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Monitoring Turfgrass Species and Cultivars by Spectral Reflectance

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Summary

Like all modern agriculture sectors, turfgrass production and management is headed towards cost reduction, resource optimization and reduction of the environmental impact. In recent years the development of new technologies has provided new tools for monitoring agricultural crops. In particular, the combined adoption of geographic information systems, global positioning systems, multispectral lenses on board satellites and cartographic techniques allow a large scale management of agricultural resources. This paper reports the results of a trial attempting to evaluate the spectral signatures of several turfgrass species\cultivars, for future use in satellite monitoring. This experimental study focused on 20 turfgrass species\cultivars, including perennial ryegrasses, tall fescues, kentucky bluegrasses, bermudagrasses (ecotypes, seeded and vegetatively propagated cultivars) and zoysiagrasses. Various agronomical and biological parameters were studied (quality, colour, dry matter, chlorophyll, carotenoids, nitrogen content) and turfgrass spectral reflectance for all entries was gathered. Results showed that, within the same species, selected vegetation indices are often able to discriminate between different cultivars that have been established and maintained with identical agronomical practices. Evaluation of the spectral reflectance of plants using field spectroradiometry provides the possibility to identify different species\ cultivars, especially through the use of hyperspectral proximity and remote sensing.

Key words. *Cynodon* – *Festuca* – *Lolium* – *Poa* – spectroradiometry – vegetation indices – *Zoysia*

Introduction

Spatial and temporal variations of soil and climate, plant adaptability and irrigation requirements are challenges for modern agriculture, including turfgrass sites. To foster input efficiency and environmental management in agriculture, two related concepts have come to the forefront over the past 20 years: precision agriculture (PA) and more recently precision conservation (PC). Precision agriculture aims to obtain detailed site-specific information by mapping the variation in important soil and plant properties, in order to allow better site-specific management. Inputs such as water, fertilizers and pesticides are applied only where, when and in the amount needed by plant for the efficient production. PC was developed to make the best management decisions to preserve the environment and sustain agriculture, rangeland and natural areas. Both PA and PC rely on advanced sensor technology, mobile sensor platforms, use of GPS (global positioning systems) and the application of GIS (geographic information systems) to analyze and display the intensive data. The concept of precision turfgrass management (PTM) has only recently been noted as a parallel to PA for precise management of pests, fertilization, salinity issues, cultivation and irrigation (Stowell and Gelernter 2006; Carrow et al. 2010; Krum et al. 2010). A recent review by Bell and Xiong (2008) on optical sensing of turfgrass illustrated that optical sensing, especially by spectral reflectance, has been an active area of research for many years. The peculiar aspect of reflectance lies in the fact that incident radiation, being only partially reflected by the external surface of the plant, interacts deeply with the reflecting crop. It is therefore partly absorbed, transmitted and reflected only after a multitude of reflectance, refraction and diffusion phenomena, both within single leaves and whole canopy. The radiation flowing back in the opposite direction of incident radiation is, by convention, referred to as "reflected radiation" and bears the "signature" of the crop that generated it (Li et al. 1993). The bands of the spectrum that have shown to be more sensitive to the varying of crops have been compared and combined in various ways according to mathematical equations generating various vegetation indices. A vegetation index is a number obtained by combining reflectance values of bands of the spectrum thus enabling, in some cases, to amplify the differences between various reflectance spectra. The analysis of radiation reflected by plants can supply precious information on species quality and colour (Bremer et al. 2011; Darvishsefat et al. 2011), Leaf Area Index (LAI) (Finke 1992; Lee 2008), chlorophyll (Munden et al. 1994), biomass (Resop et al. 2011), drought stress (Jiang and Carrow 2007; Dettman-Kruse et al. 2008) and the nutritional status (Bell et al. 2004; Bausch et al. 2008) of many plant species, including turfgrass. Therefore, it could be gathered via remote sensing as a diagnostic tool for detecting variations in all these parameters. In previous researches, vegetation indices, calculated by combining band reflectances of the spectrum, were correlated with numerous canopy parameters. Trenholm et al. (2000) and Bremer et al. (2011), reported on the utilization of NDVI and other spectral reflectance-based plant stress indices for assessing turfgrass performance, while Bell et al. (2004) provided a recent review of optical sensing in turfgrass systems. For spectral reflectance, the normalized difference vegetation index (NDVI) has been the most commonly used plant performance or stress indicator. It correlates well with turfgrass quality (a combination of shoot density, colour and uniformity) as affected by differences inherent to the species and cultivar, environmental stresses, fertilizer treatments or injury from pests. Spectral reflectance can quantify plant response to stress, fertilizer applications or disease pressure, but the actual cause can be known only from a controlled study or by field observation. Differences in spectral reflectance were also found between C_4 (bermudagrass) and C_3 (bentgrass) turfgrasses at all wavelengths and with NDVI and NIR/R (Trenholm et al. 2000). In the latter study, NDVI in particular was useful for detecting growth differences between species. Thus, spatial maps of NDVI could illustrate differences, but not reveal the underlying cause because many different factors affect NDVI responses (Carrow et al. 2010). Furthermore, there are several hyperspectral indices proposed in the literature that quantify chlorophyll concentration (Zarco-Tejada et al. 2001) allowing remote detection methods to identify and map vegetation stress through the influence of chlorophyll content variation. There are also other structural indices like SR (Simple Ratio) (Agati et al. 2013) and WI (Water band Index = R_{700}/R_{950}) useful for detecting the plant water content, while red edge position is identified as the most responsive for detecting leaf nutritional status. The R_{710} band may also be useful, which is a red-edge band sensitive to vegetation stress and a band region common in optimum hyperspectral models of many plants (Thenkabail et al. 2004). As in the last two decades new turfgrass species have been studied and introduced in Southern Europe (Croce et al. 2004; Grossi et al. 2004; Macolino et al. 2010; Lulli et al. 2012; Pompeiano et al. 2012), the aim of the research consisted in determining the proximity sensed turfgrass spectral reflectance of 20 turfgrass species and cultivars and use key biological and agronomical parameters to detect non-reflectance differences between the species\cultivars.

Materials and Methods

The study was carried out in S. Piero a Grado, Pisa at the Department of Agriculture, Food and Environment (DAFE) of the University of Pisa (43°40' N, 10° 19' E, 6 m a.s.l.). All the plots of the 20 turfgrass species and cultivars were subject to identical maintenance practices during the May–July 2012 period. The grasses were all established on a soil characterized by the following physical-chemical properties: 28 % sand, 55 % silt, 17 % clay, pH 7.8, 18 g kg^{-1} of organic matter. 20 Turfgrass species and cultivars were selected for evaluation amid mature (> 5 yr) stands. Six cool season (C_3) species and cultivars for each species, genetically light and dark green cultivars were entered in the trial:

- 2 *Lolium perenne* (*Lp*): PR 124 (light green); PR 255 (dark green);
- 2 *Festuca arundinacea* (*Fa*): TF Wolfpack (light green), TF 816 (dark green);
- 2 *Poa pratensis* (*Pp*): KB 012-4 (light green), KB 012-2 (dark green).

Fourteen warm season (C_4) species and cultivars were entered in the trial:

- 2 Ecotypes of *Cynodon dactylon* (*Cd*) selected from the collection of CeRTES (Center for Research on Turfgrass for Environment and Sports) which includes several ecotypes of *Cd* collected in different parts of the world): 'CeRTES-2' (Pisa, Italy) and 'CeRTES-4' (Chantilly, France);
- 2 Seeded *Cynodon dactylon* (*Cd*) (commercially available): 'Princess' and 'Riviera';
- 4 Vegetatively propagated bermudagrasses: 1 *Cynodon dactylon* (*Cd*) 'Barazur', 3 *Cynodon dactylon* × *C. transvaalensis* (*Cd* × *t*) hybrids: 'Tifway', 'Patriot', 'Miniverde';
- 3 *Zoysia japonica* (*Zj*): 'De Anza', 'Meyer', 'Zenith';
- 3 Fine-leaved zoysiagrasses (Patton and Reicher 2007): *Zoysia japonica* × *Z. pacifica* (*Zj* × *p*) 'Emerald', *Zoysia matrella* (*Zm*) 'Zeon', *Zoysia pacifica* (*Zp*).

Single plot surface was 2.25 m^2. The trial experimental design was a randomized block with three replications.

During the trial period a turf height of 2.0 cm was maintained by weekly mowing with a reel mower and clipping removal. Irrigation was applied as needed to avoid wilt. All species were fertilized on May 1 and May 20 for a total of 100 kg ha^{-1} N, from ammonium sulphate (21 % N). No weed or pest control was necessary during the trial.

Spectral reflectance data

Spectra were acquired using a LICOR 1800 spectroradiometer (LI-COR Inc., Lincoln, NE, USA) with a fiber optic wire and LICOR 1800-06 telescope. The telescope was mounted on a purpose-built trolley at 120 cm from the ground with a vision angle of 15 °. The monitored surface corresponded at ground level to approximately 2000 cm^2. Measures were taken on July 09 between 11.30 am and 1.30 pm (solar time), in complete absence of clouds. The radiation reflected by a white panel made from barium sulphate was measured in order to detect any possible variation in irradiance. Reflectance measures were carried out in the 390–1100 nm region at 5 nm intervals. The ratio between reflection from the turf and reflection from the white panel gave the value of spectral reflectance. Based on the available literature, a number of indices having good statistical relationships with several plant parameters have been selected for evaluation in the present study (Table 1).

Agronomical and biological data

Measures were taken on July 09, simultaneously with spectroradiometric readings. The following parameters were determined:

- turf quality (from 1 = poor to 9 = excellent), visual assessment;
- colour intensity (from 1 = very light green to 9 = very dark green), visual assessment;
- clippings nitrogen content (%): Kjeldahl assay;
- leaf chlorophyll (a, b) content and carotenoids: leaves were sampled randomly from each experimental unit and subsequently chlorophyll content analysis was performed according to the procedures of Zhang and Kirkham (1996). Green leaves were placed in Falcon

Table 1. Reflectance-based vegetation indices used in this study.

Vegetation Index	Equation	Sensitivity	References
Normalized Difference Vegetation Index (NDVI)	$NDVI = (R_{NIR} - R_{red})/(R_{NIR} + R_{red})$ $NDVI_{900} = (R_{900} - R_{680})/(R_{900} + R_{680})$ $NDVI_{775} = (R_{775} - R_{680})/(R_{775} + R_{680})$	Chlorophyll	Rouse et al. (1974)
Simple Ratio Index (SR)	$SR = R_{NIR}/R_{red}$ $SR_{900} = R_{900}/R_{680}$	Chlorophyll	Rouse et al. (1974)
Rededge	$Rededge = \frac{(R_{670} + R_{780})}{2}$	Chlorophyll	Meer and De Jong (2006)
Rededge position	The wavelength of reflectance's inflection point between 700 and 740 nm, determined by the peak value of the 1st derivative of the reflectance spectrum	Chlorophyll	Cho and Skidmore (2006)
Modified Chlorophyll Absorption in Reflectance Index (MCARI)	$MCARI = [(R_{700} - R_{670}) - 0.2 * (R_{700} - R_{550})] * (R_{700}/R_{670})$	Chlorophyll	Daughtry et al. (2000)
Transformed CARI (TCARI)	$TCARI = 3 * [(R_{700} - R_{670}) - 0.2 * (R_{700} - R_{550}) * (R_{700}/R_{670})]$	Chlorophyll	Haboudane et al. (2002)
Zarco-Tejada & Miller (ZM)	$ZM = (R_{750})/(R_{710})$	Chlorophyll	Zarco-Tejada et al. (2001)
Structure Intensive Pigment Index (SIPI)	$SIPI = (R_{800} - R_{450})/(R_{800} + R_{650})$	Chlorophyll/ Carotenoid	Peñuelas et al. (1995)
Gitelson and Merzlyak (GM)	$GM1 = R_{750}/R_{550}$ $GM2 = R_{750}/R_{700}$	Chlorophyll	Gitelson and Merzlyak (1996)
Vegetation Index (VI)	$VI = R_{775}/R_{680}$	Nitrogen	Inoue et al. (2008)
Modified Soil-Adjusted Vegetation Index (MSAVI2)	$\frac{1}{2}\left[2*R_{800} + 1 - \sqrt{[\sqrt{(2*R_{800} + 1)^2} - 8*(R_{800} - R_{670})]}\right]$	Minimize soil background and LAI variation in crops	Qi et al. (1994)
Optimized Soil-Adjusted Vegetation Index (OSAVI)	$OSAVI = (1 + 0.16) * (R_{800} - R_{670})/(R_{800} + R_{670} + 0.16)$	Minimize soil background and LAI variation in crops	Rondeaux et al. (1996)
Water Index (WI)	$WI = R_{970}/R_{900}$	Leaf water	Peñuelas et al. (1996)

tubes containing 15 ml of 80 % acetone solution, necessary for the solubilization of the pigments. The samples were allowed to settle in a cold room (−4 °C). Absorbance was measured using a spectrophotometer. Sample absorbance was converted to milligrams of chlorophyll per gram (1 L acetone = 1 g tissue) using a concentration curve developed by plotting the calculated chlorophyll concentrations of serial dilutions of a concentrated sample solution against absorbance at 663.2, 648.8 and 470.0 nm, corresponding to absorption peaks respectively of chlorophyll a (Chl a), chlorophyll b (Chl b) and carotenoids (Car).

Statistical analysis

All agronomical/biological/vegetation index data were analyzed by one-way ANOVA, and a paired Tukey's test was used to detect differences between means ($P < 0.05$) for agronomical/biological data, $P < 0.001$ for vegetation index data). All statistical analysis were carried out with a COSTAT 6.400 software (Costat 2008).

Results and Discussion

Cool season turfgrass species

Perennial ryegrass. The two cultivars (PR124 = light green, PR255 = dark green) differed significantly ($P < 0.05$) in visual turfgrass quality and in the colour ($P < 0.05$), with PR255 having a higher value than PR124 (Table 2). The two cultivars did not differ significantly in the nitrogen content (2.7 %), chlorophyll a (1.18 mg g^{-1}) and carotenoids (0.34 mg g^{-1}). The vegetation indices (Table 3) that were able to discriminate ($P < 0.001$) between these two cultivars were: $NDVI_{900}$ (900, 680), $NDVI_{775}$ (775, 680), SR_{900} (900/680), MCARI, ZM (750/710), SIPI, GM1(750/550), GM2 (750/700), VI (775/680), MSAVI and OSAVI. For all these indices, the darker perennial ryegrass obtained a higher vegetation index value.

Kentucky bluegrass. Except for the colour, the parameter for which they have been selected, the two Kentucky bluegrass cultivars did not differ significantly in any of the agronomical/biological parameters (Table 2), while the following vegetation indices returned statistically significant values ($P < 0.001$) for the two cultivars: $NDVI_{900}$ (900, 680), SR_{900} (900/680), Red Edge Position, TCARI, ZM (750/710), SIPI, GM1(750/550), GM2 (750/700), VI (775/680) and WI (970/900). For all indices, the darker variety (KB012-2) obtained higher values than the lighter variety (KB012-4), except for TCARI vegetation index. Both cultivars within a species were initially selected for their marked differences in colour. This is reflected in turfgrass visual colour ratings that confirm statistically significant differences ($P < 0.05$) among cultivars of the same species (Table 2).

The spectral reflectance characteristics of the pairs of cool-season species that are discriminated by the vegetation indices (Lp, Pp) were strongly influenced by leaf colour. In these two species, perennial ryegrasses and kentucky bluegrasses the difference between light and dark green cultivars is statistically ($P < 0.001$) evident at the peak of absorbance by chlorophyll in the red (675 nm) and its peak of reflectance in the green (555 nm) (Fig. 1 and Fig. 2). At the peak of absorbance in the red (675 nm) both light green cultivars, PR124 and KB012-4 were respectively 24 and 23 % higher than the darker cultivar PR255 and KB012-2. Similar behaviour has been reported in the reflectance at 555 nm where the light green cultivars were higher than the darker cultivar (PR124 13 % higher than PR255; KB012-4 20 % higher than KB012-2).

Table 2. Cool-season (C3) species and cultivars: Agronomical and biological parameters (quality, colour, dry matter, nitrogen content, chlorophyll a, chlorophyll b and carotenoids). Means followed by the same letter do not differ significantly according to Tukey's pairwise test ($P < 0.05$).

Sp.	Cultivar	Turf quality (1–9)	Colour (1–9)	N (%)	Chl. a (mg g^{-1})	Chl. b (mg g^{-1})	Caroten. (mg g^{-1})
Lp	PR 124	6.3 b	6.5 cd	2.8	1.12	0.58 abc	0.31
Lp	PR 255	8.5 a	8.5 a	2.6	1.24	0.75 a	0.37
Fa	TF Wolf.	6.7 b	7.0 c	2.8	0.77	0.36 c	0.22
Fa	TF 816	6.7 b	7.8 b	3.1	1.23	0.63 ab	0.34
Pp	KB 012-4	5.8 b	6.2 d	2.0	0.78	0.38 bc	0.24
Pp	KB 012-2	6.3 b	7.1 bc	2.6	1.15	0.55 abc	0.35
LSD < 0.05		1.5	0.7	ns	ns	0.26	ns

Lp: Lolium perenne; *Fa: Festuca arundinacea*; *Pp: Poa pratensis*

Table 3. Vegetation index data for the cool-season (C3) species and cultivars. Means followed by the same letter do not differ significantly according to Tukey's pairwise test (P < 0.001)

Sp.	Cultivar	$NDVI_{900}$ (900, 680)	$NDVI_{775}$ (775, 680)	SR_{900} (900/680)	Red edge	Red edge posit.	MCARI	TCARI	ZM (750/710)
Lp	PR 124	0.81 b	0.77 c	9.75 b	21.08 b	723.2 bc	2.78 b	10.24 ab	2.40 c
Lp	PR 255	0.87 a	0.84 ab	14.02 a	23.44 ab	725.1 abc	3.72 a	9.90 b	2.95 ab
Fa	TF Wolf	0.86 a	0.84 ab	13.74 a	24.60 a	725.3 ab	3.81 a	11.02 ab	2.98 ab
Fa	TF 816	0.88 a	0.86 a	15.31 a	24.09 ab	727.1 a	3.47 ab	8.85 b	3.41 a
Pp	KB 012-4	0.83 b	0.79 bc	10.51 b	24.15 a	722.8 c	3.38 ab	12.79 a	2.48 bc
Pp	KB 012-2	0.86 a	0.84 ab	13.89 a	24.57 a	725.9 a	3.54 ab	9.97 b	3.14 a
LSD < 0.001		0.03	0.06	2.75	3.06	2.45	0.81	2.62	0.54

Sp.	Cultivar	SIPI	GM1 (750/550)	GM2 (750/700)	VI (775/680)	MSAVI2	OSAVI	WI (970/900)
Lp	PR 124	0.82 b	4.78 bc	3.73 c	7.70 b	1.37 c	0.90 c	0.95 cd
Lp	PR 255	0.87 a	6.20 a	5.06 ab	11.53 a	1.42 a	0.98 ab	0.94 d
Fa	TF Wolf	0.87 a	5.64 ab	5.00 ab	11.47 a	1.41 ab	0.98 ab	0.99 b
Fa	TF 816	0.88 a	6.40 a	5.78 a	12.81 a	1.42 a	1.00 a	0.97 bc
Pp	KB 012-4	0.83 b	4.70 c	4.01 bc	8.75 b	1.38 bc	0.93 bc	0.99 b
Pp	KB 012-2	0.87 a	5.89 a	5.39 a	11.88 a	1.41 ab	0.98 ab	1.02 a
LSD < 0.001		0.03	0.88	1.15	2.68	0.03	0.06	0.02

Lp: Lolium perenne; *Fa: Festuca arundinacea*; *Pp: Poa pratensis*

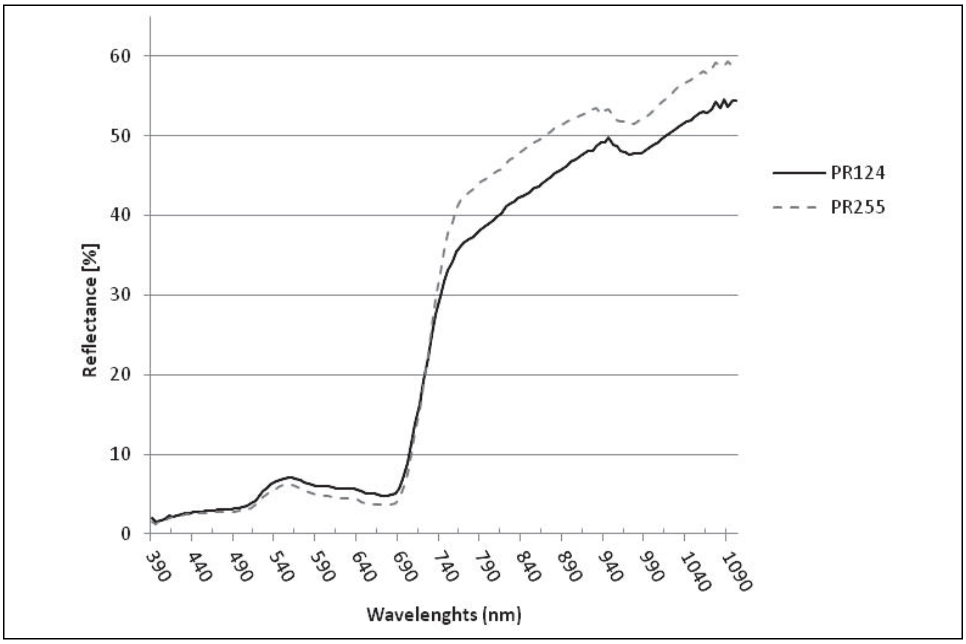

Fig. 1. Spectral reflectance curves of 2 different cultivars of *Lolium perenne* (cool-season C3): PR 124 (light green) and PR 255 (dark green)

Tall Fescue. The two tall fescue cultivars differed significantly (P < 0.05) in their colour and in the chlorophyll b content, with the darker variety (TF 816: 0.63 mg g^{-1}) having a higher content than the lighter variety (TF Wolfpack: 0.36 mg g^{-1}). The other parameters such as turf quality (6.7), nitrogen content (2.9 %), chlorophyll a (1 mg g^{-1}) and carotenoids (0.28 mg g^{-1}) did not differ statistically. No vegetation index was able to discriminate between these two cultivars in a statistically significant manner.

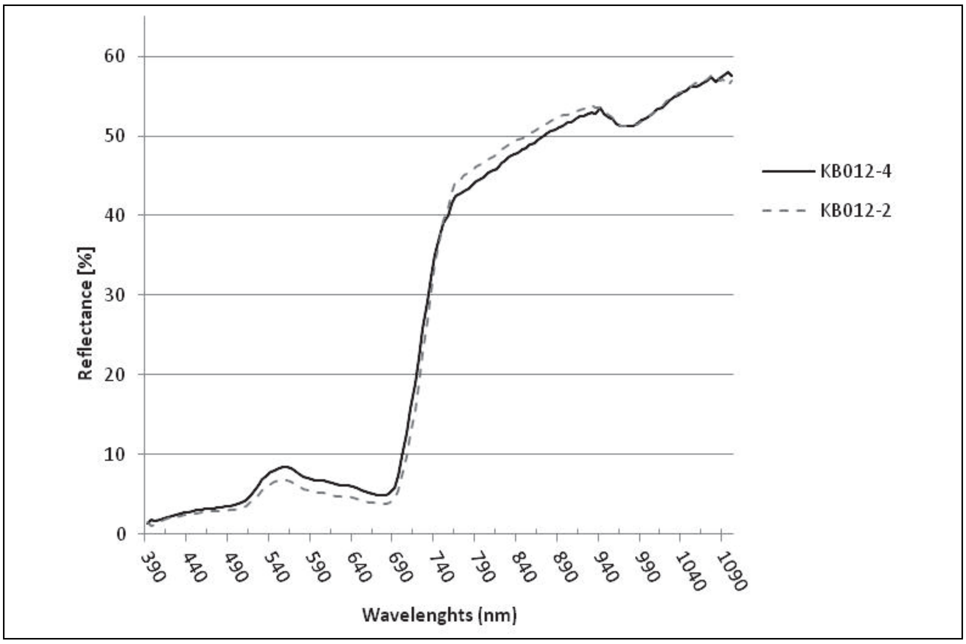

Fig. 2. Spectral reflectance curves of 2 different cultivars of *Poa pratensis* (cool-season C3): KB 012-4 (light green) and KB 012-2 (dark green)

Warm season turfgrass species

***Cynodon* spp.** The two ecotypes of *Cynodon dactylon* ('CeRTES-2' and 'CeRTES-4') did not differ statistically for any of the analyzed agronomical/biological parameters (Table 4).

Also the two commercially available seeded bermudagrass ('Princess' and 'Riviera') did not differ statistically for any of the analyzed agronomical/biological parameters (Table 4), nor is any vegetation index (Table 5) able to discriminate between the two ecotypes or the two seeded cultivars.

Table 4. Warm-season (C4) species and cultivars: Agronomical and biological parameters (quality, colour, dry matter, nitrogen content, chlorophyll a, chlorophyll b and carotenoids). Means followed by the same letter do not differ significantly according to Tukey's pairwise test ($P < 0.05$)

Sp.	Cultivar	Turf quality (1–9)	Colour (1–9)	N (%)	Chl. A (mg g^{-1})	Chl. B (mg g^{-1})	Caroten. (mg g^{-1})
Ecot.*Cd*	'CeRTES-2'	6.9 ef	7.3 bcd	3.1 a	1.15 ab	0.50	0.22 ab
Ecot.*Cd*	'CeRTES-4'	7.2 de	7.7 abc	2.7 abc	1.46 a	0.66	0.27 a
Seed.*Cd*	'Princess'	6.9 ef	6.8 cd	2.2 abcd	0.76 c	0.60	0.11 cde
Seed.*Cd*	'Riviera'	6.6 ef	6.6 d	2.4 abcd	0.63 c	0.30	0.11 cde
Cd	'Barazur'	6.3 f	8.4 a	2.6 abcd	1.17 a	0.58	0.14 bcde
Cd × *t*	'Tifway'	8.4 bc	7.6 abc	2.4 abcd	0.83 c	0.42	0.07 de
Cd × *t*	'Patriot'	8.6 ab	8.4 a	2.5 abcd	1.21 a	0.60	0.20 abc
Cd × *t*	'Miniverde'	8.5 abc	8.5 a	3.0 ab	1.23 a	0.64	0.15 bcd
Zj	'De Anza'	8.5 abc	7.6 abc	2.1 bcd	0.84 bc	0.45	0.09 de
Zj	'Meyer'	7.8 cd	7.9 ab	2.4 abcd	0.78 c	0.42	0.10 de
Zj	'Zenith'	7.2 de	7.4 bcd	2.2 bcd	0.70 c	0.37	0.10 cde
Zj × *p*	'Emerald'	8.7 ab	7.2 bcd	1.8 cd	0.60 c	0.34	0.07 de
Zm	'Zeon'	8.7 ab	7.3 bcd	1.8 d	0.64 c	0.38	0.08 de
Zp		9.2 a	7.8 abc	2.3 abcd	0.53 c	0.32	0.04 e
LSD < 0.05		0.7	0.9	0.88	0.32	ns	0.10

Ecot.*Cd*: Ecotypes of *Cynodon dactylon*; Seed.*Cd*: Seeded *Cynodon dactylon*; *Cd*: *Cynodon dactylon*; *Cd* × *t*: *Cynodon dactylon* × *C. transvaalensis*; *Zj*: *Zoysia japonica*; *Zj* × *p*: *Zoysia japonica* × *Z. pacifica*; *Zm*: *Zoysia matrella*; *Zp*: *Zoysia pacifica*

Table 5. Vegetation index data for the warm-season (C4) species and cultivars. Means followed by the same letter do not differ significantly according to Tukey's pairwise test ($P < 0.001$)

Sp.	Cultivar	NDVI$_{900}$ (900, 680)	NDVI$_{775}$ (775, 680)	SR$_{900}$ (900/680)	Red edge	Red edge posit.	MCARI	TCARI	ZM (750/710)
Ecot.*Cd*	'CeRTES-2'	0.79 c	0.77 c	8.63 d	26.81 ab	723.2 bc	2.89 cd	12.35 abc	2.76 cd
Ecot.*Cd*	'CeRTES-4'	0.81 abc	0.79 abc	9.38 cd	26.31 ab	724.0 abc	3.06 bcd	11.93 abc	2.89 bcd
Seed.*Cd*	'Princess'	0.82 abc	0.80 abc	10.37 cd	26.42 ab	724.2 abc	3.25 bcd	12.24 abc	2.92 bcd
Seed.*Cd*	'Riviera'	0.79 bc	0.77 c	8.67 d	24.28 b	722.5 c	3.17 bcd	12.74 abc	2.52 d
Cd	'Barazur'	0.79 c	0.76 c	8.57 d	25.28 ab	725.1 abc	2.17 d	9.04 c	2.87 bcd
Cd × t	'Tifway'	0.84 abc	0.82 abc	11.26 cd	24.43 b	725.4 abc	3.07 bcd	10.01 bc	3.20 abcd
Cd × t	'Patriot'	0.87 abc	0.86 abc	14.38 abc	27.82 ab	726.2 ab	3.54 bcd	10.44 bc	3.70 ab
Cd × t	'Miniverde'	0.83 abc	0.81 abc	10.95 cd	22.78 b	724.6 abc	2.93 bcd	9.28 bc	3.06 abcd
Zj	'De Anza'	0.85 abc	0.84 abc	12.38 bcd	30.39 a	724.1 abc	4.15 abc	15.26 a	3.04 abcd
Zj	'Meyer'	0.83 abc	0.81 abc	10.49 cd	25.20 ab	726.0 abc	2.63 d	9.17 bc	3.16 abcd
Zj	'Zenith'	0.80 bc	0.78 bc	9.20 cd	26.76 ab	723.5 bc	2.93 bcd	12.33 abc	2.76 cd
Zj × p	'Emerald'	0.87 abc	0.85 abc	14.30 abc	26.35 ab	726.7 ab	3.57 bcd	10.18 bc	3.52 abc
Zm	'Zeon'	0.85 abc	0.84 abc	12.65 bcd	26.26 ab	725.5 abc	3.55 bcd	11.19 abc	3.20 abcd
Zp		0.90 a	0.88 a	18.51 a	27.23 ab	727.5 a	4.40 ab	10.29 bc	3.93 a
LSD < 0.001		0.10	0.10	5.33	5.21	3.48	1.48	4.78	0.90

Sp.	Cultivar	SIPI	GM1 (750/550)	GM2 (750/700)	VI (775/680)	MSAVI2	OSAVI	WI (970/900)
Ecot.*Cd*	'CeRTES-2'	0.79 e	4.10 d	4.36 cd	7.94 de	1.36 b	0.90 bc	0.99 ab
Ecot.*Cd*	'CeRTES-4'	0.80 bcde	4.17 d	4.61 bcd	8.50 cde	1.37 ab	0.92 abc	0.95 bcde
Seed.*Cd*	'Princess'	0.82 bcde	4.40 cd	4.72 bcd	9.25 cde	1.38 ab	0.93 abc	0.97 abcd
Seed.*Cd*	'Riviera'	0.80 cde	3.99 d	4.00 d	7.84 de	1.36 b	0.89 bc	0.94 cde
Cd	'Barazur'	0.80 de	4.53 bcd	4.31 cd	7.42 e	1.36 b	0.88 c	0.95 bcde
Cd × t	'Tifway'	0.83 abcde	4.79 bcd	5.12 abcd	9.94 cde	1.39 ab	0.95 abc	1.00 a
Cd × t	'Patriot'	0.86 abcde	5.62 abc	6.39 ab	13.01 abc	1.42 ab	0.99 abc	0.97 abcd
Cd × t	'Miniverde'	0.83 abcde	4.81 bcd	4.99 bcd	9.42 cde	1.39 ab	0.94 abc	0.96 abcd
Zj	'De Anza'	0.84 abcde	4.72 bcd	5.16 abcd	11.31 bcd	1.40 ab	0.97 abc	0.96 abcd
Zj	'Meyer'	0.83 abcde	5.09 bcd	5.03 bcd	9.33 cde	1.39 ab	0.94 abc	0.98 abc
Zj	'Zenith'	0.80 cde	4.39 cd	4.40 cd	8.38 cde	1.37 b	0.90 abc	0.95 bcde
Zj × p	'Emerald'	0.87 ab	5.81 ab	5.91 abc	12.63 abcd	1.42 ab	0.99 abc	0.98 abc
Zm	'Zeon'	0.86 abc	5.33 abcd	5.32 abcd	11.29 bcde	1.41 ab	0.97 abc	0.94 de
Zp		0.89 a	6.53 a	6.98 a	16.56 a	1.43 a	1.03 a	0.94 cde
LSD < 0.001		0.07	1.35	1.91	5.00	0.06	0.12	0.05

Ecot.*Cd*: Ecotypes of *Cynodon dactylon*; Seed.*Cd*: Seeded *Cynodon dactylon*; *Cd*: *Cynodon dactylon*; *Cd × t*: *Cynodon dactylon × C. transvaalensis*; *Zj*: *Zoysia japonica*; *Zj × p*: *Zoysia japonica × Z. pacifica*; *Zm*: *Zoysia matrella*; *Zp*: *Zoysia pacifica*

The vegetatively propagated bermudagrasses differed significantly ($P < 0.05$) for (i) turfgrass quality, with 'Barazur' scores significantly lower than 'Tifway', 'Patriot' and 'Miniverde', (ii) leaf carotenoid content, with 'Patriot' showed the highest content significantly different than 'Tifway', and (iii) chlorophyll a content with 'Tifway' had the lowest content (0,83 mg g^{-1} by fresh weight) compared to any other variety. The vegetation indices that were able to discriminate ($P < 0.001$) between these four accessions were: SR$_{900}$ (900/680) (highest value: 'Patriot'; lowest value: 'Barazur'); GM2 (750/700) (highest value: 'Patriot'; lowest value: 'Barazur'); VI (775/680) (highest value: 'Patriot'; lowest value: 'Barazur'); WI (970/900) (highest value: 'Tifway'; lowest value: 'Barazur'). Fig. 3 shows that in general, in the PAR region (400–700 nm), the variation of reflectance between 'Barazur', 'Tifway', 'Patriot', and 'Miniverde' is not so evident. 'Barazur' represented one of the darkest vegetatively propagated bermu-

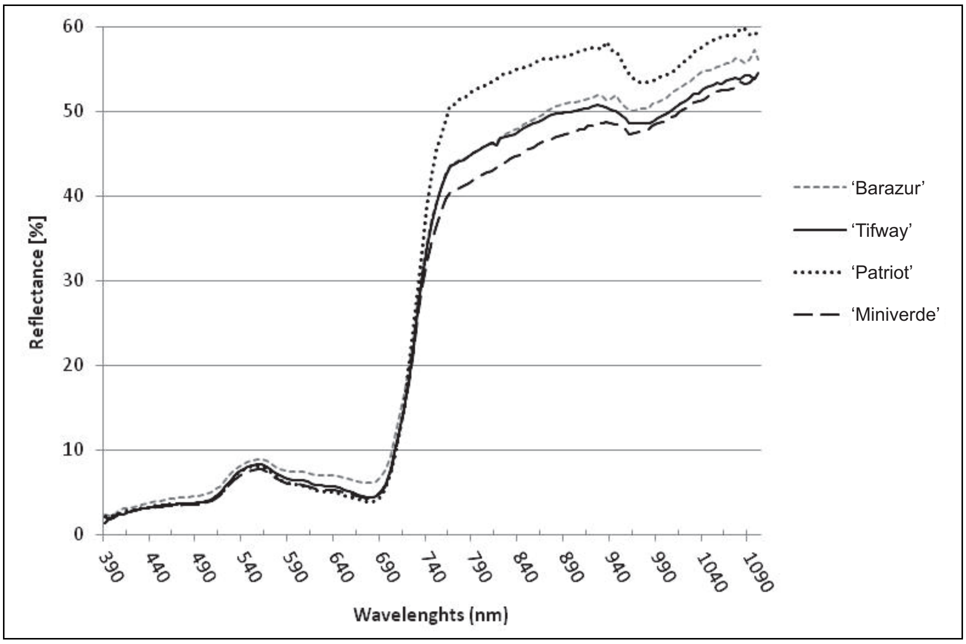

Fig. 3. Spectral reflectance curves of vegetatively propagated bermudagrasses (warm-season C4): 1 *Cynodon dactylon* 'Barazur', 3 *Cynodon dactylon* × *C. transvaalensis* hybrids: 'Tifway', 'Patriot', 'Miniverde'

dagrass evaluated in this study and the results revealed significantly ($P < 0.001$) lower values in all the vegetation indices. The reflectance spectrum obtained in Fig. 3 also indicates a difference in the spectral reflectance at near infrared wavelengths, where there was an increase in values obtained by 'Patriot' compared to the vegetatively propagated bermudagrasses. 'Patriot' also showed the highest values in all the statistically significant ($P < 0.001$) vegetation indices, except for WI (970/900) in which the highest value was obtained by 'Tifway'. The energy level of the radiation in the Near Infrared Region (NIR) is not high enough for the photochemical reaction, therefore it is not absorbed by the pigments. The level of reflected energy in the NIR is linked to several factors such as the internal structure of the leaf, the number of layers of cells, the size and the structure of the cell walls. The presence of intercellular spaces influences the reflectance in the infrared. A confirmation of the relation between the number of voids and the reflectance of leaves has been given by Gates et al. (1965) with a decrease of the reflected light in the NIR due to the infiltration of water in the leaves. These results would appear to attribute to these indices the capability of discriminating between dark green and light green and between high-quality and lower-quality vegetatively propagated bermudagrasses.

Zoysia spp. Among *Zoysia japonica* cultivars ('De Anza', 'Meyer', 'Zenith') the only parameter that differed statistically ($P < 0.05$) was turfgrass quality, with 'De Anza' scoring significantly higher than 'Zenith'. The vegetation indices that were able to discriminate ($P < 0.001$) between these three cultivars were MCARI and TCARI. For both indices 'De Anza' showed the highest value and 'Meyer' the lowest value. These results would appear to attribute to these two indices the capability of discriminating between high-quality and lower-quality zoysiagrass cultivars. The reflectance spectrum obtained in Fig. 4 highlights differences in spectral reflectance in the visible region (400–700 nm), especially at the peak of reflectance in the green (555 nm), where there is a decrease in 'Meyer'. Furthermore, at near infrared wavelengths 'Meyer' presented lower reflectance values but an increase of 'De Anza' compared to the other two japonica zoysiagrasses was also detected. 'De Anza' also showed the highest values in the statistically significant ($P < 0.001$) vegetation indices, and 'Meyer' the lowest value. These results would appear to attribute to these indices the capability of discriminating between high-quality and lower-quality zoysiagrass cultivars.

Among fine-leaved zoysiagrasses (*Zoysia japonica* × *Z. pacifica* 'Emerald', *Zoysia matrella* 'Zeon', *Zoysia pacifica*) no statistically significant differences were found for any of the agronomical/biological parameters. The vegetation indices that were able to discriminate ($P < 0.001$) between these three species were: SR_{900} (900/680) (highest value: 'Pacifica'; lowest value: 'Zeon'); VI (775/680) (highest value: 'Pacifica'; lowest value: 'Zeon'); WI (970/900) (highest value: 'Emerald'; lowest value: 'Zeon'). Fig. 5 shows that in general, in the PAR region (400–700 nm), the variation of reflectance was not relevant. Only a small decrease in reflectance values of 'Pacifica' at the peak of absorbance by chlorophyll in the red (675 nm) was witnessed. The smaller decrease of 'Pacifica' in reflectance values in the visible region determined a progressive increase at near infrared wavelengths of this specie compared to *Zoysia japonica* × *Z. pacifica* 'Emerald' and *Zoysia matrella* 'Zeon'.

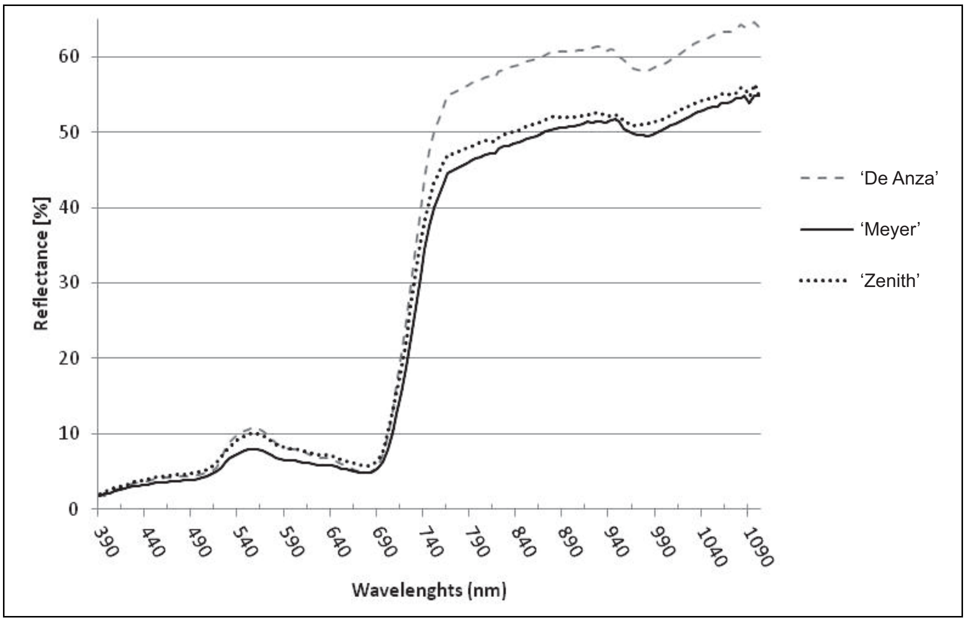

Fig. 4. Spectral reflectance curves of 3 *Zoysia japonica* (warm-season C4): 'De Anza', 'Meyer', 'Zenith'

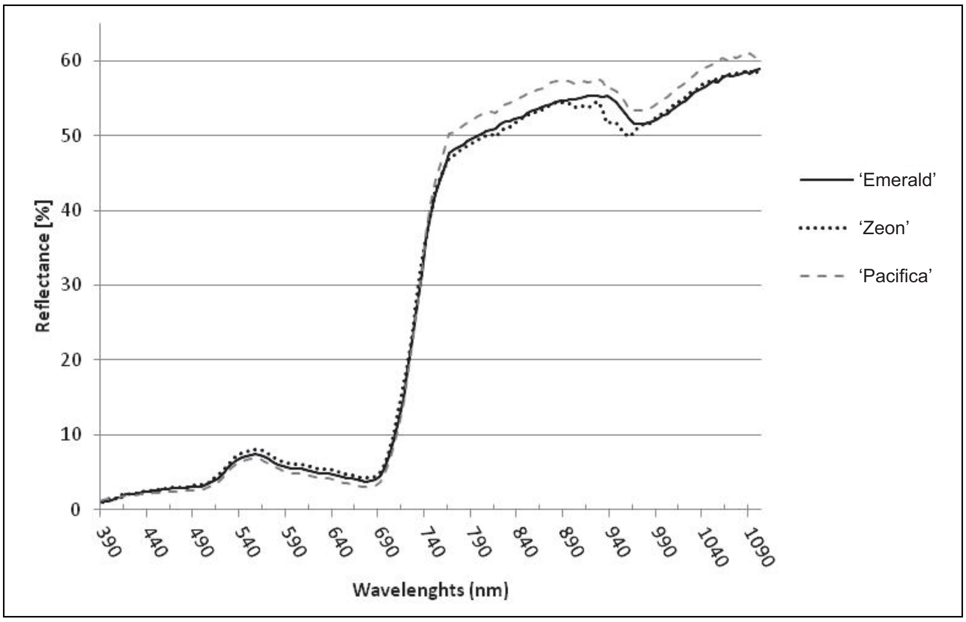

Fig. 5. Spectral reflectance curves of 3 fine-leaved zoysiagrasses: *Zoysia japonica × Z. pacifica* 'Emerald', *Zoysia matrella* 'Zeon', *Zoysia pacifica*

Conclusions

The application of vegetation indices helps to highlight spectral differences including turf quality, colour, dry matter, chlorophyll, carotenoids and nitrogen content. Results showed that, within the same species, selected vegetation indices are often able to discriminate between different cultivars that have been established and maintained with identical agronomical practices. To prove the vegetation indices as a diagnostic tool a continuation of the study over a longer period and under different vegetation conditions will be necessary, however this study allowed the preliminary evaluation of proximity-sensed spectral signatures of several turfgrass species and cultivars, in order to carry out a pre-screening of satellite spectral remote sensing as a diagnostic tool. Satellite reflectance data could be used for the detection of physiological and nutritional conditions of the various turfgrass species. Hence, the evaluation of the spectral reflectance of turfgrass plants using field spectroradiometry provides the possibility to identify and map different species\cultivars, and allows a potential large scale management and control of several agricultural (sod farms, turfgrass seed production farms, etc.) and urban (stadia, golf courses, horse racing tracks, parks and gardens, etc.) resources. Further studies will be necessary to investigate the possibility of discriminating, through the use of the vegetation indices considered in this research, between the same species\cultivars with different conditions of water, fertilizers and pesticides.

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