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Ph.D Dissertation

Monitoring turfgrass species by ground-based and satellite remote sensing

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Index

Abstract

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, within the European Union several legislative, monitoring and coordinating actions have been undertaken to encourage sustainable use of resources, reduction in the use of chemicals and improvement of the urban environment. In this respect, two concepts that are strictly related to most of the aspects above are: “precision agriculture” and “precision conservation” and more specifically “precision turfgrass management.” Optical sensing has become a crucial part of precision turfgrass management and spectral reflectance in particular has been an active area of research for many years. However, while turfgrass status evaluation by proximity-sensed spectral reflectance appears to be an established and reliable practice, much more could be achieved in terms of monitoring of large turfgrass areas through remote sensing, and in particular through satellite imagery.

This thesis reports the results of four trials attempting:

a) 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, color, 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;

b) to calculate on these 20 species and cultivars the most interesting vegetation indices by simulating the available wavelengths deriving from World View 2 satellite imagery. Results showed that within the same species selected vegetation indices are often able to discriminate between different varieties that have been established and maintained with identical agronomical practices;

c) to evaluate the proximity sensed spectral reflectance on *Festuca arundinacea* turf with 9 water replenishment levels (Linear Gradient Irrigation System) and 2 nitrogen conditions. ET_0 was estimated using the Hargreaves and Samani method. The following parameters were determined: turf quality, drought tolerance, pest problems, temperature of the surface, clippings weight and relative nitrogen content, turf growth and soil moisture. Spectral reflectance data were acquired using a LICOR 1800 spectroradiometer. Pearson correlation coefficients were studied among all parameters and vegetation indices. Nitrogen fertilization influenced significantly turf quality, clippings weight, nitrogen content and turf growth. Water replenishment influenced significantly all parameters except nitrogen content. Among all parameters the highest correlation coefficient was registered relating drought tolerance with turf quality ($r = 0.88$) and with surface temperature ($r = - 0.88$). Among vegetation indices results showed that Water Index (WI) and Normalized Difference Water Index (NDWI), are better able to discriminate between different levels of water replenishment. Comparing WI with NDWI, the correlation coefficients were higher for Water Index in all the parameters, in particular the highest WI value was registered for drought tolerance ($r = 0.91$). This preliminary research demonstrates that spectral remote sensing can be a useful diagnostic tool to detect water stress in turfgrasses;

d) to compare N status in different turfgrasses, from remote multi-spectral data acquired by GeoEye-1 satellite and by two ground-based instruments. The study focused on creating a nitrogen concentration gradient on 3 warm-season turfgrasses (*Cynodon dactylon x transvaalensis* ‘Patriot’, *Paspalum vaginatum* ‘Salam’, *Zoysia matrella* ‘Zeon’) and 2 cool-season (*Festuca arundinacea* ‘Grande’, *Lolium perenne* ‘Regal 5’). The linear gradient ranged from 0 to 342 kg ha^{-1} of N for the warm-season and from 0 to 190 kg ha^{-1} of N for the cool-season turfgrasses. Proximity and remote reflectance measurements were acquired and used to determine Normalized Difference Vegetation Index (NDVI). Results showed that the N status is highly correlated with the spectral reflectance. Our results prove that NDVI measured with the ground-based instruments are highly correlated with data from satellite. The correlation coefficients between the satellite and the other sensors ranged from 0.90 to 0.99 for the warm-season and from 0.83 to 0.97 for the cool-season species. 'Patriot' had a clippings N concentration ranging from 1,20 % to 4.1 %, thus resulting the most reactive species to N fertilization. GeoEye-1 satellite can adequately assess the N status of different turfgrass species, and its spatial variability within a field depending on the N rates applied on the surfaces. In future information obtained from satellite could allow target management depending on the real need of the turf.

1. Introduction

Recently the European Union has undertaken several monitoring (EC 2007; EC 2009; EEA 2009) and coordinating actions to encourage (a) a sustainable use of resources (EC 2011a; EC 2012a), (b) a reduction in the use of chemicals within agriculture and urban green areas, (c) a general improvement of the urban environment (EC 2012b) a drive towards environment-driven innovation (EC 2010; EC 2011b).

1.1 Precision Agriculture, Precision Conservation and Precision Turf Management

Spatial and temporal variation of soil and climate, plant adaptability and irrigation requirements are rising 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.

1.2 Spectral reflectance

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.

The analysis of radiation reflected by plants can supply precious information on species quality and color (Bremer et al. 2011; Darvishsefat et al. 2011; Caturegli et al. 2014a), Leaf Area Index (LAI) (Finke 1992; Lee et al. 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. 2010) of many plant species, including turfgrass. Therefore, reflectance can be gathered via remote sensing as a diagnostic tool for detecting variations in all these parameters

Spectral reflectance can quantify plant response to stress, fertilizer applications or disease, but the actual cause can be detected only from a controlled study or by field observation (Bremer *et al.* 2011).

1.3 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.

In previous researches, vegetation indices, calculated by combining band reflectances of the spectrum, were correlated with numerous canopy parameters. Trenholm et al. (1999), Bremer et al. (2011), Jiang and Carrow (2007), reported on the utilization of normalized difference vegetation index (NDVI) and other spectral reflectance-based plant stress indices for assessing turfgrass performance. For spectral reflectance, the normalized difference vegetation index (NDVI) has been the most commonly used plant performance or stress indicator. For instance, the most popular vegetation index, the NDVI, relies on the principle concept of a relationship between absorption of visible light and resilient reflectance of near-infrared light to the chlorophyll in vegetation (Bell *et al.* 2004, Vina *et al.* 2011, Nagendra *et al.* 2013). Green plants absorb most of the red light and reflect most of the infrared light. The relative strength of the detected light is a direct indicator of the density of the foliage in the sensor's view. The denser and more vigorous the plant, the greater is the difference between the reflected light signals. NDVI can range from 0.00 to 0.99.

It correlates well with turfgrass quality (a combination of shoot density, color and uniformity) as affected by differences inherent to the species and cultivar, environmental stresses, fertilizer treatments or injury from pests (Xiong *et al.* 2007; Taghvaeian et al. 2013). 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 Near Infrared/Red (NIR/Red) (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. 2004) allowing remote detection methods to identify and map vegetation stress through the influence of chlorophyll content variation. Among the most used chlorophyll indices are NPCI (Normalized Pigment Chlorophyll Index), SIPI (Structure Intensive Pigment Index), PRI (Photochemical Reflectance Index), GNDVI (Green Normalized Difference Vegetation Index), MCARI (Modified Chlorophyll Absorption in Reflectance Index) and YI (Yellowness Index). Furthermore, other structural indices have been developed and investigated such as SR (Simple Ratio) (Foschi et al. 2009; Agati et al. 2013), Stress index 1 (R_{710}/R_{760}), Stress index 2 (R_{710}/R_{810}), WI (Water band Index =

R_{700}/R_{950}) (Jiang and Carrow 2007) that are useful for detecting the plant water content; while Ratio Vegetation Index (RVI=NIR/Red), Red edge position and Red edge/NIR are identified as the most responsive for detecting leaf nutritional status. The R_{710} band is a red-edge band that may also be useful to monitor vegetation stress and is a band region common in optimum hyperspectral models for many plants (Thenkabail et al. 2004). Water Index (WI = R_{900}/R_{970}) has been reported to be a robust index of canopy water content (Peñuelas et al. 1997) [**Errore. L'origine riferimento non è stata trovata.**]. Another vegetation index to detect water features is normalized difference water index (NDWI), designed to maximize reflectance of water by using green wavelengths, minimize the low reflectance of NIR by water features, and take advantage of the high reflectance of NIR by vegetation and soil features (McFeeters, 1996; Xu, 2006; Caturegli et al. 2014b).

1.4 Remote sensing on turfgrass

Therefore, while turfgrass status evaluation by proximity-sensed spectral reflectance appears to be an established and reliable practice, much more could be achieved in terms of monitoring of large turfgrass areas (i.e. golf courses, parks, large sports fields, sod farms. etc) by gathering similar spectral reflectance information through remote sensing and in particular through satellite imagery.

The application of spectral reflectance data originating from satellite imagery has had until recently three major limitations for an effective use on turfgrass areas: (1) high costs of satellite imagery, (2) relatively low resolution resulting in outputs with large pixel surface, thus little suited to the smaller and very variable areas associated with turfgrass, and (3) few spectral bands, that restrict the calculations of turfgrass-specific vegetation indices (Dettman-Kruse *et al.* 2008, Lee 2008). However, a new generation of satellites have been launched, and high-resolution images with a wide array of spectral bands have become available to turf scientists. One of these is WorldView-2 (WV2), which was launched on October 2009 from Vandenburg Air Force Base in California. WV2 is the first high-resolution satellite with 8-multispectral imaging bands. It simultaneously collects Panchromatic imagery at 0.46 m and multispectral imagery at 1.84 m. This satellite is capable of collecting up to 975,000 km^2 of imagery per day (Thenkabail et al. 2004; Upadhyay et al. 2012; Immitzer et al. 2012). Another recent satellite is GeoEye-1 equipped with some of the most advanced technology ever used in a commercial remote sensing system. This satellite, launched in September 2008, is a high-resolution earth observation satellite and has the capacity to collect up to 700,000 square kilometers of panchromatic imagery (and up to 350,000 square kilometers of Pan-Sharpened Multispectral imagery) per day. The spectral range of the acquired images is panchromatic (450 - 800 nm), blue (450 - 510 nm), green (510 - 580 nm), red (655 - 690 nm), near infrared (780 - 920 nm), and the horizontal resolution is equal to 0.50 x 0.50 m. GeoEye-1 satellite has been used for studies in different sectors (Ramirez-Herrera *et al.* 2013, McFeeters 2013) such as agriculture (Mulla 2013, Yang *et al.* 2013) and urban environments (Hester *et al.* 2008, Peters and McFadden 2010, Aguilar *et al.* 2013, Chong *et al.* 2014). Data acquired by GeoEye-1 satellite could provide values of NDVI of the analyzed surfaces.

2. Monitoring turfgrass species and cultivars by spectral reflectance

2.1 Aim

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.

2.2 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 x C. transvaalensis* (*Cd x t*) hybrids*:* ‘Tifway’, ‘Patriot’, ‘Miniverde’;

3 *Zoysia japonica* (*Zj*)*:* ‘De Anza’, ‘Meyer’, ‘Zenith’;

3 Fine - leaved zoysiagrasses (Patton et al. 2007): Zoysia japonica x Z. pacifica (Zj x 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).

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 = ———	Chlorophyll	Meer and 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 *et al.* (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.* (2004)
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 & Merzlyak (1997)
Vegetation Index (VI)	VI= R_{775}/R_{680}	Nitrogen	Inoue *et al.*(2008)
Modified Soil-Adjusted Vegetation Index (MSAVI2)	–	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)

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;
- color 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 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 (1L acetone=1g 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).

2.3 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 color ($P<0.05$), 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.

Table 2. Cool-season (C3) species and cultivars: Agronomical and biological parameters (quality, color, 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)		Color (1-9)		N (%)	Chl. a (mg g^{-1})	Chl. b (mg g^{-1})		Caroten. (mg g^{-1})
Lp[a]	PR 124	6.3	b	6.5	cd	2.8	1.12	0.58	abc	0.31
Lp	PR255	8.5	a	8.5	a	2.6	1.24	0.75	a	0.37
Fa[b]	TFWolf.	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[c]	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

[a] Lolium perenne
[b] Festuca arundinacea
[c] 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[a]	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[b]	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[c]	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[a]	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[b]	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[c]	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	

[a] *Lolium perenne*
[b] *Festuca arundinacea*
[c] *Poa pratensis*

Kentucky bluegrass

Except for the color, 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 color. This is reflected in turfgrass visual color 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 color. 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 behavior 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).

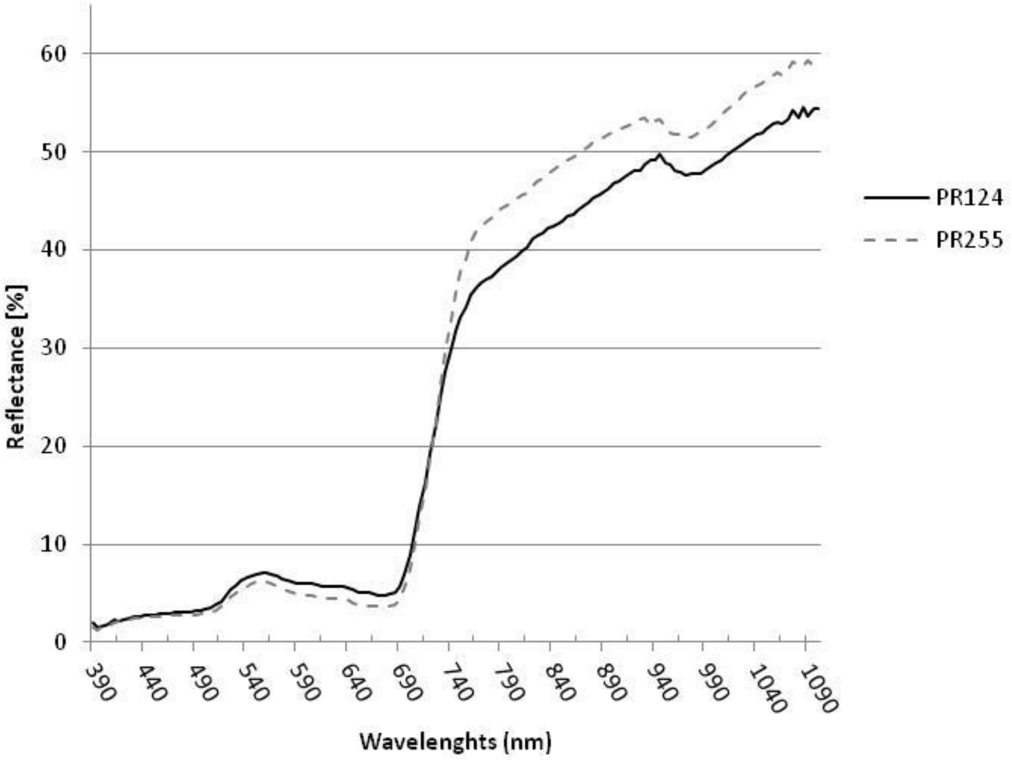

Fig. 1. Spectral reflectance curves of 2 different cultivars of *Lolium perenne* (cool-season C3): PR 124 (light green) and PR 255 (dark green)

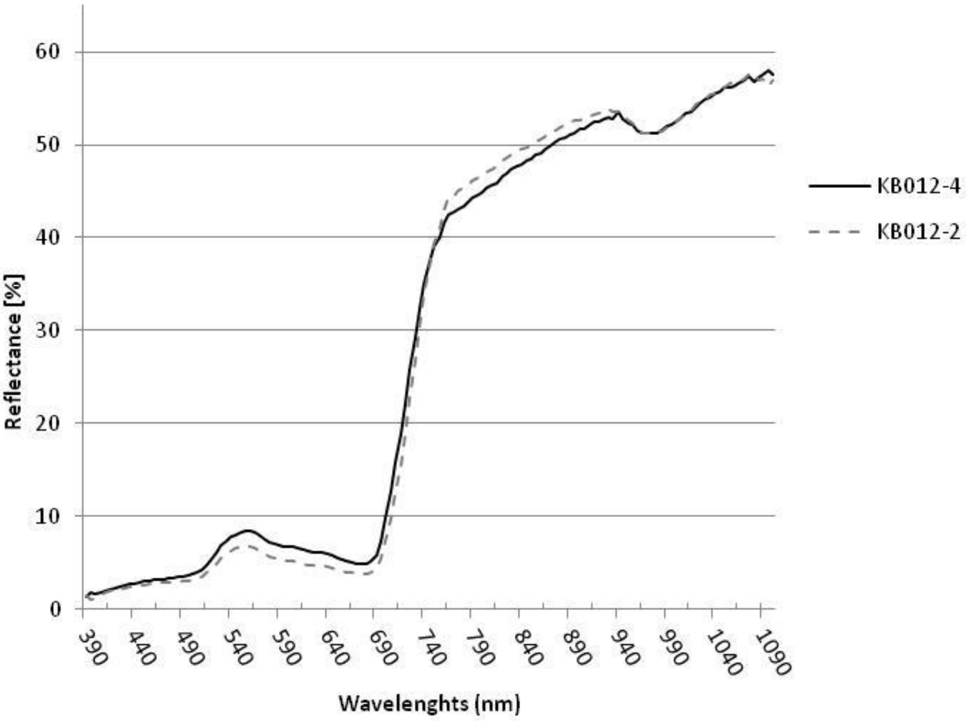

Fig. 2. Spectral reflectance curves of 2 different cultivars of *Poa pratensis* (cool-season C3): KB 012-4 (light green) and KB 012-2 (dark green)

Tall Fescue

The two tall fescue cultivars differed significantly ($P<0.05$) in their color 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.

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, color, 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)	Color (1-9)	N (%)	Chl. A (mg g^{-1})	Chl. b (mg g^{-1})	Caroten. (mg g^{-1})
Ecot.Cd[a]	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[b]	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 x t[c]	Tifway	8.4 bc	7.6 abc	2.4 abcd	0.83 c	0.42	0.07 de
Cd x t	Patriot	8.6 ab	8.4 a	2.5 abcd	1.21 a	0.60	0.20 abc
Cd x t	Miniverde	8.5 abc	8.5 a	3.0 ab	1.23 a	0.64	0.15 bcd
Zj[d]	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 x p[e]	Emerald	8.7 ab	7.2 bcd	1.8 cd	0.60 c	0.34	0.07 de
Zm[f]	Zeon	8.7 ab	7.3 bcd	1.8 d	0.64 c	0.38	0.08 de
Zp[g]		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

[a] Ecotypes of *Cynodon dactylon;* [b] Seeded *Cynodon dactylon;* [c] *Cynodon dactylon x C. transvaalensis;* [d] *Zoysia japonica;* [e] *Zoysia japonica x Z. pacifica;* [f] *Zoysia matrella;* [g] *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.	CV*	NDVI$_{900}$ (900,680)		NDVI$_{775}$ (775,680)		SR$_{900}$ (900/680)		Red edge		Red Edge posit.		MCARI		TCARI		ZM (750/710)	
Ecot.Cd[a]	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[b]	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 x t[c]	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 x 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 x t	Miniverd	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[d]	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 x p[e]	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[f]	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[g]		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		0.9	

Sp.	CV*	SIPI		GM1 (750/550)		GM2 (750/700)		VI (775/680)		MSAVI2		OSAVI		WI (970/900)	
Ecot.Cd[a]	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[b]	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 x t[c]	Tifway	0.83	abcde	4.79	bcd	5.12	abcd	9.94	cde	1.39	ab	0.95	abc	1.00	a
Cd x t	Patriot	0.86	abcde	5.62	abc	6.39	ab	13.01	abc	1.42	ab	0.99	abc	0.97	abcd
Cd x t	Miniverde	0.83	abcde	4.81	bcd	4.99	bcd	9.42	cde	1.39	ab	0.94	abc	0.96	abcd
Zj[d]	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 x p[e]	Emerald	0.87	ab	5.81	ab	5.91	abc	12.63	abcd	1.42	ab	0.99	abc	0.98	abc
Zm[f]	Zeon	0.86	abc	5.33	abc	5.32	abcd	11.29	bcde	1.41	ab	0.97	abc	0.94	de
Zp[g]		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	

[*] Cultivar

[a] Ecotypes of *Cynodon dactylon;* [b] Seeded *Cynodon dactylon;* [c] *Cynodon dactylon x C. transvaalensis*

[d] *Zoysia japonica;* [e] *Zoysia japonica* x *Z. pacifica;* [f] *Zoysia matrella;* [g] *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’). Figure 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 bermudagrass evaluated in this study and the results revealed significantly ($P<0.001$) lower values in all the vegetation indices. The reflectance spectrum obtained in Figure 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 influence 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.

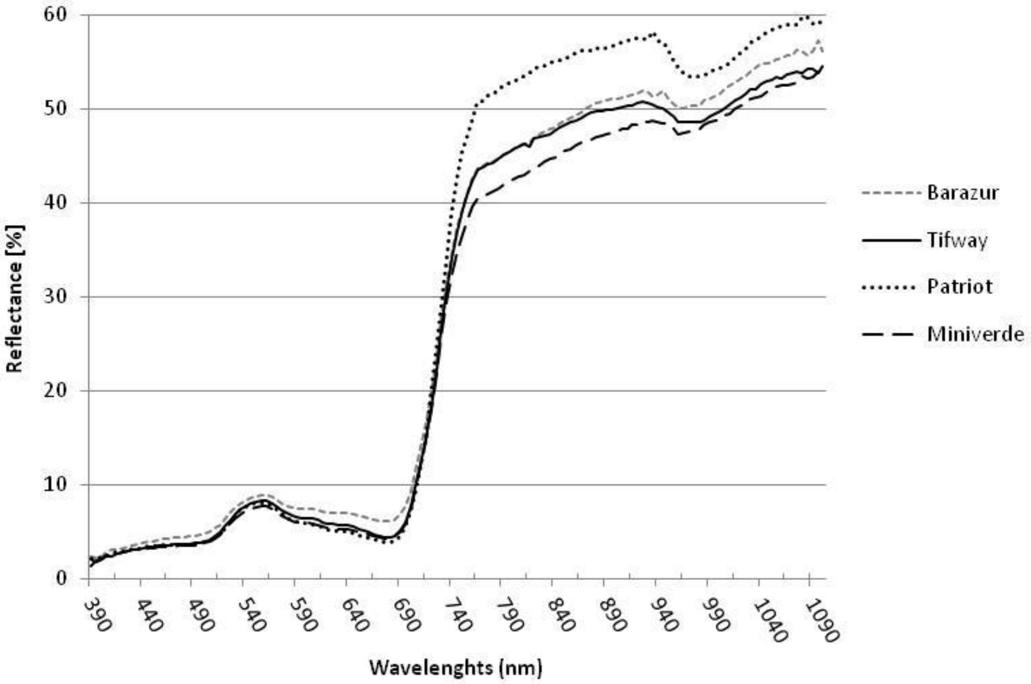

Fig. 3. Spectral reflectance curves of vegetatively propagated bermudagrasses (warm-season C4): 1 *Cynodon dactylon* 'Barazur', 3 *Cynodon dactylon* x *C. transvaalensis* hybrids: 'Tifway', 'Patriot', 'Miniverde'

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 Figure 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* x *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'). Figure 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* x *Z. pacifica* 'Emerald' and *Zoysia matrella* 'Zeon'.

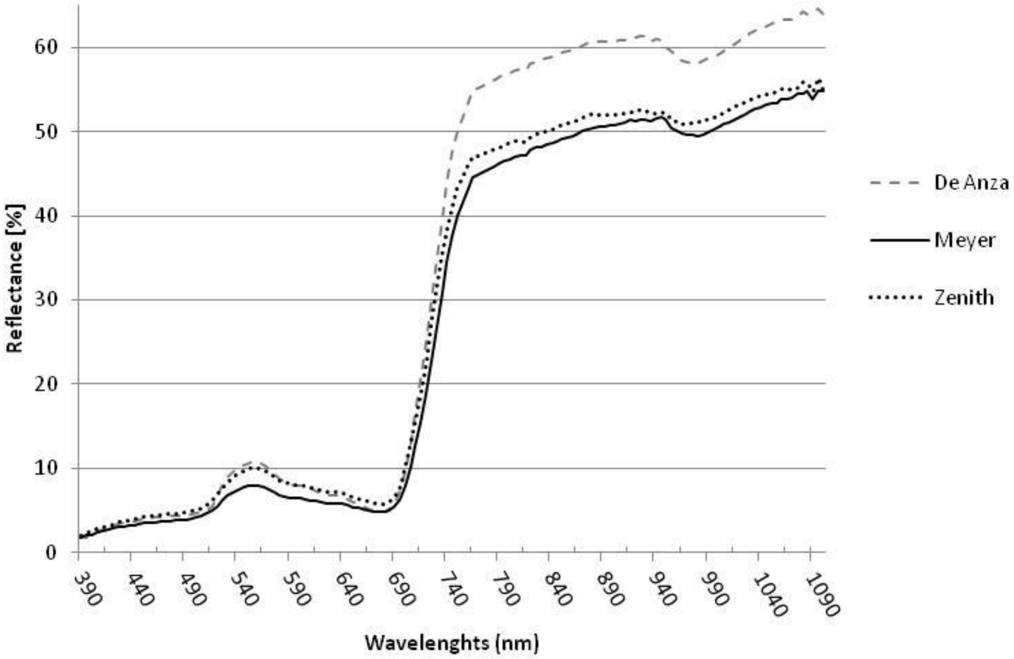

Fig. 4. Spectral reflectance curves of 3 *Zoysia japonica* (warm-season C4): 'De Anza', 'Meyer', 'Zenith'

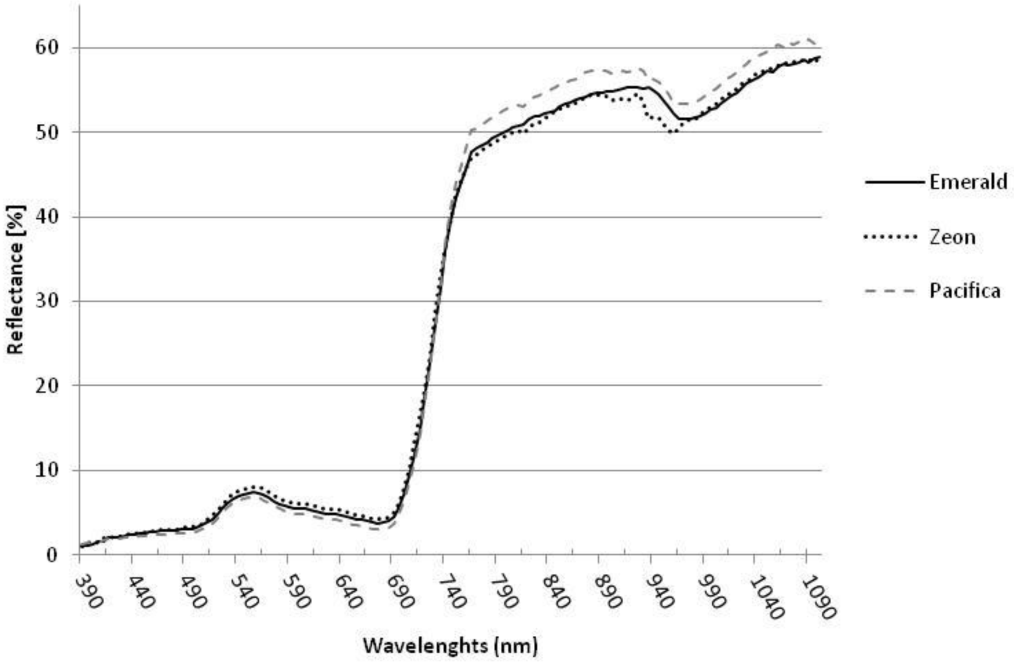

Fig. 5. Spectral reflectance curves of 3 fine-leaved zoysiagrasses: *Zoysia japonica* x *Z. pacifica* 'Emerald', *Zoysia matrella* 'Zeon', *Zoysia pacifica*

2.4 Conclusions

The application of vegetation indices helps to highlight spectral differences including turf quality, color, 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.

3. Turfgrass spectral reflectance: simulating satellite monitoring of spectral signatures of main C3 and C4 species.

3.1 Aim

This study consisted in **(a)** determining the proximity-sensed turfgrass spectral reflectance of 20 turfgrass species and varieties maintained in identical conditions, **(b)** gathering key biological and agronomical parameters (visual quality, color, water content, chlorophyll, carotenoids, nitrogen content). Then, the viability of turfgrass monitoring via WV2 imagery has been evaluated by simulating a spectral reflectance acquisition with the same bands available through WV2 imagery for correlation with the biological and agronomical parameters.

3.2 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.). The trial was held in May-July 2012 on 20 turfgrass species and cultivars 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 (1.8% dry wt.). Turfgrass species and varieties were selected for evaluation amid mature (>5 yr) stands. Single plot dimensions varied from 1.5 m^2 (C_3) to 2.25 m^2 (C_4).

Six cool-season (C_3) species and cultivars were entered in the trial (single plot size: 1.5 m^2). Where available, genetically light green and dark green varieties were entered for each species:

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 (single plot size: 2.25 m^2):

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 x C. transvaalensis* (*Cd x t*) hybrids*:* ‘Tifway’, ‘Patriot’, ‘Miniverde’;

3 *Zoysia japonica* (*Zj*)*:* ‘De Anza’, ‘Meyer’, ‘Zenith’;

3 non-japonica zoysiagrasses: Zoysia japonica x Z. pacifica (Zj x p) ‘Emerald’, Zoysia matrella (Zm)‘Zeon’, Zoysia pacifica (Zp).

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 follows: C4 one weekly irrigation with 30 mm, C3 three weekly irrigations with 15 mm. 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 carried out during the trial.

Spectral reflectance data

Spectra were acquired using a LI-COR 1800 spectroradiometer (LI-COR Inc., Lincoln, NE, USA) with a fiber optic wire and LI-COR 1800-06 telescope. The telescope was mounted on a purpose-built trolley at 120 cm from the ground with a vision angle set at 15°. The monitored surface corresponded at ground level to approximately 2000 cm^2. Measures were collected on July 09 between 11.30 am and 1.30 pm (solar time), in complete absence of clouds. The radiation reflected by a white barium sulphate panel was measured 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 proven statistical correlation with several turfgrass parameters were calculated from the wavelength bands available in WV2 satellite imagery (Table 6). The following indices were selected for evaluation in the present study (Table 7): NIR1/Red, NDVIa (NIR2, Red), NDVIb (NIR2, Green), NDVItm (NIR1, Red), MSAVI 2 (NIR1, Red).

Table 6. The multispectral bands of WorldView-2 satellite

	Wavelengths WV-2 (nm)
Blue Costal	400-450
Blue	450-510
Pancromatic	450-800
Green	510-580
Yellow	585-625
Red	630-690
RedEdge	705-745
NIR1	770-895
NIR2	860-1040

Source: www.satimagingcorp.com (last checked 25/08/2014)

Table 7. The vegetation indices obtained from the multispectral bands of WorldView-2 satellite

Vegetation Index	Equation
Normalized Difference Vegetation Index (NDVI)	NDVI = $(R_{NIR} - R_{red})/(R_{NIR} + R_{red})$ NDVIa = $(R_{NIR2} – R_{red})/(R_{NIR2} + R_{red})$ NDVIb = $(R_{NIR2} – R_{green})/(R_{NIR2} + R_{green})$ NDVItm = $(R_{NIR1} – R_{red})/(R_{NIR1} + R_{red})$
R_{NIR1} / R_{red}	R_{NIR1}/ R_{red}
Modified Soil-Adjusted Vegetation Index (MSAVI2)	–

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;

color intensity (from 1 = very light green to 9 = very dark green), visual assessment;

clippings dry biomass and relative nitrogen content: the fresh clippings were collected from 1 m^2 of stand with a reel mower, material was weighed and put in a ventilated stove at 70 °C and dried to constant weight. Dry weight data was collected and dry matter percentage was calculated;

clipping nitrogen content: Kjeldahl assay;

leaf chlorophyll content (a, b) and carotenoids: leaves were sampled randomly from each experimental unit and subsequently chlorophyll content analysis followed the procedures of Zhang e Kirkham (1996). Green leaves were placed in Falcon 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

The trial experimental design was a randomized block with three replications. 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 ($P<0.05$). All statistical analysis were carried out with COSTAT 6.400 software (CoStat 2008).

3.3 Results and discussion

Cool season turfgrass species

Both varieties within a species were initially selected for their marked differences in color. This is reflected in turfgrass visual color ratings that confirm statistically significant differences ($P<0.05$) among varieties within the same species (Table 8).

The two *Lolium perenne* varieties (PR124 = light green, PR255 = dark green) also differ significantly ($P<0.05$) only in visual turfgrass quality ($P<0.05$), with PR255 (8.5) having a higher quality than PR124 (6.3). The two varieties (PR124 = light green, PR255 = dark green) differ significantly ($P<0.05$) in all the multispectral WV2 bands and indices with the exception of Blue Coastal, Panchromatic and Red Edge bands (Table 9).

The two tall fescues also differ significantly ($P<0.05$) in their Chlorophyll b content, with the darker variety (TF816) having a higher content (0.63 mg g^{-1}) than the lighter TF Wolfpack variety (0.36 mg g^{-1}) (Table 8). The two varieties are significantly different ($P<0.05$) in the Green and Yellow bands (Table 9) with the lighter variety (TF Wolfpack) having a higher value than the darker variety (TF 816). The vegetation indices, obtained from the spectral bands that were able to discriminate ($P<0.05$) between these two varieties were: NIR1/Red and $NDVI_b$ with TF 816 having higher values than TF Wolfpack.

The two Kentucky bluegrass varieties did not differ significantly in any other agronomical/biological parameter (Table 8). The two Kentucky bluegrass varieties (KB012-4 = light green, KB012-2 = dark green) differ significantly ($P<0.05$) in all the multispectral WV2 bands and indices except for Panchromatic, NIR1and NIR2 bands. For all bands the lighter variety (KB012-4) obtained higher values than the darker variety (KB012-2). For all indices the darker variety (KB012-2) obtained higher values than the lighter variety (KB012-4) (Table 9).

Table 8. Cool-season (C$_3$) species and cultivars: biometric and biological parameters (quality, color, 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)		Color (1-9)		Dry matter (%)		N (%)	Chl. a (mg g^{-1})	Chl. b (mg g^{-1})		Caroten. (mg g^{-1})
Lp[a]	PR 124	6.3	b	6.5	cd	39.2	a	2.8	1.12	0.58	abc	0.31
Lp	PR255	8.5	a	8.5	a	39.4	a	2.6	1.24	0.75	a	0.37
Fa[b]	TFWolf.	6.7	b	7	c	29.5	c	2.8	0.77	0.36	c	0.22
Fa	TF 816	6.7	b	7.8	b	31.3	bc	3.1	1.23	0.63	ab	0.34
Pp[c]	KB 012-4	5.8	b	6.2	d	41.1	a	2.0	0.78	0.38	bc	0.24
Pp	KB 012-2	6.3	b	7.1	bc	38.0	ab	2.6	1.15	0.55	abc	0.35
MSD < 0.05		1.5		0.7		7.8		Ns	ns	0.26		ns

[a] *Lolium perenne*
[b] *Festuca arundinacea*
[c] *Poa pratensis*

Table 9. WorldView-2 bands and vegetation index data for the cool-season (C_3) species and cultivars. Means followed by the same letter do not differ significantly according to Tukey's pairwise test (P<0.05)

Sp.	Cultivar	Blue Coastal		Blue		Panchr.		Green		Yellow		Red		Red Edge	
Lp[a]	PR 124	2.38	a	3.15	b	12.19	b	6.08	b	5.86	ab	5.18	a	21.92	b
Lp	PR 255	2.25	ab	2.81	c	12.52	b	5.25	c	4.72	cd	3.96	b	22.68	b
Fa[b]	TF Wolf	2.12	ab	2.89	bc	13.28	ab	5.99	b	5.37	bc	4.34	b	23.59	ab
Fa	TF 816	2.04	b	2.69	c	12.47	b	5.14	c	4.58	d	3.8	b	21.47	b
Pp[c]	KB 012-4	2.38	a	3.47	a	14.01	a	7.13	a	6.61	a	5.47	a	25.47	a
Pp	KB 012-2	2.1	b	2.96	bc	13.09	ab	5.73	bc	5.11	bcd	4.19	b	23.06	b
MSD < 0.05		0.26		0.31		1.08		0.39		0.43		0.41		1.28	

Sp.	Cultivar	NIR 1		NIR 2		NIR1/Red		$NDVI_a$ (NIR2,Red)		$NDVI_b$ (NIR2,Green)		$NDVI_{tm}$ (NIR1,Red)		MSAVI (NIR1,Red)	
Lp[a]	PR 124	41.64	b	48.04	b	8.1	c	0.81	b	0.77	c	0.78	b	1.37	b
Lp	PR 255	47.37	a	52.73	a	11.98	ab	0.86	a	0.82	ab	0.85	a	1.42	a
Fa[b]	TF Wolf	49.32	a	53.51	a	11.37	b	0.85	a	0.8	b	0.84	a	1.41	a
Fa	TF 816	48.54	a	52.54	a	12.80	a	0.86	a	0.82	a	0.85	a	1.42	a
Pp[c]	KB 012-4	47.25	a	52.18	a	8.67	c	0.81	b	0.76	c	0.79	b	1.38	b
Pp	KB 012-2	48.84	a	52.71	a	11.72	ab	0.85	a	0.81	ab	0.84	a	1.41	a
MSD < 0.05		1.82		3.51		1.40		0.02		0.02		0.03		0.02	

[a] *Lolium perenne*
[b] *Festuca arundinacea*
[c] *Poa pratensis*

Warm season turfgrass species

The two ecotypes of *Cynodon dactylon* ('Certes-2' and 'Certes-4') and the two commercially available seeded bermudagrass ('Princess' and 'Riviera') do not differ statistically for any of the analyzed biometric parameters (Table 10). The two ecotypes and the two seeded bermudagrass do not differ statistically for any of the analyzed multispectral WorldView-2 bands, nor is any vegetation index able to discriminate between the two ecotypes or the two seeded varieties (Table 11).

Table 10. Warm-season (C_4) species and cultivars: biometric and biological parameters (quality, color, 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)		Color (1-9)		N (%)		Chl. A (mg g^{-1})		Chl. b (mg g^{-1})	Caroten. (mg g^{-1})	
Ecot.Cd[a]	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[b]	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 x t[c]	Tifway	8.4	bc	7.6	abc	2.4	abcd	0.83	c	0.42	0.07	de
Cd x t	Patriot	8.6	ab	8.4	a	2.5	abcd	1.21	a	0.60	0.20	abc
Cd x t	Miniverde	8.5	abc	8.5	a	3.0	ab	1.23	a	0.64	0.15	bcd
Zj[d]	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 x p[e]	Emerald	8.7	ab	7.2	bcd	1.8	cd	0.60	c	0.34	0.07	de
Zm[f]	Zeon	8.7	ab	7.3	bcd	1.8	d	0.64	c	0.38	0.08	de
Zp[g]		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	

[a] *Ecotypes of Cynodon dactylon*
[b] *Seeded Cynodon dactylon*
[c] *Cynodon dactylon x C. transvaalensis*
[d] *Zoysia japonica*
[e] *Zoysia japonica x Z. pacifica*
[f] *Zoysia matrella*
[g] *Zoysia pacifica*

Table 11. WorldView-2 bands and vegetation index data for the warm-season (C_4) species and cultivars. Means followed by the same letter do not differ significantly according to Tukey's pairwise test (P<0.05)

Sp.	Cultivar	Blue Coastal		Blue		Panchr.		Green		Yellow		Red		Red Edge	
Ecot.Cd[a]	Certes-2	3.99	a	5.04	a	16.06	ab	9.26	a	8.30	a	6.82	a	27.22	ab
Ecot.Cd	Certes-4	3.78	ab	4.8	ab	15.50	abc	8.84	ab	7.72	ab	6.20	abc	26.03	bcd
Seed.Cd	Princess	3.21	bc	4.34	abcd	15.33	abc	8.42	abcd	7.51	abcd	5.96	abcd	26.13	bcd
Seed.Cd	Riviera	2.99	c	4.11	abcd	14.65	bcd	8.45	abcd	7.69	ab	6.26	abc	25.62	bcde
Cd	Barazur	3.4	ab	4.56	abcd	14.59	bcd	7.77	abcde	7.32	abcd	6.56	ab	24.07	bcde
Cd x t[c]	Tifway	2.86	c	3.78	cdef	13.70	cd	7.08	bcdef	6.32	bcde	5.08	abcd	22.89	de
Cd x t	Patriot	3	c	3.74	def	14.83	bcd	6.89	cdef	5.73	de	4.48	cde	25.15	bcde
Cd x t	Miniverd	2.87	c	3.6	defg	12.88	d	6.60	ef	5.80	cde	4.82	bcde	22.1	e
Zj[d]	De anza	3.30	bc	4.42	abcd	17.19	a	8.95	a	7.64	abc	5.72	abcd	30.1	a
Zj	Meyer	2.92	c	3.89	bcde	13.94	cd	6.89	cdef	6.28	bcde	5.32	abcd	23.31	cde
Zj	Zenith	3.51	ab	4.73	abc	15.73	abc	8.64	abc	7.8	ab	6.47	ab	27.02	abc
Zj x p[e]	Emerald	2.1	d	3.02	fg	13.84	cd	6.23	ef	5.37	e	4.29	de	23.58	bcde
Zm[f]	Zeon	2.16	d	3.17	efg	14.22	bcd	6.79	def	5.94	bcde	4.76	bcde	24.58	bcde
Zp[g]		1.93	d	2.61	g	13.77	cd	5.7	f	4.71	e	3.55	e	23.46	bcde
MSD < 0.05		0.66		0.99		2.06		1.81		1.89		1.88		3.90	

Sp.	Cultivar	NIR 1		NIR 2		NIR1/Red		NDVIa (NIR2, Red)		NDVIb (NIR2, Green)		NDVItm (NIR1, Red)		MSAVI 2 (NIR1, Red)	
Ecot.Cd	Certes-2	49.69	bcd	51.19	bc	7.47	d	0.77	e	0.69	f	0.76	d	1.36	c
Ecot.Cd	Certes-4	49.51	bcd	51.25	bc	8	cd	0.78	cde	0.71	def	0.78	cd	1.37	bc
Seed.C	Princess	50.27	bcd	52.63	bc	8.54	cd	0.80	bcde	0.72	cdef	0.79	bcd	1.38	bc
Seed.C	Riviera	45.38	cd	47.19	d	7.31	d	0.76	e	0.70	ef	0.76	d	1.36	c
Cd	Barazur	47.66	bcd	51.44	bc	7.44	d	0.78	de	0.74	bcdef	0.76	d	1.36	c
Cd x t[c]	Tifway	47.28	cd	50.02	bc	9.31	bc	0.82	abcd	0.75	bcde	0.81	bcd	1.39	abc
Cd x t	Patriot	54.44	ab	55.96	ab	12.17	b	0.85	abc	0.78	ab	0.85	ab	1.42	ab
Cd x t	Miniverde	44.37	d	48.41	cd	9.26	bc	0.82	abcd	0.76	bcd	0.80	bcd	1.39	abc
Zj[d]	De anza	58.41	a	60.21	a	10.23	bc	0.83	abcd	0.74	bcdef	0.82	abcd	1.4	abc
Zj	Meyer	48.17	bcd	50.83	bc	9.09	cd	0.81	bcde	0.76	bcd	0.80	bcd	1.39	abc
Zj	Zenith	49.91	bcd	52.12	bc	7.91	cd	0.78	de	0.71	def	0.77	cd	1.37	c
Zj x p[e]	Emerald	51.92	abc	54.05	ab	12.15	b	0.85	ab	0.79	ab	0.85	ab	1.42	ab
Zm[f]	Zeon	51.43	abc	53.39	bc	10.81	bc	0.84	abcd	0.77	abc	0.83	abc	1.41	abc
Zp[g]		54.43	ab	56.18	ab	15.5	a	0.88	a	0.82	a	0.88	a	1.43	a
MSD < 0.05		7.13		6.61		3.03		0.07		0.05		0.07		0.05	

[a] *Ecotypes of Cynodon dactylon*
[b] *Seeded Cynodon dactylon*
[c] *Cynodon dactylon x C. transvaalensis*
[d] *Zoysia japonica*
[e] *Zoysia japonica x Z. pacifica*
[f] *Zoysia matrella*
[g] *Zoysia pacifica*

The vegetatively propagated bermudagrasses differ significantly (P<0.05) for (i) turfgrass quality, where 'Barazur' (6.3) scores significantly lower than 'Tifway' (8.4), 'Patriot' (8.6) and 'Miniverde' (8.5), (ii) leaf carotenoid content, where 'Patriot' (0.20 mg g^{-1}) showed a significantly higher content than 'Tifway' (0.07 mg g^{-1}) and (iii) leaf chlorophyll A content where 'Tifway' (0.83 mg g^{-1}) had the lowest content compared to any other variety (Table 10). The vegetatively propagated bermudagrasses differ significantly (P<0.05) in some spectral bands and vegetation indices as shown in Table 11. All the vegetation indices and also the Red band (630-690 nm) were able to discriminate (P<0.05) between 'Barazur' and 'Patriot'.

Among *Zoysia japonica* varieties ('De Anza', 'Meyer', 'Zenith') the only biometric parameter that differed statistically (P<0.05) was turfgrass quality, with 'De Anza' scoring significantly higher than 'Zenith'. For these varieties, the bands that differed statistically (P<0.05) were Panchromatic and Green with 'De Anza' scoring significantly higher than 'Meyer' and NIR1 and NIR2 that indicate a difference also between 'De Anza' and 'Zenith'. No vegetation index was able to discriminate between these three varieties in a statistically significant manner.

Among non-japonica zoysiagrasses (*Zoysia japonica* x *Z. pacifica* 'Emerald', *Zoysia matrella* 'Zeon', *Zoysia pacifica*) no statistically significant differences were found for any of the biometric parameters. No statistically significant differences were found for any of multispectral WV2 bands, while the only vegetation index that was able to discriminate (P<0.05) between these three species was NIR1/Red, with *Zoysia pacifica* having a higher value than the other two species (Table 11).

3.4 Conclusions

The application of vegetation indices helps to highlight spectral differences including turf quality, color, dry matter, chlorophyll, carotenoids and nitrogen content. Results showed that within the same species selected vegetation indices calculated from spectral bands available in WV2 satellite imagery are not always able to discriminate between different varieties that have been established and maintained with identical agronomical practices. This study allowed us to evaluate the spectral reflectance of several turfgrass species and cultivars in order to carry out a preliminary evaluation 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 plants using satellite spectroradiometry provides the possibility to identify and map some different species/varieties and allows a potential large scale management and control of agricultural resources.

Further studies could be useful a) to investigate the possibility of discriminating through the use of the vegetation indices considered in this research between the same species/varieties with different conditions of water, fertilizers and pesticides, and b) to validate the efficacy of satellite remote sensing, given the spectral bands and resolution presently available from satellite imagery for the evaluation of turfgrass characteristics.

4. Spectral reflectance of tall fescue (*Festuca arundinacea* Schreb.) under different irrigation and nitrogen conditions.

The issue of climate change and the sustainable use of resources is at the heart of international topics and discussions. Also in the management and maintenance of tufgrasses the current trend is heading towards an optimization of inputs, such as irrigation and fertilization. Drought stress is one of the main abiotic stresses influencing turfgrass growth and quality. Under Italian climatic conditions rainfall does not supply a sufficient amount of water, especially in the areas of south-central Italy. Therefore, irrigation management is of paramount importance for maintaining turf quality during dry periods. In the Mediterranean area tall fescue is the most suitable cool-season turfgrass (Damiani et al. 2004; Grossi et al. 2004; Volterrani et al. 2004). This species can grow at temperatures ranging from 0 to 35 °C (OGTR, 2008) and has a better ability to avoid drought stress than perennial ryegrass or Kentucky bluegrass (Huang and Gao, 1999, 2000; Carrow, 1996; Qian et al. 1997). When turf is under water stress, a light fertilization may improve the overall quality, vice versa an excessive intake of fertilizer may worsen the situation (Carrow et al. 2001) and produce detrimental effects on turf.

4.1 Aim

In this study we evaluated the proximity sensed turfgrass spectral reflectance of *Festuca arundinacea* under different water and nitrogen conditions through the application of some of the most common vegetation indices. The aim was to use proximity sensing as a diagnostic tool to better manage the available resources on turfgrasses and, on a broader view, a potential large scale management and control of irrigation via satellite remotely sensed data.

4.2. Materials and Methods

The experimental trial was carried out in S. Piero a Grado, Pisa (43° 39′ N 10° 21′ E, 5 m a.s.l.) from September 2011 to July 2012 on a stand of *Festuca arundinacea* cv 'Grande', established on a soil characterized by the following physical-chemical properties: 91% sand, 5% silt, 4% clay, pH 6.5, 1.3 g kg^{-1} of organic matter; EC 0.46 dS m^{-1}, water availability 3.45 % w/w. Seeding took place on 19 September 2011, 43 g m^{-2} seeding rates. Pre-seeding fertilization was carried out with 5 g m^{-2} of N (urea), 5 g m^{-2} of P_2O_5 from perphosphate and 10 g m^{-2} of K_2O from potassium sulphate. From November to April broadcast fertilization was carried out for a total of 6.0 g m^{-2} of N (urea). A turf height of 4.5 cm was held. Irrigation was applied as necessary to maintain a healthy turfgrass. On June 5, Linear Gradient Irrigation System (LGIS) was installed (Hanks et al. 1976; Robins, 2010; Qian and Engelke, 1999; Bañuelos et al. 2011). The central line of LGIS was composed by a row of 13 sprinklers (NaanDan Jain, mod. 5022-U) with a 7.5 m range. A spacing between sprinklers of 2.5 m was adopted. A strip 1 m wide centered on central line was left unmowed, to avoid damages to the sprinkler junctions (Fig. 6).

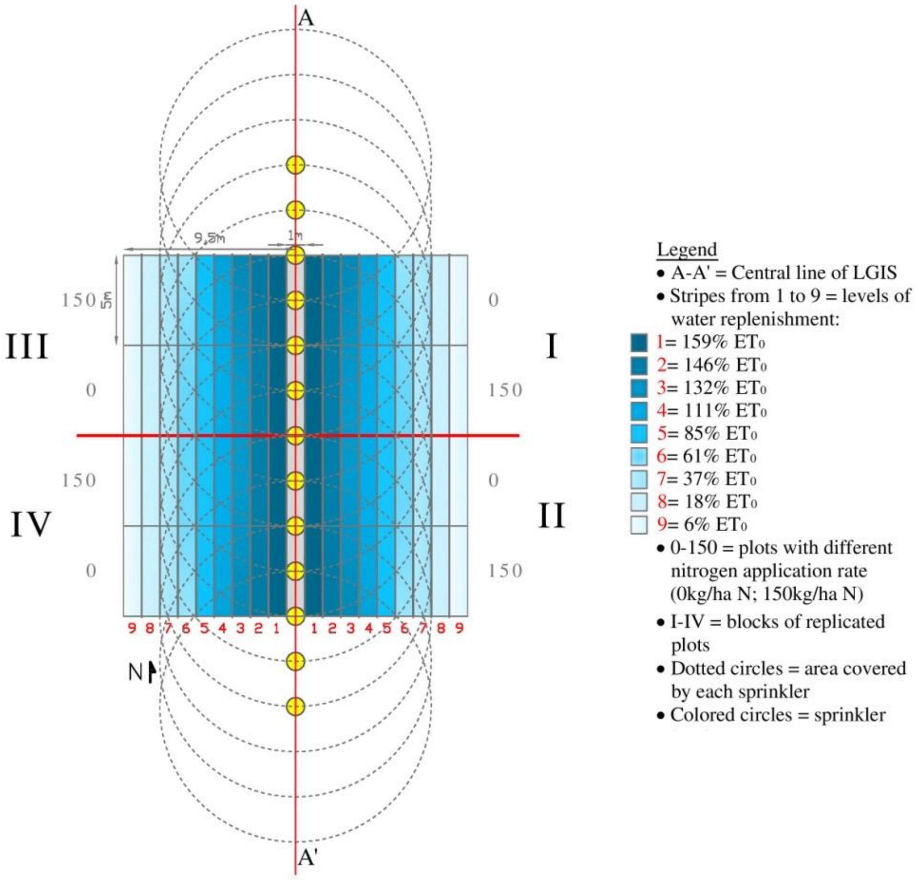

Fig 6. Layout of the experimental area.

On June 6, in order to measure the amount of water distributed by LGIS, 36 pluviometers were arranged in 4 lines of 9 each, spaced one meter on the lines, perpendicularly to the central line of LGIS, and placed in each main plot. The daily irrigation as a function of the distance from the central line of LGIS was calculated and the reference ET_0 was estimated on a daily time scale from the available meteorological data (T_{max} and T_{min}) using the Hargreaves and Samani method.

where:

T_{max} is maximum temperature [°C];

T_{min} is minimum temperature[°C];

T_{med} is mean temperature [°C];

R_a is the extraterrestrial radiation [mm day^{-1}], calculated as a function of latitude and time of year (Ra = 16.8 mm day^{-1} during the period of the trial in San Piero a Grado, Pisa). From June 5 to June 20, cumulative ET_0 was estimated (83.2 mm) and mean daily ET_0 was calculated (5.2 mm). The irrigation run time was calculated according to this daily ET_0. The irrigation of the experimental area with LGIS was started on June 25. Up to this date, the trial area was uniformly irrigated with sprinklers (NaanDan Jain mod. Super10) spaced 7.5 m with a 7.5 m range. This irrigation system was switched off on June 24. Considering that during the trial period (June 25 - July 17) on the study area there were no rainfall, we had a replenishment of 100% where the amount of water provided with the irrigation was equivalent to $ET_{0.}$ Comparing this value to the data of the cumulative irrigation, 9 levels of replenishment were calculated (Tab. 12).

Table 12. Daily irrigation (mm) during the LGIS period (June 25 - July 17), and levels of water replenishment as function of the distance from the central pipe.

Distance from the central pipe (m)	Daily irrigation (mm)	Water replenishment (%)
1	8.2	159
2	7.5	146
3	6.8	132
4	5.7	111
5	4.4	85
6	3.1	61
7	1.9	37
8	0.9	18
9	0.3	6

The irrigation was carried out every day, between 7:30 and 9:30 a.m. (period of the day when winds effect is usually negligible). The experimental design was a split-plot with 4 replications. The main treatment consisted in 2 levels of nitrogen fertilization: 0 and 150 kg N ha^{-1} and was carried out on June 20 (ammonium sulphate 21-0-0). The secondary treatment consisted in 9 levels of water replenishment: from 159 to 6% (according to the reference evapotranspiration ET_0). The main plots were 47.5 m^2 (9.5 x 5 m), while the subplots were 5 m^2 (1 x 5 m).

Biometric parameters

On July 17 the following parameters were determined:

- turf quality: (1 = poor; 9 = excellent) visual assessment (Morris and Shearman, 2006).
- drought tolerance: (1 = completely stressed; 9 = no stress) visual assessment (Morris and Shearman, 2006).
- pest problems: pests include disease, insects and weeds (1 = 100% injury; 9 = no injury), visual assessment (Morris and Shearman, 2006).
- surface temperature: an infrared thermometer (Testo mod. 825-T2) was placed 0.8 m above the surface in order to collect the surface temperature.
- clippings weight (weekly) and relative nitrogen content: clippings were collected over a surface of 0.5 m^2 after a week of undisturbed growth. Fresh clippings were weighted, put in a ventilated stove at 70 °C and dried to constant weight. Dry weight data was collected and relative nitrogen content (%) was determined by Kjeldahl methods (Bremner, 1965).
- turf growth (weekly): after a week of undisturbed growth, turf height was measured with rising disk (specific density = 750 g m^{-2}). The measured value minus the cutting height of July 10 (4.5 cm) gave the weekly turf growth.
- soil moisture: soil samples were collected at 15 cm depth, weighted, put in a stove at 105-110 °C and dried to constant weight. Soil moisture (%) was calculated as follow: [(fresh weight - dry weight) / fresh weight].

Spectral reflectance data

Together with the biometric parameters, on July 17 spectral reflectance data were acquired using a LICOR 1800 spectroradiometer (Li-Cor, 1992) 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 17 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 (Tab. 13).

Table 13. Reflectance-based vegetation indices used in this study.

Vegetation Index	Equation	Sensitivity	References
Normalized Difference Vegetation Index (NDVI)		Chlorophyll	Rouse *et al.*1974
Transformed CARI (TCARI)		Chlorophyll	Haboudane *et al.* 2002
Structure Intensive Pigment Index (SIPI)		Chlorophyll/ Carotenoid	Peñuelas *et al.* 1995
Rededge	Rededge = ————	Nitrogen	Meer and 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	Nitrogen	Cho and Skidmore, 2006
Vegetation Index (VI)		Nitrogen	Inoue *et al.* 2008
Water Index (WI)		Leaf water	Peñuelas *et al*. 1997
Normalized Difference Water Index (NDWI)		Water features	McFeeters, 1996

Statistical analysis

Statistical analysis were carried out with a COSTAT 6.400 software (CoHort Software, Monterey, CA, USA). All biometric and vegetation index data were analyzed by two-ways ANOVA, and a all pairwise Fisher's Least Significant Difference (LSD) test at the probability level of 0.05. The association between biometric parameters and the latter with vegetation indices were studied. Pearson’s correlation coefficient (r) was calculated among all the biometric parameters (turf quality, drought tolerance, surface temperature, clippings weight, nitrogen content, turf growth, soil moisture) and between the biometric parameters and the vegetation indices calculated in our research.

4.3 Results and discussion

Throughout the trial period no weeds or turf diseases occurred on turf. The analysis of the data regarding the interaction between the main and secondary treatment did not show any statistically significant differences for any parameters. Therefore, the average effects of nitrogen fertilization and water replenishment will be discussed.

4.3.1 Nitrogen fertilization

Nitrogen fertilization influenced significantly the following biometric parameters: turf quality, clippings weight, nitrogen content and turf growth. Turfgrass quality was influenced by nitrogen fertilization, even if it doesn’t achieve a sufficient value (Tab. 14). Nitrogen fertilization produces significantly higher clippings weight, relative nitrogen content and turf growth. Drought turfgrass tolerance, surface temperature and soil moisture were not influenced by nitrogen fertilization.

Table 14. Turf quality, clippings weight and relative nitrogen content, turf growth. Nitrogen fertilization (mean effect).

Nitrogen fertilization (kg ha^{-1})	Turf quality (1-9)	Clippings weight (g m^{-2})	Nitrogen content (%)	Turf growth (cm)
0	4.2	4.7	2.5	0.8
150	5.4	13.3	3.9	1.5
LSD (0.05)	0.5	5.4	0.6	0.3

Significant different means were separated using Fisher’s Least Significant Difference (LSD) at the P probability level of 0.05.

4.3.2 Water replenishment

Water replenishment influenced significantly all biometric parameters measured except nitrogen content (mean 3.3%). The higher turf quality was visually observed in 159 and 146% of replenishment (6.4), in the areas closer to the central pipe line, although there are no significant differences up to 85% of replenishing water. The quality of the turf is lower in the areas furthest from the pipe (between 3.6 and 1.5) (Tab. 15). The same trend was also observed in the drought turfgrass tolerance. Regarding surface temperature, the highest value was recorded in the two lower replenishing water 18% and 6%, respectively with 31.2 and 32.9 °C, while the temperature progressively decreased closest to the central line. The clippings weight was significantly reduced when the replenishment was lower than 61%. Tall fescue growth has been appreciable only in the areas closer to the pipe. The highest value were recorded from 85 to 159 % of replenishing water (max 2.2 cm). As expected, the soil moisture was progressively decreasing perpendicularly to the LGIS, ranging from 7.8 to 1.4 % (Tab. 15).

Table 15. Turf quality, drought tolerance, surface temperature, clippings weight and relative nitrogen content, turf growth, soil moisture. Replenishing water (mean effect).

Replenishing Water (%)	Turf quality (1-9)	Drought tolerance (1-9)	Surface temperature (°C)	Clippings weight (g m^{-2})	Turf Growth (cm)	Soil moisture (%)
159	6.4	9.0	25.8	12.5	1.8	7.8
146	6.4	9.0	25.9	13.0	2.1	6.9
132	6.3	9.0	25.8	12.2	1.9	6.2
111	6.1	9.0	26.2	10.8	2.2	6.1
85	6.1	9.0	26.1	11.7	2.1	5.1
61	5.8	7.8	27.1	8.8	1.5	3.1
37	3.6	4.0	30.0	3.4	0.8	2.3
18	1.7	1.5	31.2	5.5	0.4	1.9
6	1.5	1.1	32.9	2.2	0.1	1.4
LSD (0.05)	0.4	0.8	0.7	3.5	0.5	0.7

Significant different means were separated using Fisher's Least Significant Difference (LSD) at the P probability level of 0.05.

4.3.3 Correlation among turf quality, drought tolerance and all biometric parameters

Turf quality was positively correlated with drought tolerance (r = 0.88), turf growth (r = 0.73) and negatively with surface temperature (r = - 0.78) (Tab.16). Drought tolerance was found to be negatively correlated with surface temperature (r = - 0.88) and as expected, was positively correlated with soil moisture (r = 0.74). Thus, a good drought tolerance is equivalent of a better turf quality, with lower surface temperatures.

4.3.4 Correlation among turf quality, drought tolerance and some vegetation indices

Comparing turf quality with all the vegetation indices, it is interesting to point that the correlation coefficients (r) with Normalized Difference Vegetation Index (NDVI), Structure Intensive Pigment Index (SIPI), Vegetation Index (VI) and Water Index (WI) were higher than 0.82. All these indices have registered higher values also with drought tolerance, that was highly correlated with NDVI (r = 0.92) and SIPI (r = 0.93). It was found that SIPI, which employs ratios of reflectance at 800, 445 and 680 nm, can be used to accurately estimate the ratio of carotenoids (*Cars*) to chlorophyll *a (Chl a)* (Daughtry et al. 2000; Blackburn, 1998). With high values of *Cars* and chlorophyll *a* turf quality is higher and therefore the drought tolerance is strightly related. WI was also highly correlated with drought tolerance (r = 0.91). Differently from what expected, with normalized difference water index (NDWI), proposed by McFeeters (1996), we observed only a good correlation with drought tolerance (r = 0.71).

Table 16. Pearson correlation coefficients (r) among turf quality, drought tolerance and a) biometric parameters; b) vegetation indices. Correlation coefficients are calculated across all entries.

a) biometric parameters

r	Turf quality	Drought tolerance	Surface temperature	Clippings weight	Nitrogen content	Turf growth	Soil moisture
Turf quality	-	0.88***	- 0.78***	0.63***	0.41**	0.73***	0.65***
Drought tolerance	0.88***	-	- 0.88***	0.50**	0.21ns	0.64***	0.74***

b) vegetation indices

r	NDVI	TCARI	SIPI	Red edge	Red edge posit.	VI	WI	NDWI
Turf quality	0.87***	0.61***	0.87***	0.07ns	0.59***	0.86***	0.82***	0.52***
Drought tolerance.	0.92***	0.80***	0.93***	0.27ns	0.39*	0.88***	0.91***	0.71***

* = Significant at 0.05 level; ** = Significant at 0.01 level; *** = Significant at 0.001 level; ns = Not significant

4.4. Conclusions

This trial has shown the ability of tall fescue to tolerate a deficit irrigation with an amount of water lower than the reference evapotranspiration (ET_0), for a summer period of 3 weeks in a sandy soil. The use of a lesser amount of water and fertilization could provide environmental and economic benefits and this method could allow a target management depending on the real turf needs, less wasteful. Through the application of vegetation indices we evaluated proximity-sensed spectral reflectance of tall fescue. These indices have highlighted high correlations with some of the biometric parameters observed, above all turf quality and drought tolerance. Results showed the best vegetation indices to estimate the water content of a turf of tall fescue, in terms of different levels of water replenishment. In particular the indices with the highest correlations with drought tolerance were Normalized Difference Vegetation Index (r = 0.92), Structure Intensive Pigment Index (r = 0.93) and Water Index (r = 0.91). This research has been useful as preliminary evaluation of spectral remote sensing as a diagnostic tool. In the future it is expected that the information obtained from proximity sensed measurements could be correlated with satellite data to afford different treatments depending on the real needs.