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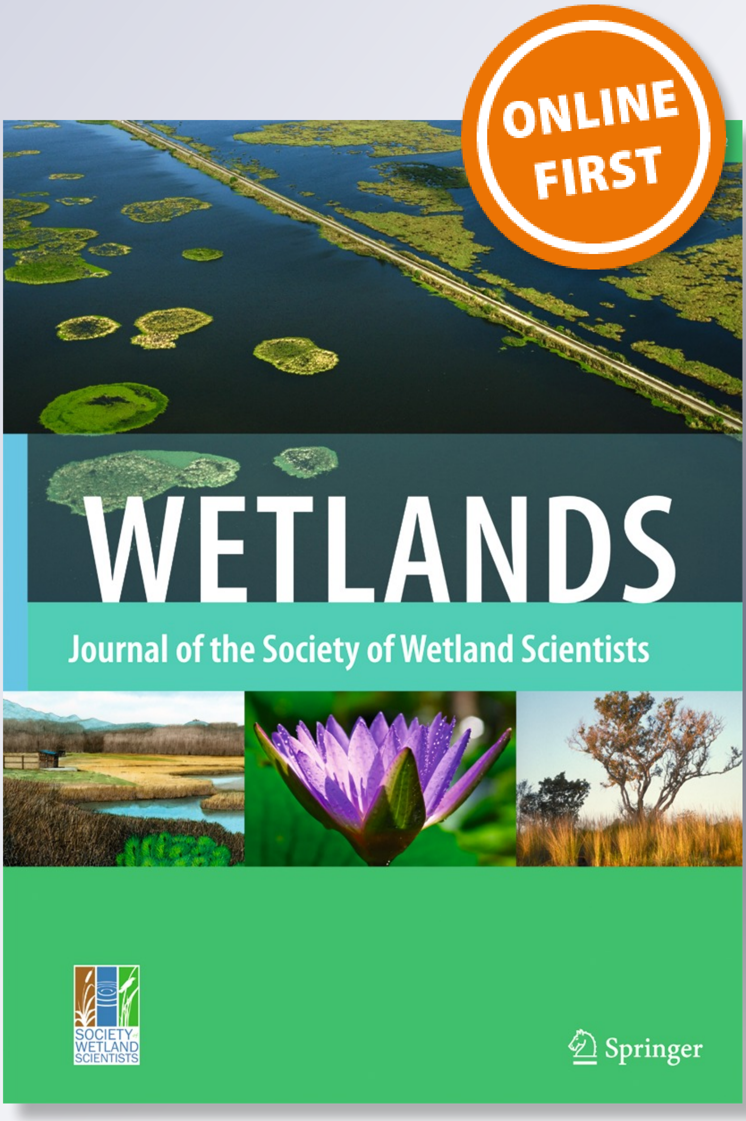

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SHORT COMMUNICATION

Relationship Between Biophysical Parameters and Synthetic Indices Derived from Hyperspectral Field Data in a Salt Marsh from Buenos Aires Province, Argentina

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Abstract Remote sensing tools allow the environmental evaluation of coastal wetlands at a landscape scale, but a deeper understanding is needed of the interactions between biophysical parameters and the electromagnetic signal. The goal of this work was to analyze and quantify the influence of the aboveground biomass and the Leaf Area Index (LAI) on the spectral response of *Spartina densiflora* marshes in Mar Chiquita coastal lagoon, Argentina. Spectral reflectance at high resolution was measured in *S. densiflora* canopies under natural conditions, manipulating standing crop by means of successive harvest. Reflectance data were acquired using a spectroradiometer in visible, near infrared (IR) and shortwave IR bands. Spectral Vegetation Indices (VI) were calculated for each standing crop-LAI situation. Several VI significantly correlated with standing crop and LAI, including indices 1) based on the red-IR edge (IR Index (IRI), 695/760 ratio, Simple Ratio (SR), Red Edge Inflection Point (REIP), and different variations of the Normalized Difference VI (NDVI Rouse, NDVI amber, NDVI NOAA, NDVI Landsat, NDVI Modis), 2) indices based on the sharp change green-IR (green NDVI (GNDVI), 800/550 ratio) and 3) indices with a correction for soil noise (OSAVI: Optimized Soil Adjusted VI (OSAVI), and Modified SAVI (MSAVI). The indices with significant regressions with standing crop and LAI were IRI, $NDVI_{Amber}$ and REIP. The total and green standing crop showed better adjustments than LAI, showing R^2 values of 0.5. These values were obtained with REIP index. Results indicate that LAI and standing crop of *S. densiflora* stands could be determined from spectral data but estimations should be taken carefully in high biomass scenarios, because of indexes saturation at higher LAI values.

Keywords Spectral indices · Remote sensing · Standing crop · Biomass · Leaf area index · *Spartina densiflora*

Introduction

Dissipation of waves and currents, increasing rate of deposition of fine sediments and nutrient uptake are functions commonly attributed to salt marshes These functions result in widely recognized ecosystem services such as the protection of the coastline and improvement of estuarine water quality (Mitch and Gosselink 2000). Because these functions and associated values depend on the ecological integrity of coastal wetlands (Bedford and Preston 1988), it is necessary to find effective indicators for quantitative and expeditive determinations of changes in their environmental health (Klemas 2001).

Landscape-level indicators (O'Neill et al. 1997) become particularly important in studying and comparing the cumulative effects of coastal ecosystem degradation over entire landscapes and regions (Haines-Young et al. 1993). In many cases, these environmental indicators are constructed from parameters that can be estimated by means of remote sensors, allowing considerable savings of time and money, especially if large coastal areas need to be monitored (Klemas 2001).

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Two of the commonly used and accepted parameters for evaluating ecosystem condition are aboveground biomass -or standing crop- and net primary productivity. Rapid changes in these parameters may be signs ecosystem stress (Jensen et al. 1998). However, field estimations of these parameters are particularly difficult for salt marshes, given the highly dynamic nature of intertidal environments, subject to erosion and deposition, and the frequently difficult access to sampling sites. Because of these difficulties, remote sensing monitoring techniques are particularly important (Vis et al. 2003).

Besides biomass, other biophysical parameters such as percent cover and leaf area index (LAI) can also be estimated through the use of remote sensing (Heege et al. 2003), providing a tool for the evaluation of one of the vegetation parameters most often required as an input to ecosystem models (Silva et al. 2008).

The particular radiometric and spectral behavior of vegetation has promoted the development of indices that summarize the information on unique values that reflect their state. The spectral signature characteristic of healthy vegetation shows a clear contrast between visible bands - and especially the red band (R, 600 to 700 nm) - and near infrared (IR, 700 to 1100 nm). While in the visible region, the leaf pigments absorb most of the energy they receive, these substances reflect IR.

Therefore, a noticeable contrast between the high spectral absorption of the red band of the spectrum and high IR reflectance occurs. This contrast is called red edge (Horler et al. 1983) and is directly related to the vigor of the observed plant cover (Fig. 1). Lower contrast values are associated with decreased plant vigor, lower biomass, or lower vegetation cover, with bare soils showing the lowest contrasts. Most widely accepted vegetation indices are based on this principle, and combine reflectance values registered in the R and IR bands of the electromagnetic spectrum. Common indices, such as the Simple Ratio (SR), and the Normalized Difference Vegetation Index (NDVI, Rouse et al. 1974) are derived from the ratio of these bands.

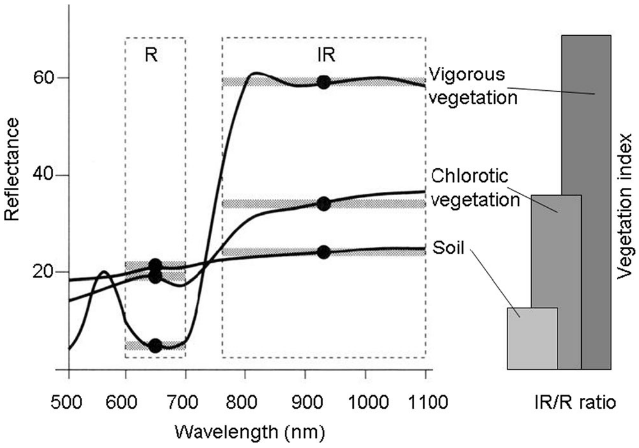

Fig. 1 Characteristic spectral signature of vegetation for portions of the electromagnetic spectrum between 0.5 and 1.1 µm. R = red, IR = infrared

Vegetation indices have been successfully related to several vegetation variables, including leaf chlorophyll content (Sellers 1985). The Fraction of Absorbed Photosynthetically Active Radiation (fAPAR, Asrar et al. 1985), for instance, has a direct and almost linear relationship with NDVI, especially when leaves are horizontal and the ground is sufficiently dark (Sellers 1989). LAI and percent green cover, also have a positive association with NDVI, especially when vegetation cover is less than 100 % (Kennedy 1989). The net productivity of vegetation, related with fAPAR through an efficiency factor for each plant, is also directly related to the NDVI (Sellers 1989). The total standing crop and the dry fraction are closely related with NDVI (Kennedy 1989), as are phenological dynamics, which follow the evolution of these parameters. One limitations of NDVI is that it has an asymptopic relationship with LAI (Sellers 1987) and tends to saturate at LAI values above 4 (Baret et al. 1995). This has led to the development of a number of alternative indices, some of which require the use of hyperspectral data.

The indices that we considered in this work can be organized into three groups: 1) indices based on the red-IR contrast (NDVI, SR, IRI, REIP, 695/760), 2) indices based on the green-IR contrast (GNDVI, 800/550), 3) indices accounting for soil effects (OSAVI, MSAVI); and 4) indices based on the relative green maximum in relation to the absorption valley at red region (PRI1 and PRI2 and TCARI and MCARI). Among these indices, stands out NDVI, based on the contrast between the maximum absorption in the red due to chlorophyll and the maximum reflection in the infrared caused by leaf cell structure. The original formulation of NDVI (Rouse et al. 1974) uses reflectance (ρ) at 864 and 671 nm. NDVIAmber (Solari et al. 2008), is a variant of NDVI that uses ρ at 590 nm (amber region of the spectrum) instead of ρ at 671 nm, and NDVI is usually calculated according to the wavelengths integrated in the red and IR bands of different sensors (NOAA, Landsat and Modis,etc)..

SR (simple ratio, Jordan 1969, Rouse et al. 1974) directly compares the reflection and the pigment absorption peak which means it is sensitive to changes in chlorophyll content (Slater and Jackson 1982). Both NDVI and SR are the structural indices (Eitel et al. 2008), and according to Peñuelas et al. (1993), both correlate with the chlorophyll content and the photosynthetic efficiency of emerged plants biomass. However, the SR compared with NDVI is more influenced by environmental factors such as clouds and the ground (Slater and Jackson 1982).

The IRI (infrared index, Reusch 1997) is an index associated with plant biomass and changes in foliage (Steininger 2000). Sticksel et al. (2004) found that this index was useful for detecting crop parameters agronomically important in wheat, and showed no saturation effects.

Index 695/760, called Carter ratio (Carter 1994, Carter et al. 1996) is a ratio of bands sensitive to vegetation stress

(Van-der-Meer 2003). This ratio, for example, was effective in distinguishing mangrove leaves between stressed and non-stressed condition (Wang and Sousa 2009).

REIP index, defined as the maximum value of the first derivative curve in the region 680–750 nm (Guyot and Baret 1988). This index has been used as a health indicator of foliage and leaf chlorophyll in vascular plants.

GNDVI (Green Normalized Difference Vegetation Index, Gitelson et al. 1996) is an index similar to the NDVI that uses a green band instead of red. Gitelson et al., (1996) found that GNDVI was more sensitive than NDVI to identify different levels of chlorophyll concentration, highly correlated with plant N. Other authors established significant relationships between this index and LAI, biomass, N and chlorophyll content in grasses (Silva et al. 2008).

Ratio 800/550 (Buschman and Nagel 1993) was used as a LAI estimator in corn crop cycle and showed linear relationships (Kemerer et al. 2007), while Inada (1985), meanwhile, showed that this ratio was the most effective estimate of chlorophyll content of rice leaf (Takebe et al. 1990).

MSAVI and OSAVI are indices that minimize the soil noise (Qi et al. 1994), conceptually based on SAVI (Huete et al. 1994), having the advantage of not requiring the a priori data of vegetation cover. The MSAVI (Modified Soil Adjusted Vegetation Index, Qi et al. 1994) has the additional advantage of no saturation at high plant cover (one of the limitations of NDVI, Jiang et al. 2007).

OSAVI (optimized soil adjusted vegetation index, Rondeaux et al. 1996) has, as its main advantage, simplified formulation. In any case, these indices reduce soil noise with the cost of reducing its dynamic range and are slightly less sensitive than the NDVI at low vegetation cover.

The Modified Chlorophyll Absorption in Reflectance Index (MCARI), Transformed Chlorophyll Absorption in Reflectance Index (TCARI) utilize the position of the chlorophyll red-edge. Daughtry et al. (2000) recommended the use of MCARI. There is also a large body of work supporting the use of Photochemical Reflectance Index (PRI) (e.g., Gamon et al., 1997; Peñuelas et al., 1994).

Field radiometry allows ground based estimations of spectral parameters (Trishchenko 2009). The spectral characterization of different land cover types provides useful information for the development, refinement, and evaluation of models that relate biophysical attributes with remote sensed data. Ground measurements obtained at high spectral resolution, and over different portions of the spectrum, allow users to take advantage of the existing satellite information more efficiently. In addition, this information may help developers designing new satellites. In Argentina, the National Space Program includes satellite missions like SAD-D-Aquarius and SAC-E-SABIAMAR, especially designed for marine and coastal applications, which would be greatly improved by making use of field spectral data.

Although hyperspectral data have been widely used in coastal environments for the characterization and creation of models to retrieve biophysical attributes of *Spartina alterniflora* salt marshes (Klemas 2001), there are no previous works in *S. densiflora* marshes.

The purpose of this work was to analyze the influence of the standing crop and Leaf Area Index on the spectral response measured by a field radiometer, in salt marshes dominated by *S. densiflora* at Mar. Chiquita, Argentina. By means of regression models, we analyzed and quantified the relationship between biophysical parameters of interest and commonly used indices derived from multispectral satellite data.

Materials and Methods

Study Site

The Mar. Chiquita coastal lagoon is on the coast of the Buenos Aires Province, Argentina, 26 km north of Mar. del Plata city (37° 32′ to 37° 45′ S and 57° 19′ to 57° 26′ W, Fig. 2). It is located in a temperate zone with a mean annual rainfall of 807.7 mm and a mean annual temperature of 13.8 °C (period 1931–1990, data provided by the Servicio Meteorológico Nacional Argentino).

The Mar. Chiquita lagoon is a brackish waterbody that covers about 60 km^2, with a drainage basin of about 10000 km^2 and affected by 1 m amplitude tides (Marcovecchio et al. 2006). The lagoon is separated from the sea by a barrier dune over 40 km long and connects to the ocean through a single tidal channel.

The intertidal zone is characterized by the presence of extensive salt marshes dominated by *Spartina densiflora* Brong. (Cagnoni 1999, Fig. 3, Table 1). *S. densiflora* is a perennial grass that forms dense clumps and exhibits C4 photosynthetic metabolism, as do all species of this genus. It presents a wide range of environmental tolerance, and can be found from brackish to hypersaline conditions, and intertidal to strictly terrestrial habitats (Vicari et al. 2002). This species is characterized by a caespitose growth form, expanding vegetatively by short tillers or sexually via high seed production (Bortolus 2006).

Spartina densiflora populations are found in middle and upper intertidal zones, including ecotones with adjacent terrestrial ecosystems (Castillo et al. 2000). This distribution pattern is observed both in the Buenos Aires province where this species is native (Bortolus 2006. González Trilla et al. 2010) and in the U.S. and Europe where it is invasive (Castillo et al. 2000.; Nieva et al. 2001)..

The location of this species within the elevation gradient is equivalent to that of *Spartina patens* (Aiton) Muhl. in the

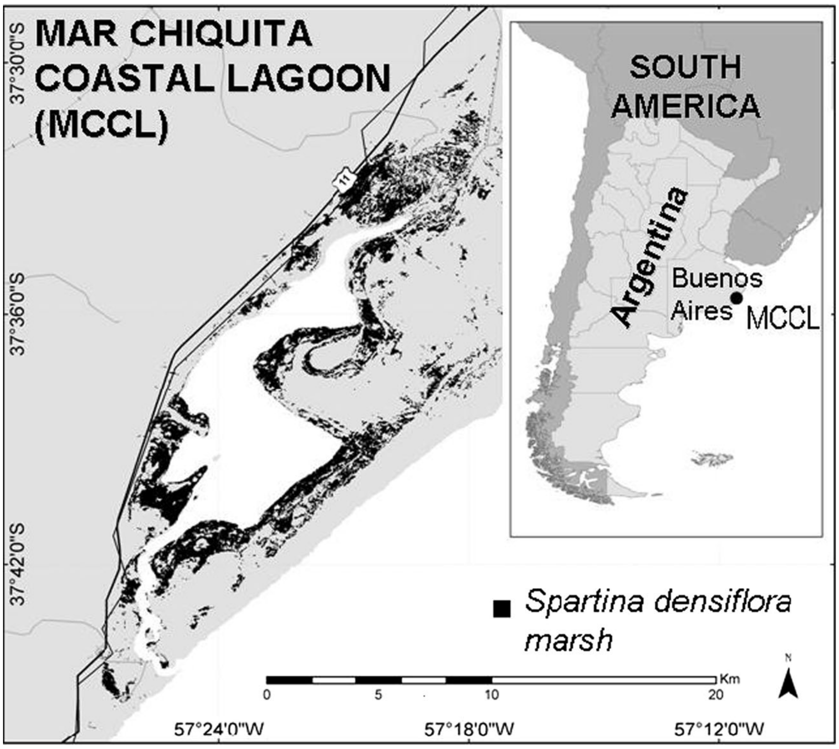

Fig. 2 Study site

northern hemisphere (Mitsch and Gosselink, 1993). In the study area, almost monospecific stands of *S. densiflora* can be found in the upper intertidal zone, and form the lower limit of the salt marsh (Cagnoni 1999. González Trilla et al. 2010). At immidiately higher elevations, pure stands are replaced by a mixed *Juncus acutus* - *S. densiflora* community (Fig. 3), and at even higher elevations, typical pampean grasslands species appear (Cagnoni 1999). The largest area of *S. densiflora* occurs between the mean high tide (MHW) and the mean higher high water (MHHW), or 0.40 to 0.97 m above mean sea level (Fig. 3, Table 1).

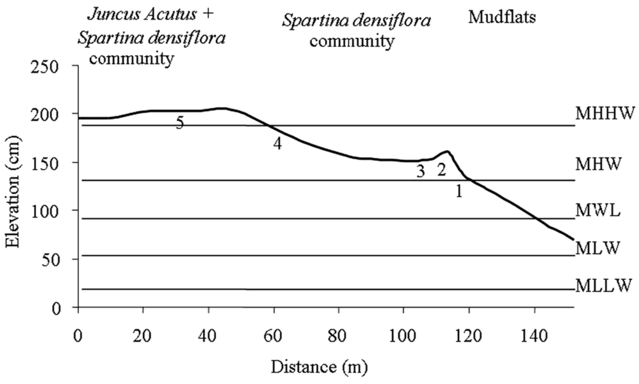

Fig. 3 Topographic profile of the study site. MHHW Mean Higher High Water, MHW Mean High Water, MWL Mean Water Level, MLW Mean Low Water, MLLW Mean Lower Low Water. Local data were referred to the Mar. del Plata tide gauge. Tide gauge data were referred to the study site through measurements of water depth on the ground which were correlated with the height of water in the tide gauge of Mar del Plata

Field Data Collection

Surface reflectance data were obtained using a field spectrometer (FieldSpec® Analytical Spectral Devices, Inc.), which covers the regions of the spectrum between 350 and 2500 nm, with a bandwidth of 1 nm. Regions between 1344 and 1446 nm and between 1799 and 1996 were removed due to noise related to atmosphere absorption in those ranges.

Surface spectral reflectance (ρ for a given wavelength λ) is estimated as the ratio of the energy of wavelength λ reflected by the surface ($\Phi_{r\lambda}$) and the incident energy of wavelength λ ($\Phi_{i\lambda}$).

$$\rho_\lambda = \Phi_{r\lambda}/\Phi_{i\lambda} \tag{1}$$

Simultaneous measurements were performed on the marsh and a barium sulfate (spectralon) surface, which served as a reference target for calibration (surface 99 % reflective). Measurements were performed in February 2009 at 15 field sites where *S. densiflora* is the dominant species. The sampling days were selected in order to have low tide at midday (between 10:00 and 15:00 h). The low tide is necessary to minimize the amount of water in the substrate, while measurement at mid-day is needed to minimize the effect of the solar illumination angle. To avoid the effects of clouds and varying illumination conditions between samples, all measurement were taken under clear sky conditions.

Table 1 Characteristics of the sites referred to in the topographic profile of Fig. 3

Site	Community	Sediment textural group	Mean height (cm)	Standing crop (g m^{-2})	Dead fraction (%)
1	*S. densiflora*	Mud	29	568	5
2	*S. densiflora*	Mud	36	833	23
3	*S. densiflora*	Mud	31	474	42
4	*S. densiflora*	Sandy mud very fine	34	1485	59
5	*S. densiflora* + *J. acutus*	Mud	46	3574	73

To perform measurements, the bare spectroradiometer optical fiber was held in zenith position (viewing angle 0°) at a height of 80 cm above the soil surface (which is always above the canopy), in order to determine a circular area of about 40 cm diameter on the ground (field of view, FOV = 25°). The sampling unit was a circular area of 50 cm diameter, with a centered effective viewing area of 40 cm diameter. The perimetral 10 cm wide ring was considered as a transitional area (Fig. 4).

Biomass and LAI typically show large seasonal variations in temperate regions. To evaluate changes in vegetation cover, avoiding the effects of changing soil conditions (background reflectance) we designed a sampling method based on partial harvests. This sampling technique allows varying standing crop levels, maintaining constant substrate conditions. Aboveground biomass/LAI was manually modified in each sample unit by successive partial harvests, performed by removing whole stems. Each 50 cm diameter plot started with full standing crop (state 1) and was successively harvested until it reached a final status of bare soil (state 5). For most sites, the number of stems was roughly estimated at the full standing crop state, and a 25 % of the original number of stems was removed in each successive harvest (commonly between 200 and 400 stems). In sites with low biomass/plant cover, we established a minimum number of 200 stems per harvest. Accordingly, a higher percent of stems was removed per harvest, and the number of harvests (states) was reduced. The exact number of stems and the amount of biomass removed in every harvest was determined a posteriori.

The harvested shoots were stored in plastic bags and taken to the laboratory, where the standing crop LAI and other biophysical variables were determined, for all sites and all standing crop levels (sites and states). The variables considered were:

Plant Height: the mean and maximum length of the stems present in the plot, obtained from measurements of individual tiller heights.

Density: the number of stems present in the plot per unit area (m^2).

Total and green standing crop, dry fraction: Total standing crop was estimated from the dry weight (after dried in a 70 °C oven up to constant weight) of both green (live) and dead plant parts, while green standing crop was estimated using only the green parts. Both data were expressed in g m^{-2}, while the dry fraction was expressed as a percentage of total harvest.

Leaf Area Index (LAI) was estimated as the sum of live leaf areas present in the plot, divided by plot area. For this species, González Trilla et al. (2013) developed a regression equation to relate the area of a leaf with its length (Eq. 2). The equation was constructed from measurements performed on 385 individual leaves, from different

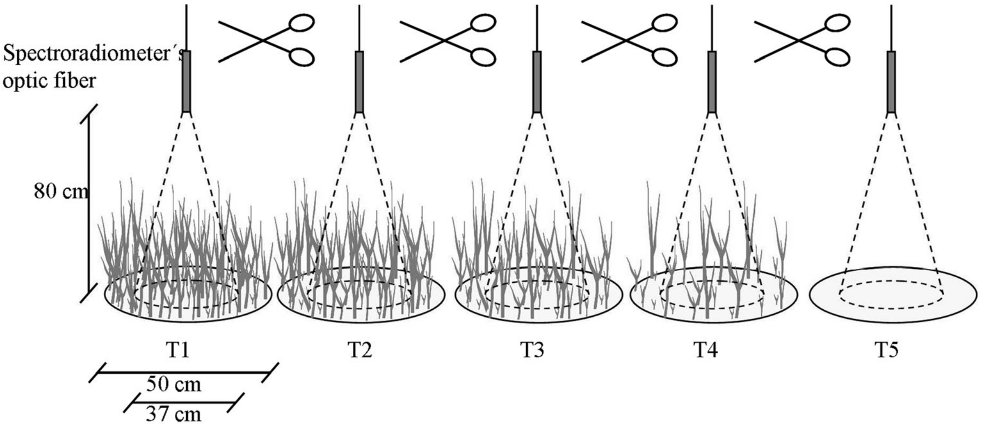

Fig. 4 Sampling design with partial successive harvests specially developed for this work. The spectral reflectance of the same site at different times (T1... T5) was determined. Between two consecutive times tillers were randomly harvested diminishing standing crop from an initial high value at T1 to a final zero standing crop scenario (bare soil, T5). Scissors represent random harvests.

stems, randomly collected within this same marsh. Green leaf area was estimated by measuring the length of all green leaves present on each stem harvested, and applying Eq. 2 (a is the area of a leaf, measured in cm^2, and l is its length, measured in cm) González Trilla et al. 2013):

$$
\begin{aligned}
a &= 0,2213 \times l - 0,2761 \\
\mathrm{R}^2 &= 084; \mathrm{N} = 385
\end{aligned}
\qquad (2)
$$

Various synthetic indices used in the literature (Table 2) were estimated from the reflectance signatures. The indices were related to the field vegetation data to determine their sensitivity in the estimation of biophysical parameters. Correlation analysis was used to evaluate the linear association between indices, standing crop, and LAI. Regression analysis was performed to build regression equations between each index and the biophysical parameters (Sokal and Rohlf 1995).

Results

Visited field sites had mean tiller heights ranging from 26 to 51.1 cm and maximum heights ranging from 76 to 118 cm. Stem densities ranged from 1174 to 8500 shoots m^{-2}, percentage of vegetation cover ranged from 51 to 100 %, LAI from 1.21 to 3.67, standing crop values ranged from 147.6 to 2075.6 g m^{-2} and dried fraction values from 52 to 71.1 %.

Variables related to plant structure were highly correlated among themselves (Table 3), particularly total and green standing crop, and LAI The dry fraction, on the other hand, did not show a high correlation with any other variables. LAI and green standing crop correlated

Table 2 Indices calculated in this study

Index	Index equation	Author
$\mathrm{NDVI}_{\mathrm{Rouse}}$	(ρ864 - ρ671)/(ρ864 + ρ671).	Kriegler et al. (1969),
$\mathrm{NDVI}_{\mathrm{NOAA}}$	(Avρ720–1100) - Avρ580–680)/(Avρ720–1100 + Avρ580–680)	Rouse et al. (1974)
$\mathrm{NDVI}_{\mathrm{Landsat}}$	(Av ρ760–900 - Avρ630–690)/(Av ρ760–900 + Avρ630–690)	
$\mathrm{NDVI}_{\mathrm{Modis}}$	(Av ρ841–876 - Avρ620–670)/(Av ρ841–876 + Avρ620–670)	
$\mathrm{NDVI}_{\mathrm{Amber}}$	(ρ864 - ρ590)/(ρ864 + ρ590).	
GNDVI_1	(ρ800 - ρ550)/(ρ800 + ρ550)	Gitelson et al. 1996
GNDVI_2	(ρ780 - ρ550)/(ρ780 + ρ550)	Gitelson et al. 1996
$\mathrm{GRDI}_{\mathrm{range}}$	(ρ555– ρ670)/(ρ555+ ρ670)	Gitelson et al. 1996
$\mathrm{GRDI}_{\mathrm{range}}$	(Av ρ545–565 – Avρ660–680)/(Av ρ545–565 + Avρ660–680)	
IRI	ρ740/ρ730	Reusch (1997)
$\mathrm{VARI}_{\mathrm{green}}$	(Av ρ545–565 – Avρ660–680)/(Av ρ545–565 + Avρ660–680- Avρ470–490)	Gitelson et al. 2002
PRI 1	(ρ529 – ρ569)/(ρ529 + ρ569).	Gamon et al. (1992)
PRI 2	(ρ570 – ρ531)/(ρ570 + ρ531).	Gamon et al. (1992)
WBI	ρ900/ρ970	
MCARI	(ρ700 - ρ670) - 0.2 (ρ700 - ρ550) (ρ700/ρ670)	Daughtry et al. (2000)
TCARI	3 ((ρ700 - ρ670) - 0.2 (ρ700 - ρ550) (ρ700/ρ670))	Haboudane et al. (2002)
MSAVI	$0.5\ (2\ \rho800 + 1 - \sqrt{(2\ \rho800 + 1)^2 - 8\ (\rho800 - \rho670)})$	Qi et al. (1994)
695/420	ρ695/ρ420	Carter (1994)
695/760	ρ695/ρ760	Carter et al. (1996)
800/550	ρ800/ρ550	(Buschman and Nagel 1993
REIP	700 + 40 ((ρ670 + ρ780)/2 - ρ700)/(ρ740 - ρ700)	Guyot and Baret 1988).
OSAVI	(1 + 0.16) (ρ800 – ρ670)/(ρ800)	Rondeaux et al. (1996)
SR	ρ800/ρ670	Jordan (1969); Rouse et al. (1974)

AV: Average, *R*: reflectance in the corresponding wavelength. *ρ*: reflectance, *Av*: average, mean value for the wavelenght interval indicated. $\mathit{NDVI}_{\mathit{Rouse}}$: Normalized Difference Vegetation Index as ascribed by Rouse et al. (1973); $\mathit{NDVI}_{\mathit{NOAA}}$, $\mathit{NDVI}_{\mathit{Landsat}}$, $\mathit{NDVI}_{\mathit{Modis}}$: Normalized Difference Vegetation Index calculated for NOAA, Landsat and Modis data; *GNDVI*: Green *NDVI;*$\mathit{GRDI}_{\mathit{range}}$: Green Red Difference Index; *IRI*: Infrared Index; $\mathit{VARI}_{\mathit{green}}$: Visible Atmospherically Resistant Index; *PRI*: Photochemical Reflectance Index; *WBI*: Water Band Index; *MCARI*: Modified Chlorophyll Absorption in Reflectance Index; *TCARI*: Transformed CAR Index; *MSAVI*: Modified Soil Adjusted Vegetation Index; *REIP*: Red Edge Inflection Point; *OSAVI*: Optimized Soil-Adjusted Vegetation Index; *SR*: Simple Ratio

Table 3 Correlations between structural variables of the vegetation

	Total standing crop	Green standing crop	Dead fraction (%)	Max. height	Mean height	Density	LAI
Total standing crop	**1,00**	**0,99**	**0,42**	**0,73**	**0,70**	**0,72**	**0,94**
Green standing crop		**1,00**	0,34	**0,74**	**0,71**	**0,72**	**0,96**
Dead fraction (%)			**1,00**	**0,43**	**0,43**	0,23	0,23
Max. height				**1,00**	**0,83**	0,24	**0,61**
Mean height					**1,00**	0,18	**0,59**
Density						**1,00**	**0,84**
LAI							**1**

Significative correlations at $\alpha = 0.05$ are shown in bold. N = 53

to the same indices and, although they were correlated with most indices, the coefficients were generally moderate.

For total standing crop, the indices showing the highest correlation coefficients were R695/R760, IRI, $\text{NDVI}_{\text{Amber}}$ and REIP, with correlation coefficients between 0.6 and 0.73. For LAI, the strongest correlations were with the R695/R760, IRI, and $\text{NDVI}_{\text{Landsat}}$ and $\text{NDVI}_{\text{Amber}}$ indices, with correlation coefficients between 0.63 and 0.76 (Table 4).

The indices that had higher correlation coefficients were IRI, REIP and $\text{NDVI}_{\text{Amber}}$ (Table 5), with total and green sanding crops, and LAI. Regression models derived from these same indices were all significant and logarithmic. Total and green standing crops were the biophysical variables with

Table 4 Correlations between structural variables of the vegetation and several vegetation indices derived from hyperspectral data

	Total standing crop	Green standing crop	Dead fraction (%)	Max. height	Mean height	Density	LAI
$\text{NVDI}_{\text{Rouse}}$	**0,56**	**0,59**	0,28	**0,57**	**0,59**	**0,52**	**0,63**
$\text{NVDI}_{\text{NOAA}}$	**0,40**	**0,40**	**0,37**	**0,61**	**0,62**	0,25	**0,35**
$\text{NVDI}_{\text{Landsat}}$	**0,56**	**0,59**	0,27	**0,57**	**0,58**	**0,51**	**0,63**
$\text{NVDI}_{\text{Modis}}$	**0,55**	**0,58**	0,31	**0,62**	**0,63**	**0,48**	**0,60**
GNDVI 1	**0,42**	**0,44**	0,25	**0,61**	**0,58**	0,29	**0,43**
GNDVI 2	**0,43**	**0,45**	0,23	**0,59**	**0,56**	0,30	**0,44**
GRDI	**0,39**	**0,41**	−0,08	−0,17	−0,11	**0,57**	**0,52**
$\text{GRDI}_{\text{Range}}$	**0,38**	**0,40**	−0,09	−0,19	−0,11	**0,57**	**0,52**
$\text{VARI}_{\text{Green}}$	**0,40**	**0,43**	−0,07	−0,16	−0,08	**0,59**	**0,54**
PRI 1	0,32	0,33	0,15	0,18	0,07	0,28	0,33
PRI 2	**−0,33**	**−0,34**	**−0,20**	**−0,23**	**−0,13**	**−0,38**	**−0,34**
WBI	−0,21	−0,17	**−0,71**	**−0,35**	**−0,56**	−0,02	−0,02
MCARI	0,04	0,05	−0,31	**−0,45**	**−0,39**	0,29	0,14
TCARI	−0,07	−0,07	**−0,34**	**−0,46**	**−0,42**	0,16	−0,01
695/420	−0,05	−0,07	0,19	**0,33**	0,28	−0,24	−0,19
695/760	**−0,62**	**−0,65**	−0,19	**−0,53**	**−0,54**	**−0,61**	**−0,72**
800/550	**0,42**	**0,45**	0,22	**0,61**	**0,58**	0,25	**0,42**
OSAVI	**0,50**	**0,52**	0,01	0,26	0,29	**0,56**	**0,59**
SR	**0,56**	**0,59**	0,17	**0,49**	**0,48**	**0,50**	**0,63**
MSAVI	**0,44**	**0,45**	−0,07	0,12	0,15	**0,51**	**0,51**
IRI	**0,69**	**0,73**	0,26	**0,70**	**0,68**	**0,56**	**0,76**
REIP	**0,59**	**0,60**	**0,40**	**0,80**	**0,77**	**0,40**	**0,57**
$\text{NDVI}_{\text{Amber}}$	**0,66**	**0,70**	0,28	**0,73**	**0,71**	**0,55**	**0,72**
REP	0,01	0,01	**0,53**	**0,75**	**0,71**	0,12	0,14

Correlations shown in bold were significative at $\alpha = 0.05$. N = 53

Table 5 Regression equations between total and green standing crop, and LAI (Leaf Area Index) and several vegetation indices derived from hyperspectral data

	Total standing crop	Green standing crop	LAI
IRI	$y = 0{,}0131\mathrm{Ln}(x) + 0{,}9914$ $R^2 = 0{,}4137$	$y = 0{,}0148\mathrm{Ln}(x) + 0{,}9965$ $R^2 = 0{,}4361$	$y = 0{,}018\mathrm{Ln}(x) + 1{,}0611$ $R^2 = 0{,}3413$
REIP	$y = 1{,}6678\mathrm{Ln}(x) + 709{,}9$ $R^2 = 0{,}5065$	$y = 1{,}8313\mathrm{Ln}(x) + 710{,}83$ $R^2 = 0{,}5003$	$y = 2{,}0756\mathrm{Ln}(x) + 718{,}86$ $R^2 = 0{,}3407$
$\mathrm{NDVI}_{\mathrm{Amber}}$	$y = 0{,}0288\mathrm{Ln}(x) + 0{,}0362$ $R^2 = 0{,}4447$	$y = 0{,}0326\mathrm{Ln}(x) + 0{,}0479$ $R^2 = 0{,}4651$	$y = 0{,}039\mathrm{Ln}(x) + 0{,}1901$ $R^2 = 0{,}3535$

All regressions were significative at $\alpha = 0.05$

highest R^2 values (from 0.41 to 0.5 for total standing crop, and from 0.43 to 0.5 for green standing crop). LAI showed lower values, with a maximum R^2 of 0.35 for $\mathrm{NDVI}_{\mathrm{Amber}}$.

Discussion

Sampled sites showed wide variability in the biophysical parameters considered. In all cases, the dry fraction exceeded 50 % of the standing crop, reaching maximum values of 71.1 %. High levels of dry standing crop in these marshes have previously been reported (e.g. González Trilla et al. 2010) and are related to a combination of the high primary productivity of the species (Vicari et al. 2002) and the low energy of the environment. Tidal currents are a major force that removes dry matter in these systems (Nieva et al. 2001), and marshes in the study area occupy a relatively high position in the topographic profile, with a low tidal exposure.

Several of the biophysical vegetation variables were correlated with each other, in particular, green and total standing crop, and LAI. The close relationship between LAI and standing crop has been reported by several authors (e.g. Sun et al. 2009) and is closely related to the electromagnetic energy interception surface. Since these parameters are correlated, they can be estimated from one another.

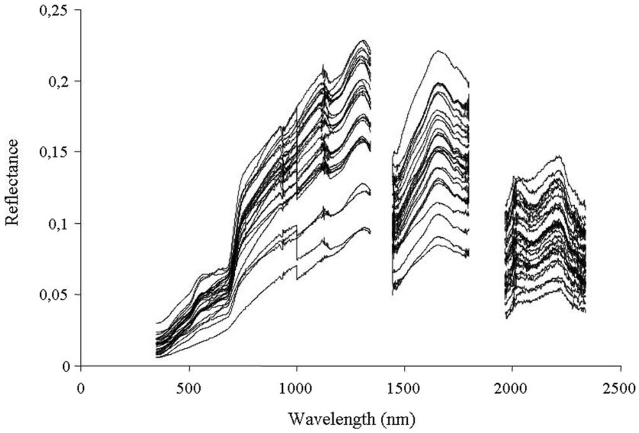

Fig. 5 *Spartina densiflora* spectral signatures recorded with a field radiometer

The spectral signatures registered with the field radiometer (Fig. 5) showed a smooth profile in relation to the expected signature for vegetation (Jakubauskas et al. 2000). In all cases signatures showed low values in the visible region while the relative maximum in the green portion was absent or almost imperceptible. This fact can be related to low levels of photosynthetic pigments in the plot becouse of the high proportion of dead material. A Red edge is clearly present in the red-IR region, although the maximum reflectance values achieved in the IR portion of the spectrum are relatively low.

A large number of indices showed significant correlations with the variables describing vegetation structure, particularly with the green and total standing crop, and LAI. The dry fraction was significantly correlated with WBI (Water Band Index), which is the ratio between reflectance at 900 and 970 nm (Peñuelas et al. 1993; Gamon and Qiu 1999). This later index is associated with plant water content (Sims and Gamon 2002), particularly in green leaves (Peñuelas et al. 1993) and can also be an indicator of leaf area (Gamon and Qiu 1999; Claudio et al. 2006). According to Claudio et al. (2006), WBI is significantly correlated with NDVI, revealing a strong relationship between water content of tissues and the structure of the green canopy. Frank and Menz (2003) also suggest the WBI as an alternative indicator of green vegetation.

According to the literature, one of the constraints of NDVI is that it saturates at high LAI values (generally higher than 4) presenting an asymptotic relationship (Baret et al. 1995; Sellers 1987). Several authors have suggested the advantage of IRI and REIP indices, which showed linear relationships without a saturation effect (Sticksel et al. 2004).

In this work, REIP, NDVI and IRI all showed logarithmic regressions with standing crop and LAI, which limits their application. However, it should be mentioned that no previous work has been done on the estimation of these parameters with vegetation indices for *S. densiflora* marshes, and this work lays the groundwork for future studies. These estimates may be useful for monitoring standing crop in salt marshes dominated by this specie, either in South America where it is native, or in United States and Spain, where it is invasive. In these other regions, the results should be further calibrated with local data.

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