field site was above normal for the months of September (+154.7 mm) and October (+137.9 mm), but below normal for August (-8.4 mm), November (-47.0 mm) and December (-15.7 mm); whereas precipitation at the Delta field site was above normal in October only (+135.1 mm), and below normal for August (-12.4 mm), September (-11.9 mm), November (-65.8 mm), and December (-27.2 mm). Digital photographs of all mounds were taken and classified by percentage of turfgrass cover. Data reduction was accomplished by segmenting spectra into wavebands spanning 50 nm. Analysis of variance (ANOVA) was used to elucidate significant waveband and target combinations using Proc Mixed (Littell et al. 1996, SAS System for Mixed Models); means were considered different at α=0.05.

Peak summer season hyperspectral results (14 and 16 August 2006), for sparsely-covered ant mounds (≤50% vegetation) from sites in the North Central Hills and Delta physiographic regions of Mississippi, indicated that mean reflectance values for targets (i.e., ant-affected versus undisturbed bermudagrass, ant mound soil, and undisturbed bare soil) averaged over 50 nm bandwidths (Table 1) were most distinctive from each other at 650 - 700 nm (F=31.8; df=3, 8.3; P<0.0001), 1450 - 1500 nm (F=36.9; df=3, 6.2; P<0.001), and 2000 - 2050 nm (F=50.2; df=3, 5.6; P<0.001). Reflectance data collected during the late Summer-Fall transition (19 - 20 September 2006) displayed shifts in mound feature recognition in the visible (VIS) and near-infrared (NIR) regions (Fig. 1A), with distinctive bandwidths constrained to just the VIS region (Table 1), ranging from 600 - 700 nm (600 - 650 nm range, F=31.3, df 3, 5.7, P < 0.001 and 650 - 700 nm range, F=43.0, df 3, 5.7, P < 0.001). Fall datasets (acquired 23 October and 3 November 2006—Table 1) displayed the most robust differences in the 2000 - 2100 nm range (F=33.5, df 3, 31.0, P < 0.0001 and F=32.9, df 3, 31.0, P < 0.0001), followed by 650 - 700 nm (F=21.9, df 3, 37.4, P < 0.0001), 600 - 650 nm (F=15.8, df 3, 37.4, P < 0.0001), 1050 - 1100 nm (F=13.1, df 3, 30.9, P < 0.0001), 900 - 950 nm (F=12.4, df 3, 30.9, P < 0.0001), and 850 - 900 nm (F=12.1, df 3, 30.9, P < 0.0001). Ant-affected turfgrass (especially on mound perimeters—designated as PG) was not reliably distinguishable from unaffected turfgrass (approx. 2 m from each mound—noted as GR) from August through November (Table 1). In addition, significant

Table 1. Comparison of reflectance values (mean ± SEM) from select wavebands for the four target types acquired in imported fire ant infested turfgrass settings

Waveband (nm)	Target	Aug 2006	Sep 2006	Oct-Nov 2006	Dec 2006
600-650	BS	0.24 ± 0.02 a	0.24 ± 0.02 a	0.25 ± 0.02 a	0.23 ± 0.02 a
	GR	0.07 ± 0.02 c	0.07 ± 0.02 c	0.12 ± 0.02 bc	0.20 ± 0.02 a
	MD	0.13 ± 0.02 b	0.15 ± 0.02 b	0.15 ± 0.02 b	0.26 ± 0.02 a
	PG	0.05 ± 0.02 c	0.05 ± 0.02 c	0.08 ± 0.02 c	0.13 ± 0.02 b
650-700	BS	0.26 ± 0.02 a	0.26 ± 0.02 a	0.28 ± 0.02 a	0.25 ± 0.02 a
	GR	0.07 ± 0.02 c	0.07 ± 0.02 c	0.12 ± 0.02 bc	0.24 ± 0.02 a
	MD	0.15 ± 0.02 b	0.16 ± 0.02 b	0.17 ± 0.02 b	0.30 ± 0.02 a
	PG	0.04 ± 0.02 c	0.04 ± 0.02 c	0.08 ± 0.02 c	0.16 ± 0.02 b
850-900	BS	0.37 ± 0.03 a	0.36 ± 0.03 ab	0.38 ± 0.03 b	0.33 ± 0.04 a
	GR	0.39 ± 0.02 a	0.43 ± 0.03 a	0.46 ± 0.03 a	0.37 ± 0.04 a
	MD	0.26 ± 0.02 b	0.23 ± 0.03 b	0.26 ± 0.03 c	0.41 ± 0.04 a
	PG	0.42 ± 0.02 a	0.43 ± 0.03 a	0.43 ± 0.03 ab	0.38 ± 0.04 a
1050-1100	BS	0.44 ± 0.03 a	0.40 ± 0.03 a	0.45 ± 0.03 b	0.38 ± 0.04 a
	GR	0.45 ± 0.02 a	0.48 ± 0.03 a	0.53 ± 0.03 a	0.45 ± 0.04 a
	MD	0.31 ± 0.02 b	0.27 ± 0.03 b	0.31 ± 0.03 c	0.48 ± 0.04 a
	PG	0.46 ± 0.02 a	0.47 ± 0.03 a	0.48 ± 0.03 ab	0.46 ± 0.04 a
1450-1500	BS	0.49 ± 0.02 a	0.42 ± 0.03 a	0.47 ± 0.03 a	0.37 ± 0.04 b
	GR	0.21 ± 0.02 c	0.17 ± 0.03 b	0.25 ± 0.03 b	0.40 ± 0.04 ab
	MD	0.32 ± 0.02 b	0.31 ± 0.03 a	0.34 ± 0.03 b	0.50 ± 0.04 a
	PG	0.15 ± 0.02 c	0.14 ± 0.03 b	0.20 ± 0.03 b	0.30 ± 0.04 b
2000-2050	BS	0.48 ± 0.03 a	0.39 ± 0.03 a	0.45 ± 0.03 a	0.33 ± 0.04 b
	GR	0.14 ± 0.03 c	0.10 ± 0.03 b	0.18 ± 0.03 c	0.35 ± 0.04 b
	MD	0.31 ± 0.03 b	0.31 ± 0.03 a	0.32 ± 0.03 b	0.50 ± 0.04 a
	PG	0.08 ± 0.03 c	0.07 ± 0.03 b	0.13 ± 0.03 c	0.24 ± 0.04 b
2050-2100	BS	0.49 ± 0.03 a	0.41 ± 0.03 a	0.47 ± 0.03 a	0.36 ± 0.04 b
	GR	0.15 ± 0.02 c	0.12 ± 0.03 b	0.19 ± 0.03 c	0.31 ± 0.04 b
	MD	0.31 ± 0.02 b	0.32 ± 0.03 a	0.34 ± 0.03 b	0.52 ± 0.04 a
	PG	0.10 ± 0.02 c	0.09 ± 0.03 b	0.15 ± 0.03 c	0.24 ± 0.04 b

Abbreviations: BS=bare soil (undisturbed), GR=unaffected turfgrass approx. 2 m from ant mound perimeter, MD=ant mound soil, and PG=ant-affected turfgrass at mound perimeter.

Mean values (for a particular waveband and target assemblage as grouped by date) followed by the same letter are not significantly different at $P = 0.05$.

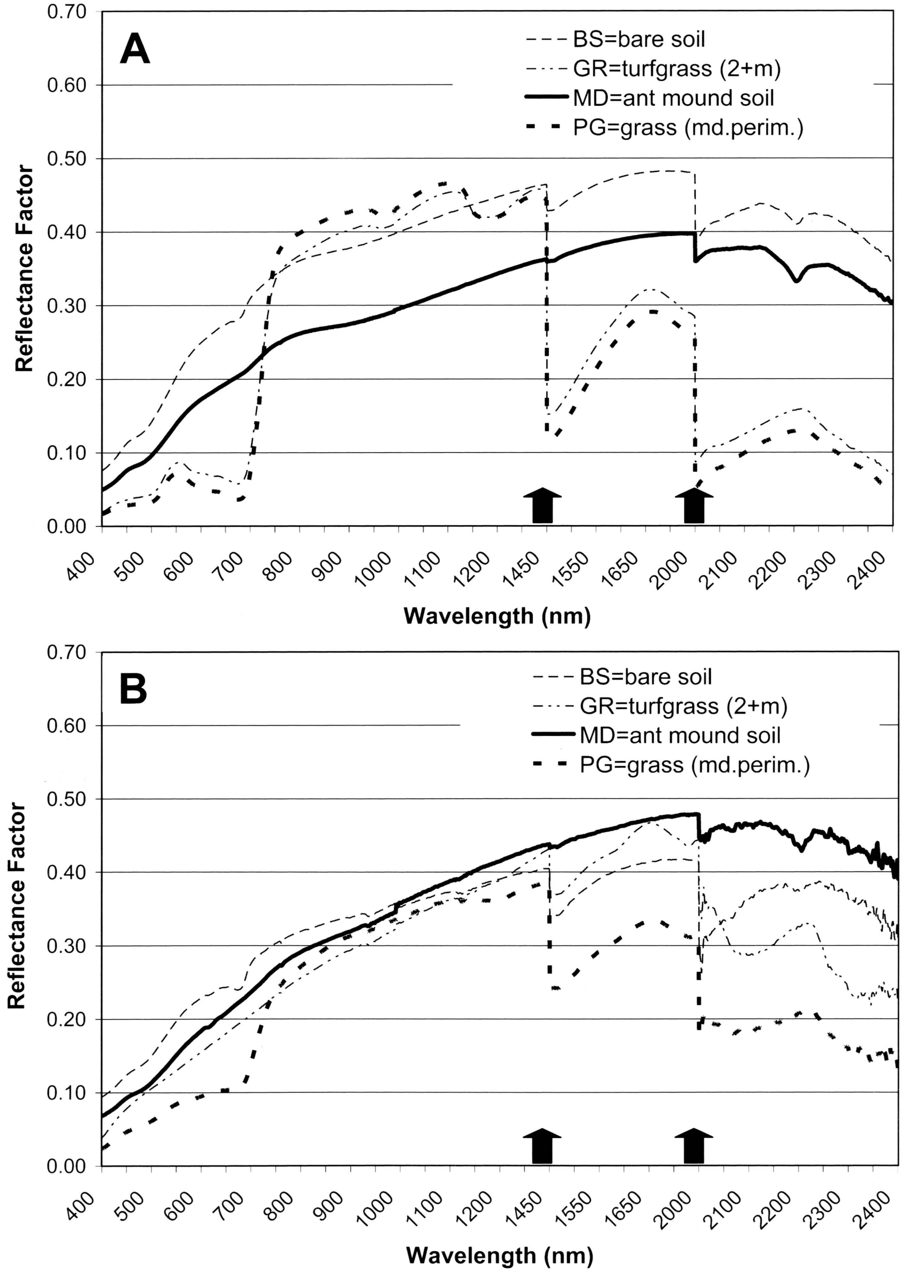

Fig. 1. Mean reflectance values for the four targets acquired from imported fire ant mounds and associated control locations for (A) 20 September and (B) 4 December 2006. Water absorption features from 1301 - 1449 nm and 1751 - 1999 nm (denoted by arrows) have been removed.

site-date interactions were detected for the 400 - 700 nm and 800 - 1300 nm ranges (F=12.3, df 1, 39.3, P=0.0011 and F=9.3, df 1, 27.3, P=0.0050, respectively) for these Fall (late October-early November) datasets as 11 days elapsed before weather conditions were suitable to resume data acquisition and moisture conditions varied from one site to the other.

As turfgrass dormancy progressed from late October through December, evapotranspiration rates declined, and soils approached field capacity (DeFauw, pers. obs.), the reflectance responses of the 4 targets exhibited convergence in the visible (VIS, 400 - 700 nm) and near-infrared (NIR, 700 - 1300 nm) regions in December (acquired 4 and 5 December 2006—Fig. 1B). However, at this time, ant-affected turfgrass (i.e., perimeter grass, PG) was distinctive from the other 3 targets, exhibiting substantially lower reflectance values, in select VIS wavebands (Fig. 1B; Table 1). In the short-wave infrared region (SWIR, ≥2000 nm in this particular case), ant mound soil reflectance (December 2006) was markedly higher than bare soil (BS) or turfgrass targets (GR and PG—Table 1).

Spectral signatures portray complex interactions of various factors including moisture, texture/structure, mineralogy/nutrient status, as well as some specific information on the nature of chemical bonds. Hyperspectral data acquired in tandem with soil and turfgrass samples harvested from a sod production agroecosystem (20 September 2006, North Central Hills physiographic region of Mississippi) facilitated some finer-scale distinctions of biochemically and physiologically meaningful relationships in the context of turfgrass response to imported fire ant-mediated soil matrix disturbances. A number of studies have demonstrated that broad band remote sensing data are inadequate for discerning biochemical properties of vegetation, and that high spectral resolution data (i.e., narrow wavebands of 10 nm or less) are usually required (e.g., Broge and Mortensen 2002, Rem. Sens. Environ. 81:45 - 57). In a separate analysis, spectral signatures (obtained 20 September 2006) were segmented into 10 nm wavebands. Analysis of variance results for waveband-target interactions indicated that wavebands centered at 685 nm (F=45.72, df 3, 5.9, P < 0.001), 915 nm (F=9.36, df 3, 3.0, P = 0.048), 1075 nm (F=9.62, df 3, 3.0, P = 0.046), 1455 nm (F=20.86, df 3, 3.0, P = 0.016), and 2015 nm (F=34.69, df 3, 3.1, P = 0.007) were the most significant discriminators (i.e., differences among the 4 targets were the greatest for these particular wavebands) at all locations in September.

Leaf pigments strongly influence hyperspectral reflectance patterns in the visible (VIS) region of the spectrum (e.g., Gausman 1982, Rem. Sens. Environ. 13:233 - 238). Vegetation indices commonly use reflectance values varying from 670 - 695 nm (e.g., Carter 1994, Int. J. Rem. Sens. 15: 697 - 704; Haboudane et al. 2004, Rem. Sens. Environ. 90:337 - 352) that have been related to chlorophyll/carotenoid content. DeFauw et al. (2008a, J. Entomol. Sci. 43:121 - 127) reported that ant-affected turfgrass from a sod production agroecosystem had greater concentrations of N, P, S, Cu, and Fe compared with undisturbed turfgrass which may, in turn, be related to changes in the structure and concentrations of pigment-protein complexes in these leaf blades. However, lower reflectance values from 430 - 680 nm (that coincide with the bimodal absorption spectra of free chlorophylls a and b—e.g., Blackburn 2007, J. Exp. Bot. 58:855 - 867) obtained for the majority of ant-affected turfgrass targets strongly suggest that chlorophyll concentrations were impacted (Fig. 1A). Our narrow band results indicated centers at 685, 675, 665, and 695 nm (ranked in descending order based on magnitudes of the F-values) as highly significant ($P \leq 0.0002$); however, careful inspection of spectra acquired from the 2 target types indicated that some signatures from undisturbed and ant-affected turfgrass were intermixed. Despite this intermixing, it was observed that approx. 60% of the spectra (from 20 September 2006) with higher reflectance values from 430 - 680 nm were obtained from undisturbed turfgrass (Fig. 1A). All spectra obtained from turfgrass at ant mound perimeters in September exhibited substantially lower reflectance values, especially in the 600 - 700 nm range; however, 40% of the spectra from undisturbed turfgrass exhibited lower reflectance values that fell within this range, too.

The spectral reflectance of soils is determined by an assemblage of physical factors different from those of vegetation including moisture content, organic matter (OM) content, iron-oxide content, particle-size distribution, and mineralogy; among these variables, moisture content is deemed the most important as it has the greatest overall impact on soil reflectance (e.g., Baumgardner et al. 1985, Adv. Agron. 38:1 - 44). Hyperspectral patterns for soil targets from September depicted a general increase in soil reflectance with increasing wavelength; ant mound soils generally exhibit lower reflectance values overall (Fig. 1A). This distinction was probably due to soil moisture contrasts as well as OM content and soil texture/structure or the interaction of all three, although Latz et al. (1984, Soil Sci. Soc. Am. J. 48:1130 - 1134) commented that OM and iron oxide contents were the most important soil properties influencing spectral reflectance characteristics of eroded soils, especially in the ranges spanning 500-800 nm and 800 - 1100 nm, respectively. DeFauw et al. (2008b, Insect. Soc., URL http://www.springerlink.com/content/0173332500k45314/fulltext.pdf) reported that no significant differences in available Fe were detected between the soils from imported fire ant mounds versus undisturbed soils in September; however, in December mean Fe concentration of ant mound soils was substantially lower than undisturbed soils from a sod production agroecosystem dominated by silt loam soils. Presence of iron oxides in soils is characterized by a broad absorption feature (centered at 900 nm); this feature is represented by a slight inflection in September (Fig. 1A), however, relatively high soil water content probably masked the expression of this feature in December.

Water content is the dominant factor affecting leaf reflectance in the NIR region (700 - 1300 nm) (e.g., Asner 1998, Rem. Sens. Environ. 64:234 - 253). Inversions in the reflectance patterns of ant-affected and undisturbed turfgrass were frequently observed from August through early November. This variability greatly diminished the usefulness of this region in distinguishing relevant vegetative features.

At wavelengths greater than 1300 nm (SWIR region) water content heavily influences reflectance patterns in photosynthetically active vegetation (e.g., Asner 1998). Undisturbed turfgrass generally exhibited higher reflectance values compared with ant-affected turfgrass (Fig. 1A). However, at the 50 nm segmentation used for this feasibility study in cost-effective sensor development the contrast between these 2 targets was not significant (Table 1).

The reflectance characteristics of ant mound soils versus undisturbed soils typically exhibit significant contrasts at wavelengths greater that 1300 nm in August, October, November and December (Table 1). However, intermixing of reflectance patterns for ant mound versus bare soil targets were observed in about 40% of the spectra acquired in September; these collection dates were within 1 - 2 d of precipitation events. During December, as soil water contents were approaching field capacity, mean reflectance of ant mound soils was significantly greater than undisturbed bare soils (Table 1). In addition, a discriminating spectral feature known as the cellulose absorption feature was observed near 2100 nm (Fig. 1B); this feature distinguishes plant matter from soils (Nagler et al. 2000, Rem. Sens. Environ. 71:207 - 215) and provides an additional new opportunity to enhance imported fire ant mound recognition capabilities from remotely-sensed datasets acquired during the late Fall through Winter seasons.

Reflectance wavebands (50 nm in width) have been identified that enhance the detection of imported fire ant mound features in turfgrass across seasons. Turf response to soil disturbances by mound-building ants was highly variable; the 'persistence' of lush perimeter vegetation (Green et al. 1977, Photogramm. Eng. Rem. Sens. 43:1051 - 1057; Vogt 2004 a,b, Environ. Entomol. 33:1045 - 1051, 1718 - 1721) was not a reliable companion indicator of ant mound soil disturbances (or 'mound features') in sod production or golf course settings using this multispectral, band-segmentation approach. DeFauw et al. (2008b) suggested that sod production fields may represent the most unstable of the agroecosystems that imported fire ants regularly colonize and successfully reinfest; turfgrass harvesting in some tract corridors resulted in imported fire ant mound locations shifting from week to week in response to turf removal. Thus, in some cases, the turfgrass surrounding newly-formed mounds may not have sufficient time to develop a characteristic response (i.e., lower reflectance from 430 - 685 nm). In addition, the patchiness of mower-induced damage to turfgrass as well as the patchiness of drought-stressed turfgrass may have introduced additional complexities that were not systematically accounted for in this pilot study.

Hyperspectral distinctions between bare soils and mound soils, however, were more consistent over several consecutive months (August-November) in the wavebands spanning 600 - 700 nm and 1050 - 1100 nm, and for dates in August, October, November and December in the 2000 - 2400 nm range. Convergences in reflectance patterns of some ant mound and bare soil spectra were observed in September as these collection dates were within 1 - 2 d of precipitation events. Bare soil surfaces roughened by raindrop impact would result in generally lower reflectance values. Also, active rebuilding of mound surfaces following a rainfall event would likely contribute to these water content-related inversions as ants bring excavated moist soil pellets to the surface. In addition, moisture retention properties of ant mound soils may differ due to greater concentration of organic matter (OM) compared with undisturbed soils; DeFauw et al. (2008b) reported that OM content of ant mound soils from a sod production setting was over 50% greater than undisturbed soils in September and 40% greater than adjacent control soils in December (2006).

The results of this pilot investigation suggest that mower-mounted spectral devices designed to recognize and map imported fire ant infestations need to provide 3 - 5, user-selected wavebands (VIS, NIR, and SWIR) to optimize ant mound detection across seasons. An on-site calibration phase of ant mound versus bare soil conditions would be necessary to fine-tune the on-the-go sensor system to soil moisture contrasts between these 2 targets. In addition, it is recommended that this type of ground-based remote sensing system include an auxiliary light source to reduce or eliminate the effect of ambient radiation fluctuations on the data collected by the sensor array. Development of new remote sensing monitoring tools, employing seasonally-acquired hyperspectral data in turf as a model system, will aid in the implementation of site-specific management of imported fire ant infestations in perennial, warm-season turfgrass settings, help foster sustainable reduction of fire ant populations, and benefit a broad array of stakeholders.

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