

# Seasonal landscape and spectral vegetation index dynamics in the Brazilian Cerrado: An analysis within the Large-Scale Biosphere–Atmosphere Experiment in Amazônia (LBA)

L.G. Ferreira<sup>a,\*</sup>, H. Yoshioka<sup>a</sup>, A. Huete<sup>a</sup>, E.E. Sano<sup>b</sup>

<sup>a</sup>Department of Soil, Water, and Environmental Science, University of Arizona, Tucson, AZ 85721, USA

<sup>b</sup>Brazilian Agricultural Research Organization (Embrapa Cerrados), BR-020, Km 18, Cx. Postal 08223, Planaltina-DF, 73301-970, Brazil

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## Abstract

The Brazilian Cerrado biome comprises a vertically structured mosaic of grassland, shrubland, and woodland physiognomies with distinct phenology patterns. In this study, we investigated the utility of spectral vegetation indices in differentiating these physiognomies and in monitoring their seasonal dynamics. We obtained high spectral resolution reflectances, during the 2000 wet and dry seasons, over the major Cerrado types at Brasília National Park (BNP) using the light aircraft-based Modland Quick Airborne Looks (MQUALS) package, consisting of a spectroradiometer and digital camera. Site-intensive biophysical and canopy structural measurements were made simultaneously at each of the Cerrado types including Cerrado grassland, shrub Cerrado, wooded Cerrado, Cerrado woodland, and gallery forest. We analyzed the spectral reflectance signatures, their first derivative analogs, and convolved spectral vegetation indices (VI) over all the Cerrado physiognomies. The high spectral resolution data were convolved to the MODIS, AVHRR, and ETM<sup>+</sup> bandpasses and converted to the normalized difference vegetation index (NDVI) and the enhanced vegetation index (EVI) to simulate their respective sensors. Dry and wet season comparisons of the measured biophysical attributes were made with the reflectance and VI data for the different Cerrado physiognomies. We found that three major domains of Cerrado could be distinguished with the dry and wet season spectral signatures and vegetation indices. The EVI showed a higher sensitivity to seasonality than the NDVI; however, both indices displayed seasonal variations that were approximately one-half that found with the measured landscape green cover dynamics. Inter-sensor comparisons of seasonal dynamics, based on spectral bandpass properties, revealed the ETM<sup>+</sup>-simulated VIs had the best seasonal discrimination capability, followed by MODIS and AVHRR. Differences between sensor bandpass-derived VI values, however, varied with Cerrado type and between dry and wet seasons, indicating the need for inter-sensor VI translation equations for effective multi-sensor applications.

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## 1. Introduction

The Brazilian Cerrado is the largest region of neotropical savanna vegetation in the world, covering approximately 45% of South America. It is among the most humid of the world's savannas with a conspicuous seasonal contrast observed between the dry and rainy seasons. Approximately 90% of the rainfall is concentrated during the months of October through April while the dry season has close to zero rainfall in some months with air humidity

less than 20% in August and September (Castro, Moreira, & Assad, 1994). The strong seasonality in climate, accompanied with extreme soil nutrient impoverishment, high Al toxicity, and the widespread occurrence of fires has imposed enormous environmental pressures on the Cerrado biome. This has resulted in a wide range of adaptive, phenological strategies, and a rich biome of land cover types and biodiversity (Ratter, Bridgewater, Atkinson, & Ribeiro, 1996; Ratter, Ribeiro, & Bridgewater, 1997). Thick xeromorphic leaves, protective barks, and an extensive lateral and vertical root network provide adaptations to the strong seasonal rainfall. The grass species further possess protective lower stems to allow rapid recovery from drought and many plant species have underground

\* Corresponding author.

E-mail address: [laerte@iesa.ufg.br](mailto:laerte@iesa.ufg.br) (L.G. Ferreira).

lignotubers permitting immediate growth at the onset of the rains (Eiten, 1993).

The Cerrado biome comprises a vertically structured mosaic of grassland, shrubland, and woodland. Unlike the drier savannas, the majority of Cerrado trees and shrub species are mesophyllous and lack a distinctive leaf drop in their phenology. They metabolize throughout the year, drawing on soil water reserves and moisture stored within the rooting zone (Sarmiento, 1983). The strong seasonal variations in rainfall induce large seasonal fluctuations in energy, water, and carbon fluxes (Grace, 2000). Vourlitis et al. (2000) found the dense Cerrado woodland canopies within the Cerrado/seasonal tropical forest ecotone region to be a carbon source at the onset of the wet season (October–November) and a carbon sink for the remainder of the wet season. The more common *stricto sensu* Cerrado type (dense shrubs with a grass understory) behaves as a substantial carbon dioxide sink during the wet season and a carbon source during the brief, peak of the dry season period (Miranda et al., 1997; Monteiro, 1995). Our ability to assess the capacity of the Cerrado biome to sequester and store carbon dioxide is greatly dependent on our understanding of the distinct seasonality behavior of the different physiognomies within the Cerrado biome.

The Brazilian Cerrado is the second most important biome in South America and has been subject to the most rapid land conversion in Brazil exceeding that of the tropical forests (Sano, Barcellos, & Bezerra, *in press*; Skole, Chomentowski, Salas, & Nobre, 1994). In the context of the Amazon region, it becomes crucial to understand Cerrado dynamics and its potential to influence the regional energy, water, and carbon balances within the Cerrado biome as well as adjacent forests of Amazônia. The Cerrado provides a valuable endpoint from which climate and anthropogenic related forcings in the Amazon forests may be better understood.

Effective monitoring of the Brazilian Cerrado will most likely involve both moderate and fine resolution satellite sensors. The moderate resolution imaging spectroradiometer (MODIS) was recently launched onboard the Earth Observing System (EOS) Terra platform and provides a suite of vegetation products useful for terrestrial ecosystem studies (Justice et al., 1998; Running et al., 1994). Two MODIS vegetation indices, the normalized difference vegetation index (NDVI) and the enhanced vegetation index (EVI), are produced at 250 m, 500 m, and 1 km resolutions with 16-day compositing periods and are designed for change detection, land conversion, and seasonal and inter-annual monitoring of the Earth's vegetation. The MODIS NDVI product has the potential to extend the existing 20+-year NOAA-AVHRR-derived NDVI time series of global vegetation dynamics and offers many opportunities to analyze vegetation dynamics of Amazônia and the surrounding Cerrado region. The Landsat ETM<sup>+</sup> sensor enables close-up studies of land surface changes within the Cerrado with 30-m spatial resolution and in synergy with MODIS pro-

vides improved opportunities for land surface characterization and continuous monitoring of the entire Amazon region and surroundings.

In this study, we investigated the utility of spectral vegetation indices in differentiating the Cerrado physiognomies and in monitoring their seasonal dynamics within the Cerrado biome. A comparison of dry–wet seasonal dynamics for the major Cerrado physiognomies were made with high spectral resolution reflectances and with convolved MODIS, AVHRR, and ETM<sup>+</sup> bandpass versions of vegetation indices. Our objective was to better understand Cerrado landscape dynamics and the ability of remote sensing data to characterize seasonality and inter-annual variations. We also explored inter-sensor relationships with the MODIS, ETM<sup>+</sup>, and AVHRR sensors for time series, continuity, and sensor synergy applications for monitoring Cerrado seasonal behavior.

## 2. Experimental design

### 2.1. Study area

Two intensive field campaigns were conducted within Brasilia National Park (BNP), from April 16th through May 5th (wet season) and from July 17th through July 20th (dry season). Brasilia National Park is the largest Large-Scale Biosphere–Atmosphere Experiment in Amazônia (LBA) core site in the Cerrado biome and comprises an area of approximately 30,000 ha in the northern Federal District, Brazil, between 15°35' and 15°45' south latitude and 47°53' and 48°05' west longitude (Fig. 1). This site encompasses the major savanna formations encountered in the Cerrado biome, including the transitions from the dominant herbaceous stratum (savanna grassland and shrub savanna) to the more complex, woody dominated stratum (wooded savanna and the savanna woodland) (Ribeiro & Walter, 1998). Fig. 2 shows the strong seasonal patterns in monthly precipitation observed at BNP for the years 1999, 2000, and the average of the last 10 years.

### 2.2. Airborne data

The data analyzed in this paper were acquired with the MODLAND Quick Airborne Looks (MQUALS) package, consisting of a spectroradiometer<sup>1</sup> operating within the range, 269–1068 nm, with a 1.6-nm sampling interval and 2.5-nm full-width half-maximum, a GPS, and a visible digital camera (Huete et al., 1999). The instruments were attached to an ultra-light aircraft and flown over the study area, over the 2000 growing season, on May 5 (wet season) and July 18 (dry season) to acquire top-of-the canopy, nadir reflectance values, and digital images over

<sup>1</sup> HandHeld FieldSpec (Analytical Spectral Devices, Boulder, CO).

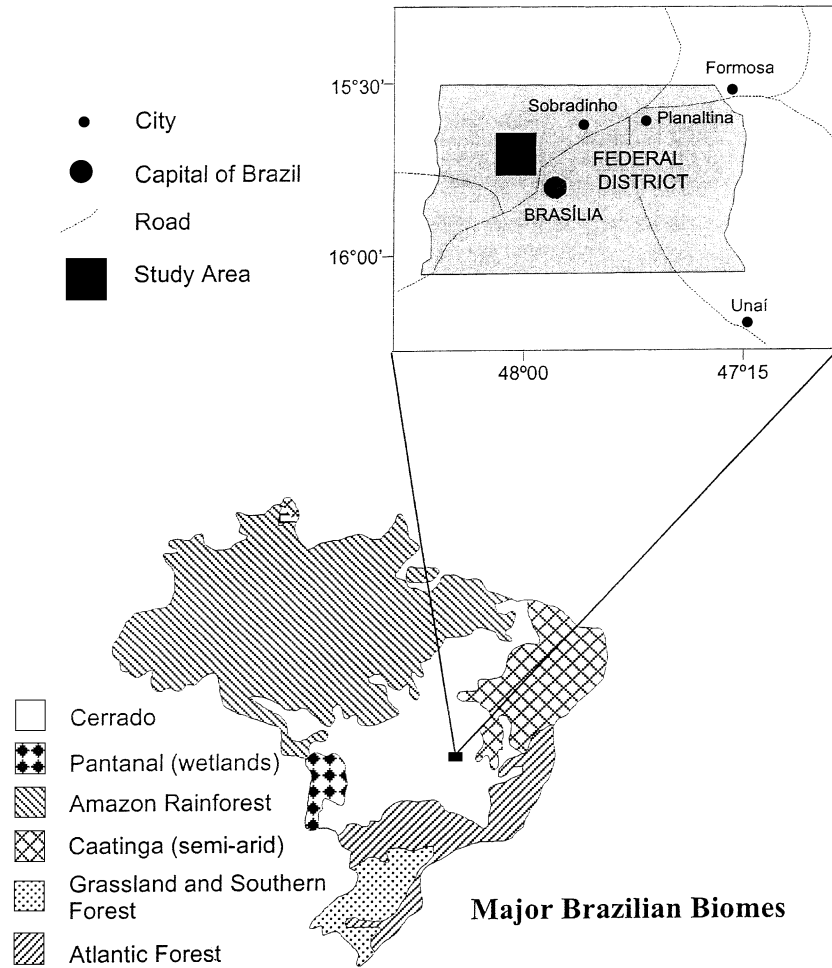


Fig. 1. The major Brazilian biomes and location of the study area (Brasilia National Park).

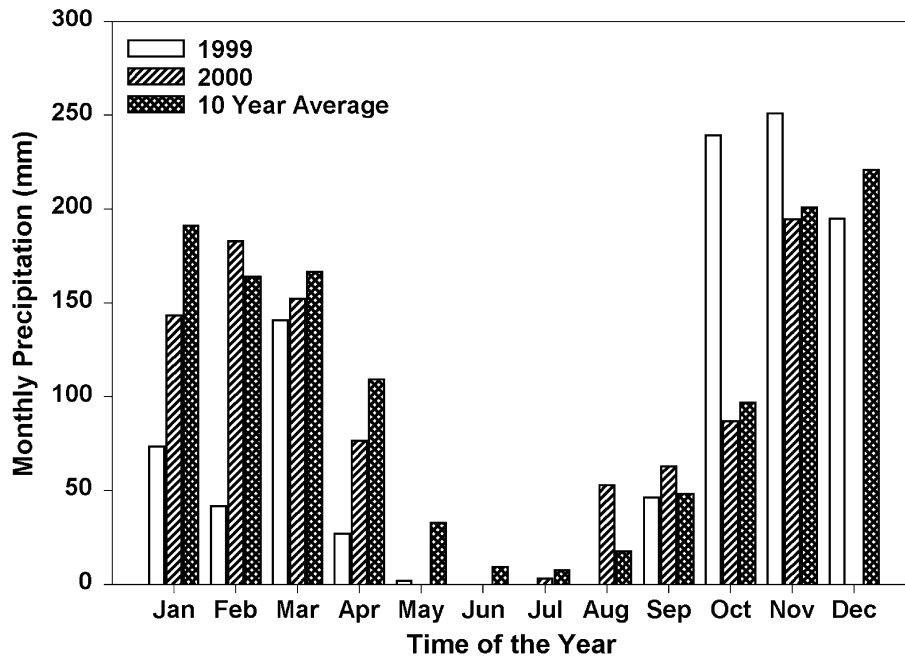


Fig. 2. Monthly precipitation pattern at Brasilia National Park for 1999, 2000, and the average of the last 10 years.

the major Cerrado physiognomies (Cerrado grassland, shrub Cerrado, wooded Cerrado, Cerrado woodland) and gallery forest.

The ultra-light flew at 200 m above ground level, hence atmospheric influences were negligible, at an average speed of about 25 m/s such that all the five sites could be sampled within a 1-h interval at nominal solar zenith angles of 41° and 44°, respectively, for wet (May 5) and dry (July 18) seasons. The spectroradiometer sampled with a 10° field-of-view and integration time of 68 ms, recording an average of three readings every three seconds. This resulted in approximate ground samplings of 35 m diameter, sampled at intervals of 25 m along the flightline. The onboard GPS allowed us to geolocate all measurements and to precisely fly over the field biophysical sampling sites established at four of the Cerrado formations (Fig. 3). A minimum of 11

spectral readings and four digital images were acquired for each site (Fig. 4).

2.3. Biophysical data

Linear transects of 250 m length were established at each Cerrado type for biophysical and structural canopy analyses. Ground measurements included height and spacing of both the herbaceous and arbustive/arborescent layers, as well as percent cover estimations of green grass, standing litter, woody plants, and bare soil, recorded at 1-m intervals. Percent green cover values of the Cerrado canopies were also made from the airborne, nadir-look digital pictures and understory green cover estimates were also derived from nadir-view digital pictures taken along the transects at 10-m intervals from 1 m height. These pictures were split into

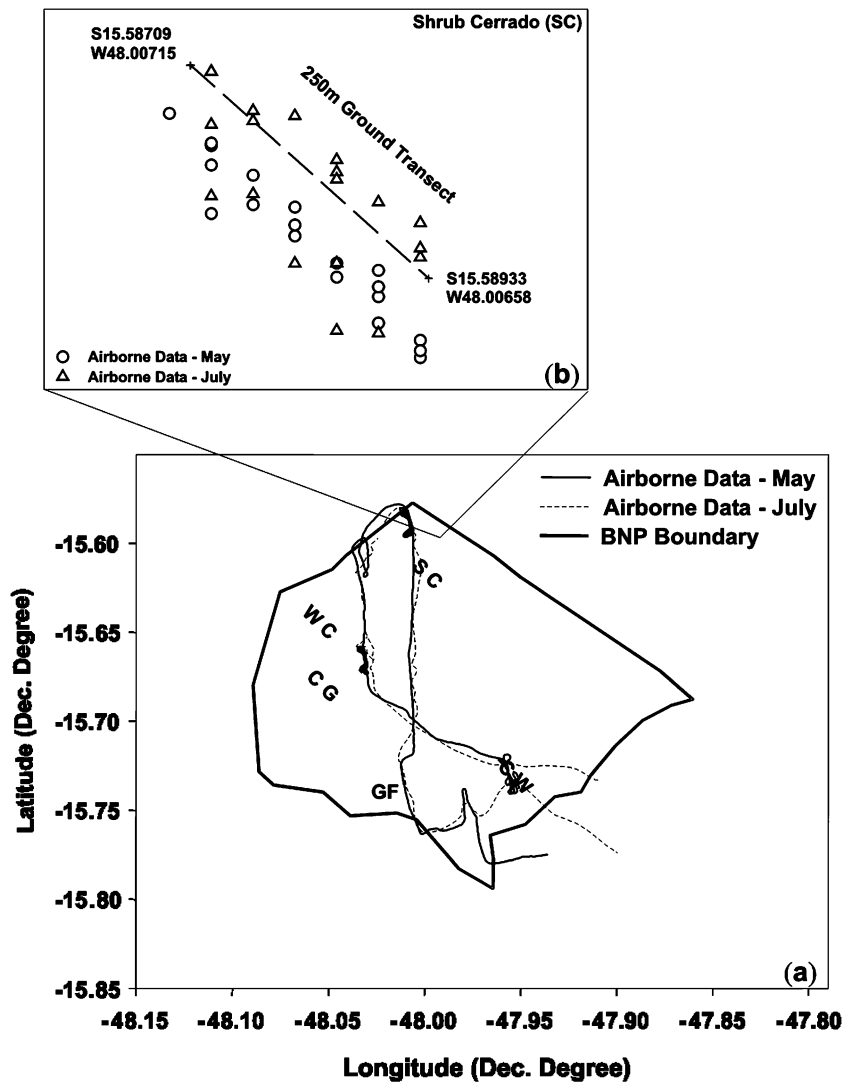


Fig. 3. MQUALS data acquisition over Brasilia National Park and over the five vegetation communities investigated in this study (a) (Cerrado grassland—CG, shrub Cerrado—SC, wooded Cerrado—WC, Cerrado woodland—CW, and gallery forest—GF). The airborne and ground data-sampling scheme is highlighted for the shrub Cerrado site (b).

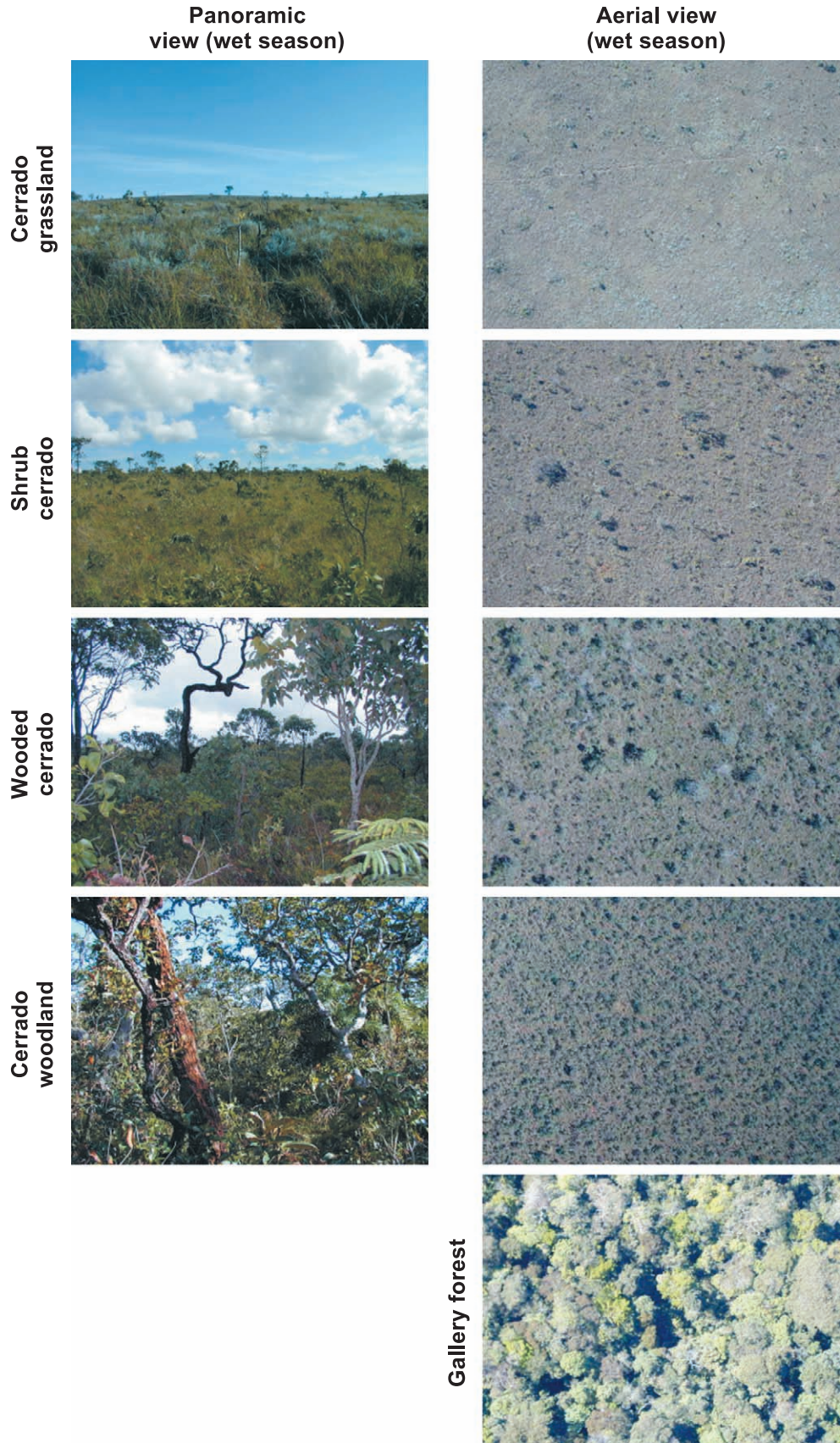


Fig. 4. Ground and aerial views (wet season) of the major physiognomies found at Brasilia National Park.

their R G B bands from which a ‘greenness’ threshold was applied.

#### 2.4. Reflectance retrieval and analysis approach

The retrieval of top of canopy reflectances was accomplished by ratioing the spectroradiometer voltage output to that obtained over a calibrated spectralon panel standard and adjusted to the sun-angle-dependent reflectance of the panel. Reference panel measurements were made at the airport prior to and immediately following the 1-h overflights and a time-based weighted average was used to compute reflectances. A second spectralon panel and Exotech radiometer were also used in the field to continuously record site irradiance and provide a quality check on the reflectance computations.

The atmospheric free, nadir-looking reflectance data were then convolved to the MODIS, ETM<sup>+</sup>, and AVHRR (NOAA 11) bandpass filters (Fig. 5) and converted to the NDVI and the EVI according to the following equations:

$$\text{NDVI} = \frac{\rho_{\text{NIR}} - \rho_{\text{Red}}}{\rho_{\text{NIR}} + \rho_{\text{Red}}} \quad (1)$$

$$\text{EVI} = \frac{(\rho_{\text{NIR}} - \rho_{\text{Red}})}{(L + \rho_{\text{NIR}} + C_1\rho_{\text{Red}} - C_2\rho_{\text{Blue}})} * G \quad (2)$$

where  $\rho$  is the surface bidirectional reflectance in each respective band,  $L$  is a canopy background adjustment factor that normalizes differential red and NIR extinction through the canopy, and  $C_1$  and  $C_2$  are coefficients accounting for atmospheric aerosol effects. In this study, the values for  $L$ ,

$C_1$ ,  $C_2$ , and  $G$  (gain factor) were equivalent to those adopted in the actual MODIS EVI product, i.e. 1, 6, 7.5, and 2.5, respectively (Huete et al., in press).

### 3. Results

#### 3.1. Biophysical

The structural and biophysical parameters measured in the Cerrado physiognomies considered in this study are shown in Table 1 and depicted with ground landscape and airborne digital pictures in Fig. 4. There is a continuous and systematic increase in the percentage of woody layer vegetation cover from the Cerrado grassland and shrub Cerrado, to the wooded Cerrado and Cerrado woodland, and then gallery forest. Tree spacing decreased and height of the woody vegetation layer increased along this sequence of Cerrado formations. The herbaceous understory percent green cover decreased slightly, in both wet and dry seasons, across the sequence from herbaceous Cerrado grassland to the Cerrado woodland formations. Green understory cover in the wet season was approximately twice that of the dry season. The overall landscape percent green cover (i.e. overstory trees and understory grasses), derived from the airborne digital pictures (50 m footprint) increased from the herbaceous (40% and 46%) to woody Cerrado formations (60% and 63%) to the gallery forest (85%) for the wet season (Table 1). The total landscape green cover was lower in the dry season than the wet season, particularly in the more herbaceous Cerrado formations.

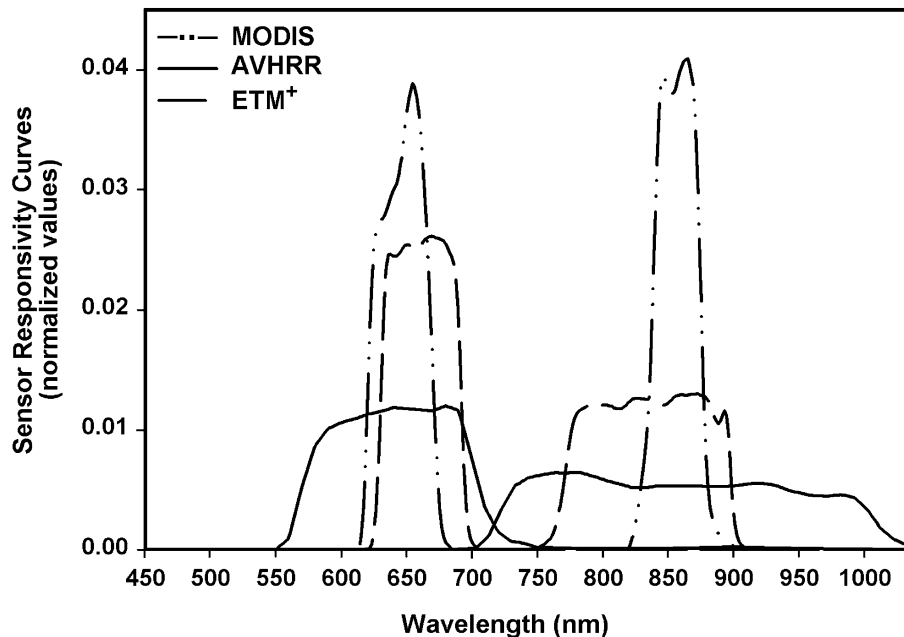


Fig. 5. MODIS, ETM<sup>+</sup>, and AVHRR blue, red, and NIR response curves.

Table 1  
Structure and conditions of the major physiognomies at Brasilia National Park

Major physiognomies at the Brasilia National Park	Above-ground characteristics	% Cover of woody layers		Average height of trees (m)		Average tree spacing (m)	Understory % green cover			Landscape % green cover				
		Shrubs	Trees	Shrubs	Trees		Wet	Dry	Seasonal variation		Wet	Dry	Seasonal variation	
									Abs. diff.	Rel. diff.			Abs. diff.	Rel. diff.
Cerrado grassland	Open grassland	<1.15	–	<1.4	–	–	43.0	23.1	20.0	46.4	40.0	18.3	21.7	54.2
Shrub Cerrado	Open grassland with sparse shrubs	4.3	0.6	0.8/1.6	4.7	33.6	45.2	20.4	24.8	54.9	46.1	25.6	20.5	44.6
Wooded Cerrado	Shrubland with sparse trees	24.3	5.4	0.79/1.17	5.3	13.0	42.8	22.0	20.8	48.5	60.4	48.3	12.1	20.1
Cerrado woodland	Mixed grassland, shrubland, and trees up to 7 m	20.9	24.5	1.65/2.5	5.7	7.3	37.9	14.5	23.4	61.8	63.4	51.5	11.9	18.8
Gallery forest <sup>a</sup>	Evergreen woodland mainly along streams	–	70–95	–	20–30	–	–	–	–	–	85.5	80.3	5.2	6.0

Obs.: Numbers in *italic* indicate the predominant average when two layers were identified.

<sup>a</sup> Data from Ribeiro and Walter (1998).

### 3.2. Optical

Major differences among these Cerrado types were observed in their spectral signatures over both dry and wet seasons (Fig. 6). The wet season spectral signatures separated nicely into the three major physiognomic domains in the red spectral region from 600 to 700 nm. The two herbaceous Cerrado physiognomies (Cerrado grassland and shrub Cerrado) had nearly identical red spectral responses, while the woody Cerrado formations, wooded Cerrado and Cerrado woodland, had similar and intermediate red spectral responses with the densely vegetated gallery forest showing the lowest red spectral responses. There were no clear separations in spectral response in the other portions of the spectrum except the high NIR response from the dense gallery forest.

Overall, the absorbance features in the red wavelength region and the high reflectance patterns in the NIR region (around 825 nm) become more prominent as the amount of landscape green cover and woody vegetation increased (Fig. 6a). Although similar trends can be observed for the dry season spectral signatures, there is a significant reduction in the red–NIR contrast for all the Cerrado formations, except the gallery forest (Fig. 6b). This reduction in red–NIR contrast can be readily observed in the first derivative spectral signature plots, which are a measure of the slope of the NIR–red edge (Fig. 7). The slope of the red–NIR edge decreases with a reduction in photosynthetic activity, independent of the brightness or amplitude of the spectral signature. The main source of spectral variability observed in the first derivative spectral signatures was along the red edge at ~ 720 nm, with the gallery forest showing the highest signal, followed by the woody Cerrado formations

with the herbaceous formations having the lowest signals. In the dry season, only the gallery forest has a sharp red edge and high first derivative signal, but one can still observe differences in the woody and herbaceous Cerrado formation signals.

### 3.3. Vegetation indices

Fig. 8 shows a good correlation between the vegetation indices (first derivative, NDVI, and EVI) and landscape green cover. Overall, and for both seasons, the three measures of photosynthetically active vegetation behave fairly similar and are well correlated with landscape green cover. This would indicate that the two coarse-band VIs are able to depict the red–NIR contrast of the red edge fairly well. There are only minor differences among the three relationships, such as the behavior of the dry season gallery forest, which has a higher value than the wet season measure in the case of the first derivative (Fig. 8a). Although more data points are needed, there appears to be separate dry and wet season relationships between the three VIs and landscape green cover with the wet season data possessing higher values. There also appears to be physiognomy-dependent relationships between the VIs and landscape green cover from the wet to dry season values. However, data for an entire growing season would be needed to confirm this.

### 3.4. Seasonal variations and dynamics

Seasonal variations in landscape vegetation dynamics were compared with the dry and wet season vegetation index responses using both absolute and relative measures

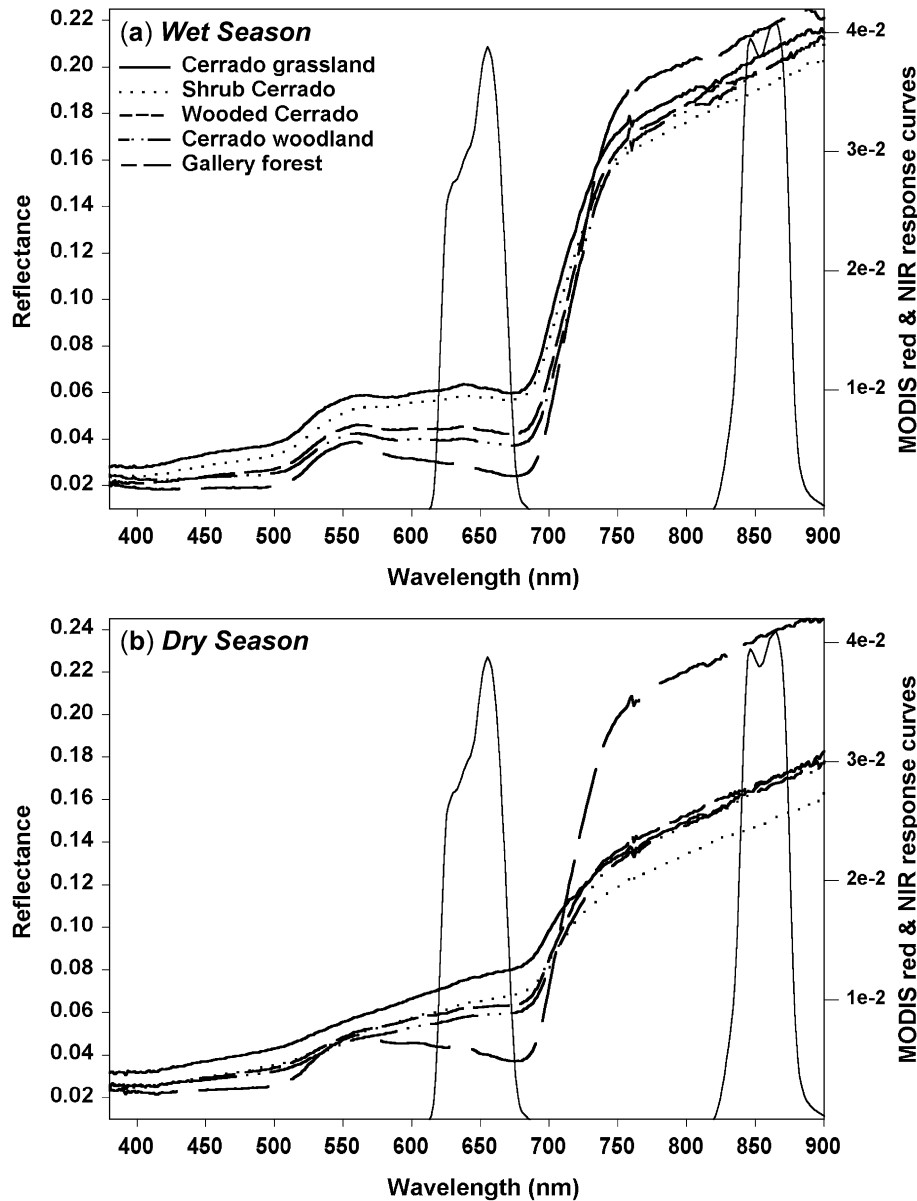


Fig. 6. Average spectral signatures for the five physiognomies investigated in this study for both wet (a) and dry (b) seasons (normalized MODIS red and NIR response curves also shown in figure).

of percent variations. The equations used to depict seasonal variation were:

Absolute Seasonal Variation

$$= (\text{Wet Season}_{(\%GC,VI)} - \text{Dry Season}_{(\%GC,VI)}) \quad (3)$$

Relative Seasonal Variation

$$= \left( \frac{\text{Wet Season}_{(\%GC,VI)} - \text{Dry Season}_{(\%GC,VI)}}{\text{Wet Season}_{(\%GC,VI)}} \right) * 100. \quad (4)$$

The absolute measure of dry to wet season variations in VI or green cover is equivalent to a “simple difference” or subtraction of two images for change detection analysis. The relative difference represents a “normalized” measure of seasonal variations that allow direct comparisons across dissimilar variables, such as percent green cover (%GC) vs. VI response, NDVI vs. EVI, and MODIS vs. ETM<sup>+</sup> sensors.

Landscape variations in green cover between wet and dry seasons decreased, in both absolute and relative measures, from the herbaceous Cerrado formations to the woody Cerrado formations and the gallery forests (Table 1). Absolute differences varied from approximately 20% over the herbaceous Cerrado, 12% over the woody Cerrado types, to 5% over the gallery forest (Table 1). The respective,

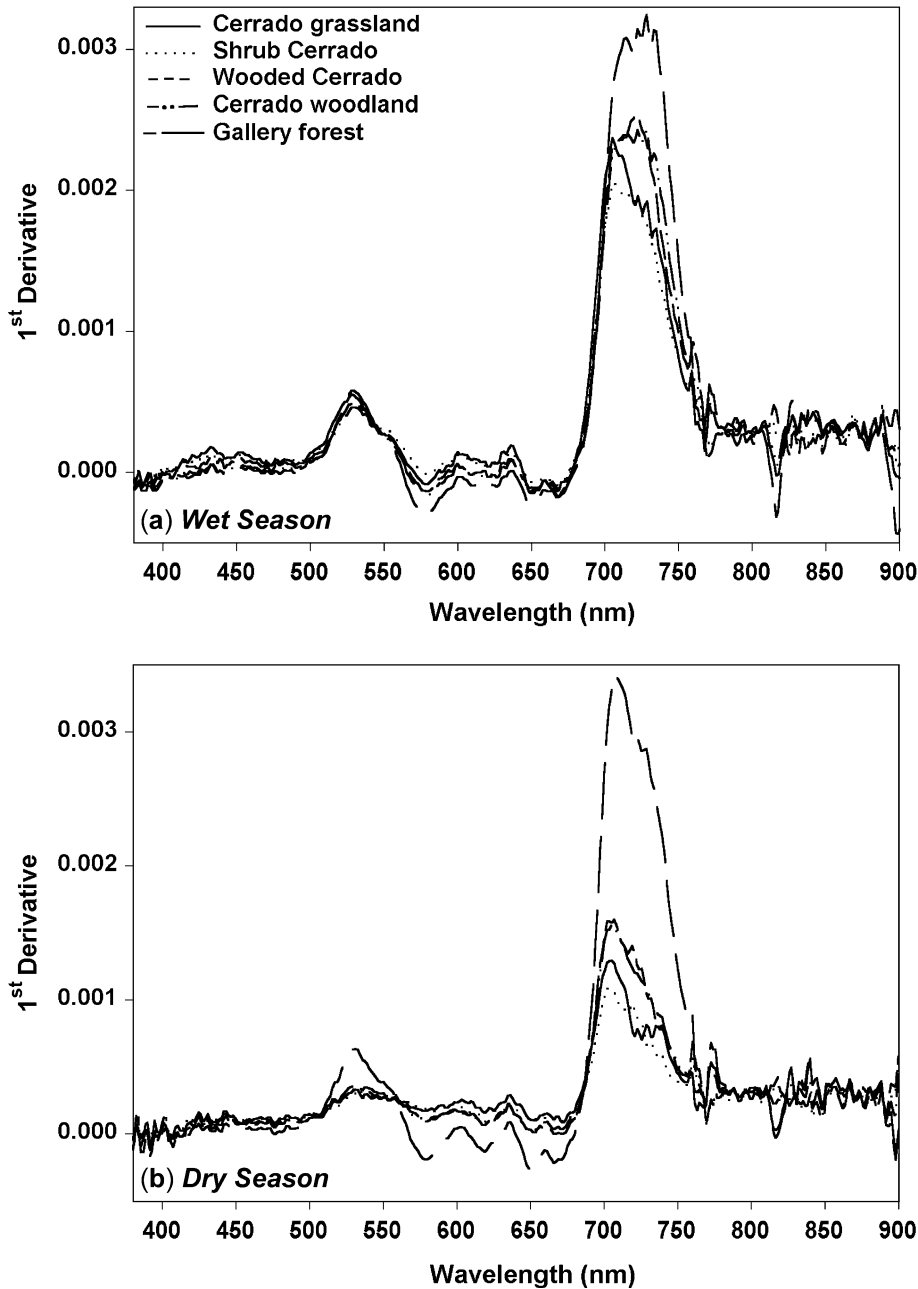


Fig. 7. Average first derivative spectra for the five physiognomies investigated in this study for both wet (a) and dry (b) seasons.

normalized measures of seasonal variation were approximately 50%, 20%, and 6%. The seasonal variations in landscape green cover thus varied distinctly for the three major Cerrado physiognomies, namely the herbaceous, woodland, and forest domains.

Vegetation index seasonal variations did not necessarily follow the seasonal variations observed in landscape green cover. NDVI seasonal variations, as measured by the simple wet–dry difference, increased from the herbaceous Cerrado physiognomies to the woody Cerrado formations, whereas EVI simple differences (wet minus dry) remained fairly constant across the Cerrado types (Fig. 9a). This occurred

despite the observed decrease in landscape green cover differences over these Cerrado types between the two seasons (Table 1). Only over the gallery forest did the simple wet–dry differences decrease simultaneously for both VIs and landscape green cover values (Fig. 9a). Overall, the NDVI had higher percent seasonal variation values, however, as we found in this study, simple subtraction of NDVI or EVI images for seasonal change analysis lead to erroneous interpretations of actual landscape seasonal dynamics.

The relative measure of percent seasonal variation showed a more accurate depiction of landscape dynamics.

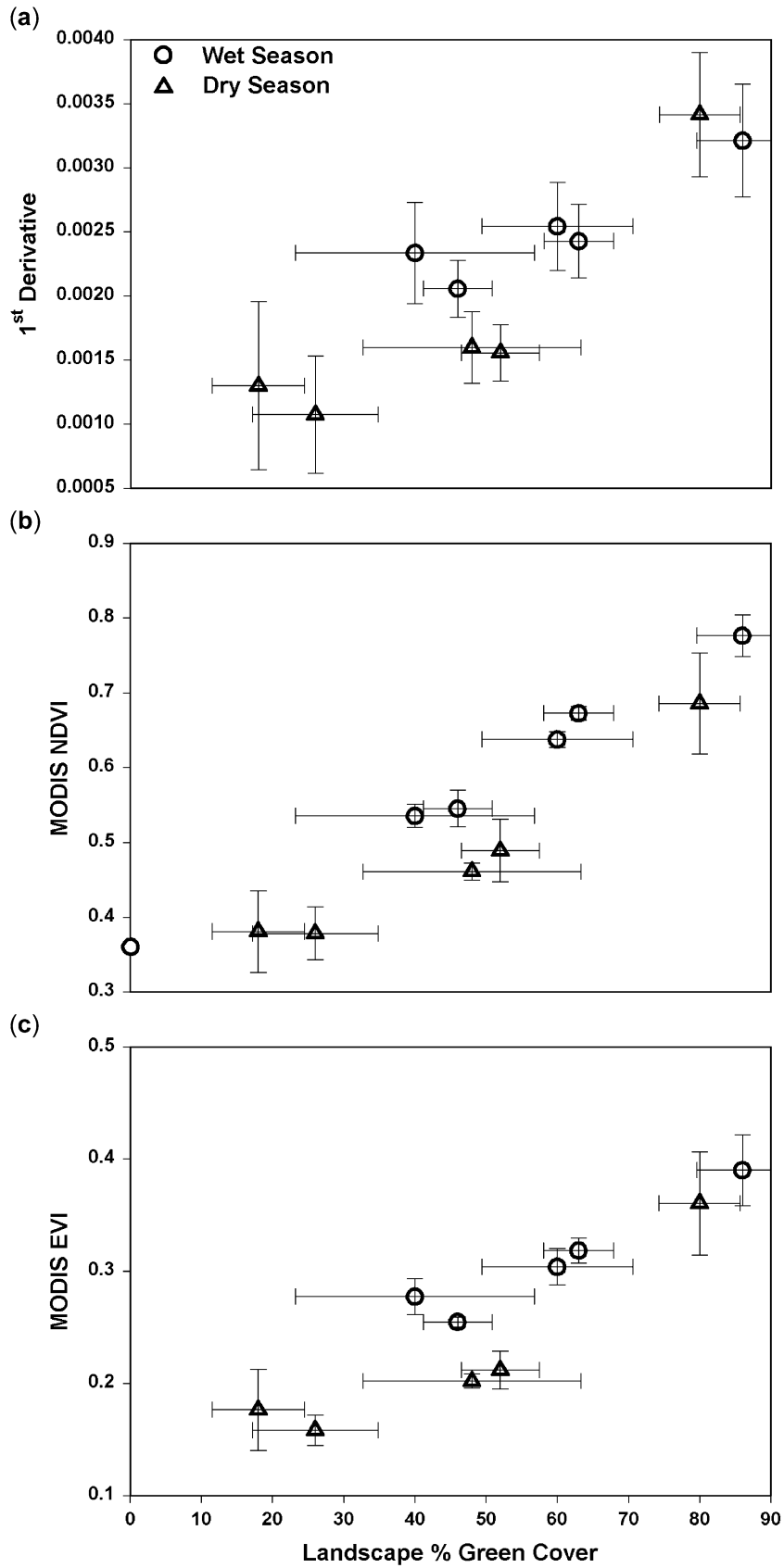


Fig. 8. Biophysical relationships of landscape green cover with the first derivative (a), MODIS NDVI (b), and MODIS EVI (c) for all physiognomies.

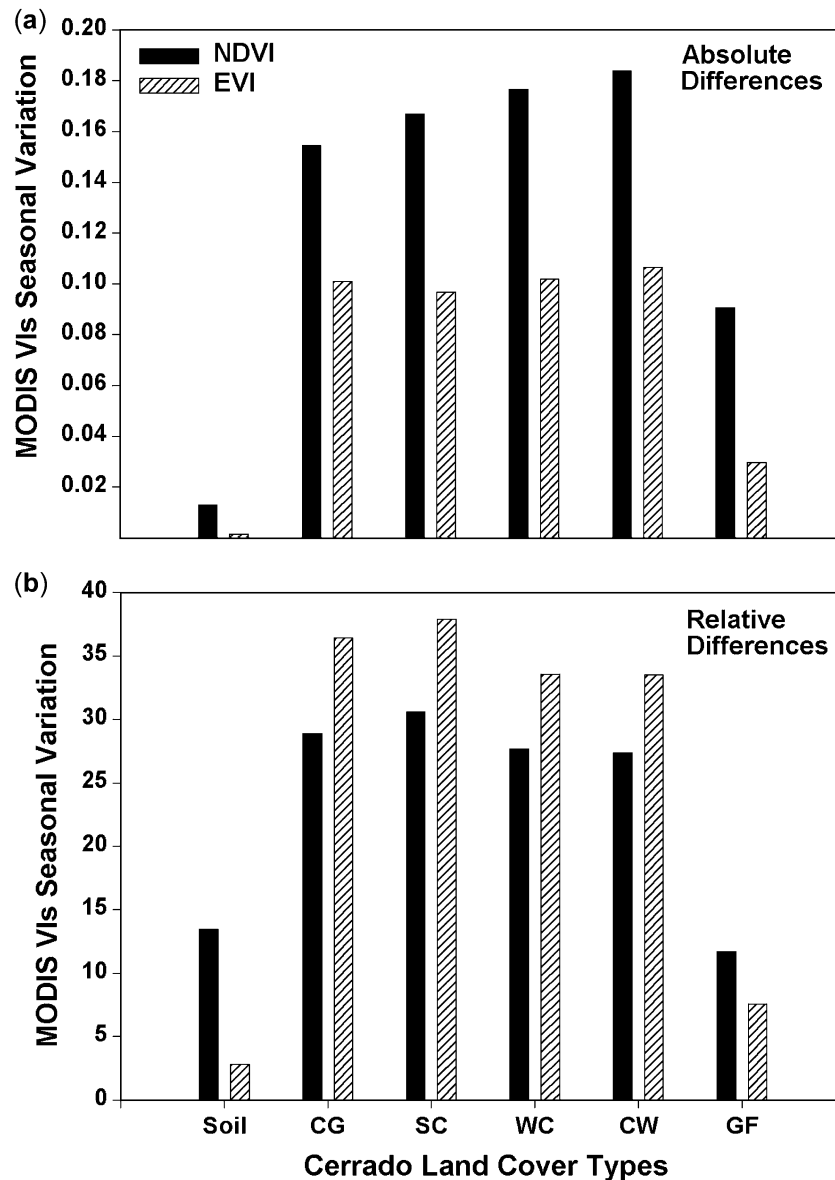


Fig. 9. MODIS NDVI and EVI absolute seasonal variation for the five physiognomies at Brasilia National Park and for a bare soil region (a), and the correspondent relative seasonal variations (b) for the five physiognomies investigated in this study (Cerrado grassland—CG, shrub Cerrado—SC, wooded Cerrado—WC, Cerrado woodland—CW, and gallery forest—GF).

The bar graphs show the higher sensitivity of EVI to seasonality, and also show EVI and NDVI seasonality decreasing from the herbaceous zones to the woody zones. The wet–dry season VI response from the herbaceous dominated physiognomies (e.g. Cerrado grassland and shrub Cerrado) had relative seasonal variations as high as 38%, compared with the more wooded physiognomies, such as the gallery forest, which had relative VI variations under 10% (Fig. 9b). The more developed woody layers of the Cerrado woodland and wooded Cerrado were able to buffer (and mask) the seasonal changes taking place at the understory level (Table 1).

It is worth noting, however, the overall lower sensitivity of the VIs to depict landscape dynamics. Whereas landscape

green cover seasonal variations ranged from 5% in the gallery forest to 55% in the Cerrado grassland (Table 1), the equivalent VI seasonal variations were restricted from 12% to 29% in the case of the NDVI and 8% to 36% for the EVI (Fig. 9b). The seasonal responses in both VIs over the herbaceous dominated physiognomies (i.e. Cerrado grassland and shrub Cerrado) were lower than the corresponding relative differences in percent green cover values at the landscape scale, while for the woody formations (i.e. wooded Cerrado and Cerrado woodland), NDVI and EVI show larger seasonal variations (Fig. 9b and Table 1). In the case of the gallery forest, relative seasonal variations were nearly the same for the VIs and percent green cover. In general, the relative seasonal variations of the two VIs were

fairly constant across the herbaceous and woody Cerrado types despite a large gradient in landscape green cover seasonality. This demonstrates some of the insensitiveness of the VIs in depicting actual landscape dynamics.

3.5. Inter-sensor VI comparisons

There is great interest in utilizing multi-sensor datasets for improved characterization and monitoring of the land surface. Two of the most relevant multi-sensor applications of interest to this study include: (1) AVHRR-MODIS time series continuity and (2) MODIS-ETM<sup>+</sup> formation flying whereby ETM<sup>+</sup> offers high spatial resolution ‘zoom’ capability minutes apart from a MODIS sensor overpass. The tremendous variability in the red and NIR bandpasses for

these three sensors can be seen in Fig. 5. The AVHRR sensor possesses very broad bands while MODIS measures the red and NIR portions of the spectrum with very narrow bands.

An apparent effect of sensor dependency on VI measurements over the Cerrado is the systematically lower VI values shown by the ETM<sup>+</sup> and AVHRR sensors in both wet and dry seasons (Fig. 10). The differences between MODIS and ETM<sup>+</sup> VIs were much greater in the dry season than in the wet season and were larger in the herbaceous Cerrado types (10%) and minimal in the gallery forest (2%) (Fig. 10a). The MODIS-ETM<sup>+</sup> differences encountered with the EVI were slightly higher than the NDVI. The lower VI values from ETM<sup>+</sup> compared to MODIS can be attributed to the closer proximity between the ETM<sup>+</sup> red and NIR band-centers,

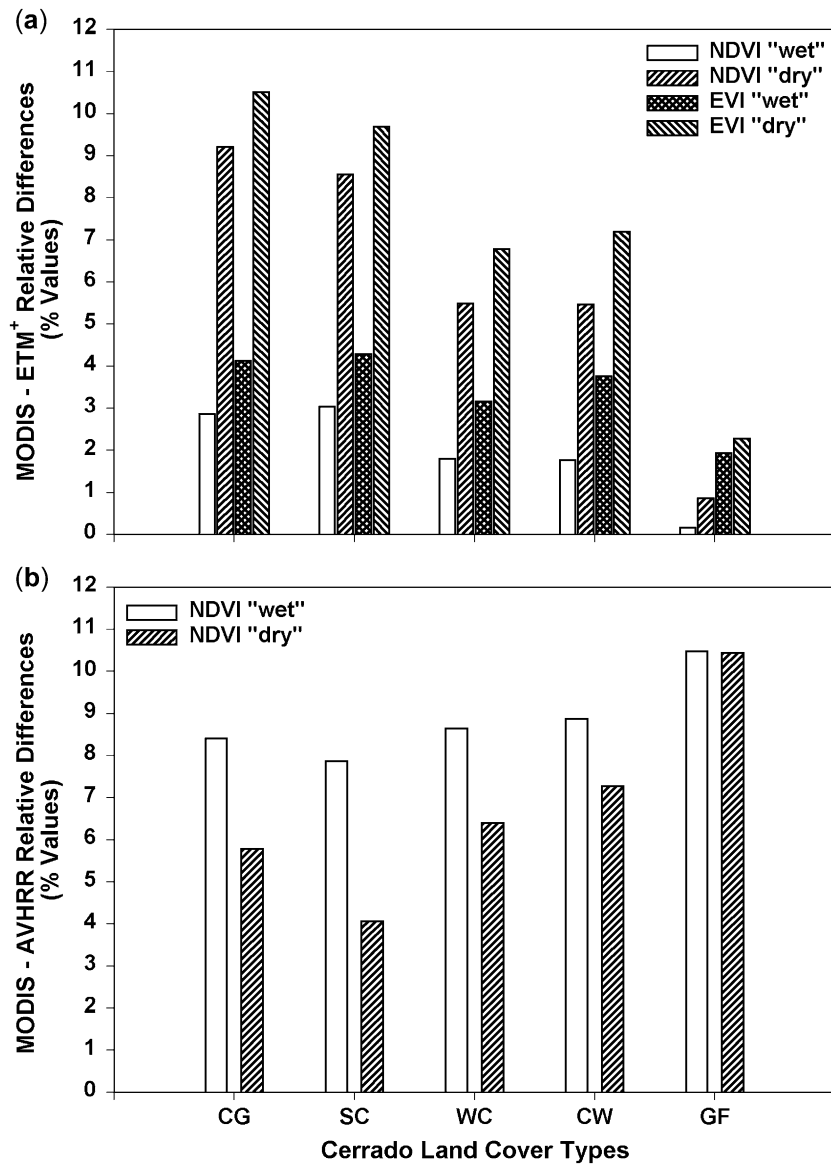


Fig. 10. Relative differences between the MODIS and ETM<sup>+</sup> VIs (a) and MODIS and AVHRR NDVI (b) for both wet and dry seasons (Cerrado grassland—CG, shrub Cerrado—SC, wooded Cerrado—WC, Cerrado woodland—CW, and gallery forest—GF).

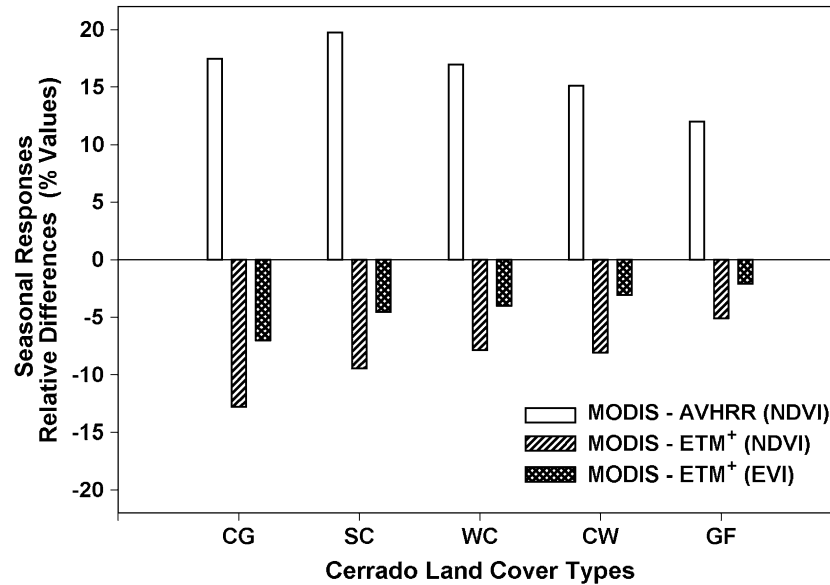


Fig. 11. Relative differences in the VI's seasonal responses between MODIS and AVHRR and between MODIS and ETM<sup>+</sup> (Cerrado grassland—CG, shrub Cerrado—SC, wooded Cerrado—WC, Cerrado woodland—CW, and gallery forest—GF).

which results in lower red–NIR contrast and lower VI values (Fig. 5).

Differences between the MODIS and AVHRR NDVI values behaved in an opposite manner with greater NDVI differences in the wet season than in the dry season and with greater differences in the gallery forest compared with those from the herbaceous and woody Cerrado types (Fig. 10b). The considerably broader AVHRR red bandwidth, which includes some part of green as well as the red-edge wavelengths leads to a higher red-band reflectance values than ETM<sup>+</sup> and MODIS, reducing the red–NIR contrast and resulting in lower VI values. This broadband effect is particularly evident over densely vegetated canopies and thus MODIS–AVHRR NDVI discrepancies become more prominent as one goes from the Cerrado grassland to the gallery forest and from dry season to wet season. In the dry season, the increase in red reflectance is very small due to the lack of a steep red edge and a weak green peak and MODIS–AVHRR discrepancies in NDVI will be small.

The overall sensitivity of the sensor-dependent VIs in depicting landscape seasonal dynamics is depicted in Fig. 11. Wet to dry season relative variations were higher with the ETM<sup>+</sup>-simulated VIs compared with those from MODIS, particularly when the NDVI was used as the measure of landscape vegetation dynamics. Landscape seasonal variations were much higher with the MODIS-simulated NDVI compared with that of AVHRR (Fig. 11). The observed differences in seasonal response between MODIS and ETM<sup>+</sup> and between MODIS and AVHRR VIs follow a vegetation gradient with sensor-dependent differences greatest in the herbaceous Cerrado formations and decrease over the woody Cerrado types and gallery forest. This shows the VI products from the ETM<sup>+</sup> sensor to be most sensitive in

depicting the seasonal dynamics of the different Cerrado formations, followed by the MODIS sensor, and then the AVHRR.

In summary, the inter-sensor VI comparisons over the Cerrado have shown MODIS and AVHRR NDVI differences to become greater in the more vegetated woody Cerrado and gallery forest for both dry and wet seasons (Fig. 10b) and that dry to wet differences between the two sensors decrease across the same sequence of Cerrado canopies (Fig. 11). Thus, the MODIS sensor bandpasses would not only yield a higher NDVI signal, but also would depict seasonal variations with a higher fidelity. On the other hand, MODIS and ETM<sup>+</sup> VI differences decrease with increasing amounts of vegetation (grassland–woody–forest) in the dry season with slight trends in the wet season (Fig. 10a) resulting in dry–wet season differences that are greater for the ETM<sup>+</sup> sensor (Fig. 11).

Table 2  
Atmospheric simulations/wet–dry season scenarios

Scenarios	Wet season		Dry season	
	Model	Visibility (km)	Model	Visibility (km)
1	"no atmosphere"			
2	continental (CO)	100	dynamic biomass burning (BB)	100
3	continental (CO)	100	dynamic biomass burning (BB)	10
4	continental (CO)	10	dynamic biomass burning (BB)	100
5	continental (CO)	10	dynamic biomass burning (BB)	10

Water vapor and ozone content of 3 g/cm<sup>2</sup> and 0.247 cm atm (wet season), and 2 g/cm<sup>2</sup> and 0.247 cm atm (dry season), respectively.

Table 3  
VI's seasonal response-maximum atmosphere-induced variations (relative to scenario 1<sup>a</sup>)

Atmospheric model	EVI				NDVI					
	MODIS		ETM <sup>+</sup>		MODIS		ETM <sup>+</sup>		AVHRR	
	Increase	Decrease	Increase	Decrease	Increase	Decrease	Increase	Decrease	Increase	Decrease
CO100 × BB100	1.08	none	1.72	0.20	0.45	0.80	2.03	0.62	6.65	none
CO100 × BB010	1.21	3.93	3.17	4.52	16.49	none	17.93	none	29.75	none
CO010 × BB100	none	1.10	none	2.11	none	18.67	none	19.63	none	24.69
CO010 × BB010	none	5.05	0.39	6.52	4.67	0.46	6.40	0.56	15.49	none

<sup>a</sup> Refer to Table 2.

3.6. Atmospheric effects on the NDVI and EVI seasonal responses

The atmosphere radiative properties over the Cerrado region show significant seasonal variation (Kauffman et al.,

1998), due to the widespread occurrence of fires in the dry season (Coutinho, 1990; Ferreira, Sano, & Assad, 2000; Nepstad et al., 1997) and the high combustion factors of the Cerrado physiognomies (Kauffman, Cummings, & Ward, 1994; Kirchoff & Alvala, 1996; Ward et al., 1992). The high

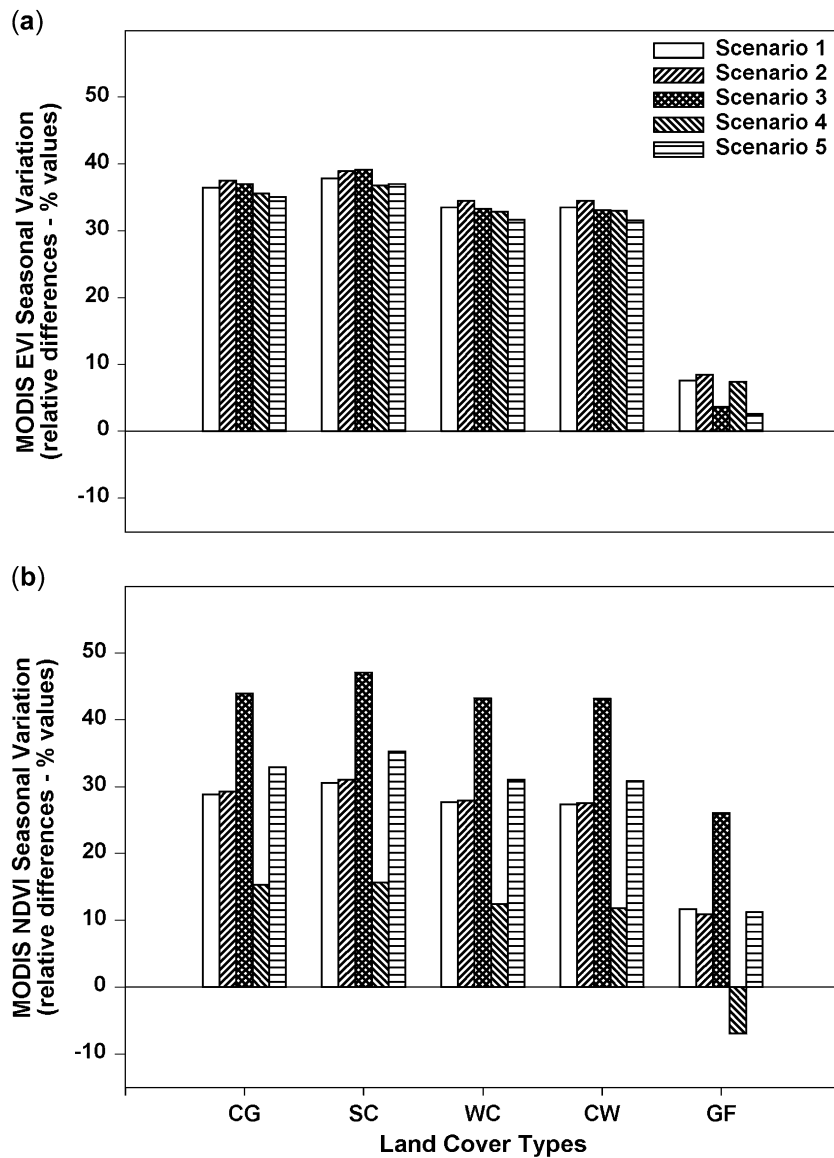


Fig. 12. MODIS NDVI and EVI seasonal responses under different aerosol loadings and wet and dry season atmospheric scenarios (Cerrado grassland—CG, shrub Cerrado—SC, wooded Cerrado—WC, Cerrado woodland—CW, and gallery forest—GF).

spatial and temporal variations in the optical thickness and aerosol properties render atmosphere correction of remote sensing data a difficult task. Even in the case of MODIS-retrieved surface reflectance data, the effects of residual aerosols are likely to be felt, since the aerosol correction product is at much coarser resolution ( $\sim 20$  km) compared to the MODIS VI products (i.e. 250, 500, and 1 km) (Vermote, EL Saleous, et al., 1997).

Thus, the seasonal responses of spectral vegetation indices will also vary with the atmosphere conditions prevalent in both the wet and dry seasons. We evaluated these effects with simulations of atmosphere turbidities (visibility levels of 10 and 100 km) over the previously obtained sensor-convolved surface reflectances. Using the 6S radiative transfer model (Vermote, Tanre, Deuze, Herman, & Morcrette, 1997), a continental aerosol model was used to represent the atmosphere for the wet season and a dynamic biomass-burning model represented the atmosphere in the dry season (Lenoble & Brogniez, 1984). The simulated at-sensor and top-of-atmosphere (TOA) reflectances were then Rayleigh and ozone corrected to simulate ‘partially’ atmosphere corrected surface reflectances with distinct aerosol residuals (Tanre, Holben, & Kaufman, 1992). The five atmosphere simulations involving the dry and wet seasons are summarized in Table 2.

The relative seasonal differences in NDVI and EVI were estimated for the MODIS, AVHRR, and ETM<sup>+</sup> VIs with the five wet–dry season scenarios (Table 2). Overall, the EVI relative seasonal responses were minimally affected by the simulated atmospheric conditions, showing a maximum increase of 3% over the shrub Cerrado and a decrease of about 7% over the gallery forest (Table 3). The NDVI seasonal responses, by contrast, increased by as much as 30% over the shrub Cerrado and decreased as much as 25% over the gallery forest (Fig. 12). As seen in Table 3, atmospheric effects on VI seasonal responses were sensor-dependent and showed less impact on the MODIS bandwidths and most impact on the AVHRR bands. In spite of the atmosphere-induced changes in the VIs, their seasonal responses could still be grouped according to the three major Cerrado domains (i.e. herbaceous, woody, and forested) and the overall decrease in seasonal dynamics could still be observed from the Cerrado grassland to the gallery forest.

#### 4. Conclusions

Savannas are a major component of the world’s vegetation accounting for 30% of the terrestrial primary production (IPCC, 1990). Accurate assessments of the seasonal dynamics of savanna vegetation are of fundamental importance in understanding the functioning of these ecosystems and in the implementation of sustainable development practices. In this study, the seasonal behavior of some of the major Cerrado physiognomies were investigated with dry and

wet season radiometric data and corresponding field biophysical measurements over the Brasilia National Park, a representative site of the Cerrado biome.

We found the various physiognomies could be grouped into three major domains (herbaceous, woody, and forested) with relative seasonal differences in percent green cover at the landscape scale decreasing from the Cerrado grassland (54%) to the gallery forest (6%), while the simulated MODIS NDVI and EVI showed variations ranging from about 29% to 12% and from 36% to 8%, respectively. We found very good ‘global’ biophysical relationships between the various spectral measures of photosynthetically active vegetation (PV) used in this study, including the first spectral derivative, the NDVI and the EVI with landscape percent green cover. However, there appeared to be significant secondary influences in which the dry season biophysical relationships differed from the wet season relationships (Fig. 8), and it appeared that the slope of the biophysical relationships also significantly differed for each major Cerrado domain (grass, wood, and forest). Further physiognomic-intensive studies, coupled with canopy modeling, are needed to characterize such physiognomy-dependent biophysical relationships and assess their significance to Cerrado monitoring and transformation studies.

The ETM<sup>+</sup> VIs showed systematically larger seasonal variations compared to the MODIS VIs, which seemed to be related to the closer proximity between the ETM<sup>+</sup> red and NIR band-centers. The AVHRR NDVI, on the other hand, showed the lowest variations and the least “contrast” in seasonal responses, due to the considerably broader red and NIR bandwidths that reduced their contrast and sensitivity to vegetation differences.

NDVI seasonal responses were found to be very sensitive to the simulated atmosphere scenarios conducted in this study, which included dry season biomass burning and wet season conditions with variable aerosol loadings. In contrast, the EVI was resistant to atmospheric effects and EVI seasonal responses with landscape green cover dynamics were minimally affected. The effects of residual aerosol loadings were strongly coupled to “bandwidth”, resulting in more serious influences on the AVHRR NDVI, followed by the ETM<sup>+</sup> VIs, and MODIS VIs.

The results in this study show that the MODIS VI products should significantly improve our ability to consistently monitor the seasonal and inter-annual vegetation changes in the Cerrado physiognomies. The EVI showed more sensitivity in detecting seasonal changes among the various Cerrado formations. In addition, the use of ETM<sup>+</sup> may effectively complement and extend the functionality of the coarser resolution MODIS datasets.

There are additional biophysical and structural canopy parameters needed for a more complete characterization of Cerrado physiognomies and their potential monitoring with remotely sensed data. Given the three-dimensional canopy structural aspects of the different Cerrado classes (e.g. shrub and tree clumping and overstory/understory layers), the

landscape green cover parameter must be complemented with additional information such as leaf area index (LAI) and extent of non-photosynthetically active vegetation (NPV) in the woody layer. Additional studies are needed in the short-wave infrared (SWIR) portion of the spectrum in which the NPV component aspects of the woody and herbaceous layers within the Cerrado physiognomies can be investigated. Remotely sensed structural measurements are needed with laser systems such as LVIS and/or with bidirectional sensors such as the multi-angle imaging spectroradiometer (MISR), onboard the EOS-Terra platform.

Further investigations are needed before making full use of the numerous remote sensing systems orbiting the earth to monitor and study the Cerrado biome. As shown in this study, differences in VI values among the MODIS, AVHRR, and ETM<sup>+</sup> sensors varied with Cerrado type and dry–wet season vegetation cover conditions, indicating a need for inter-sensor VI translation equations. These inter-sensor translation equations are also needed to achieve true continuity between present and historic datasets (e.g. AVHRR and MSS), and allow a more complete and accurate picture of the intense and rapid transformations occurring in the Cerrado biome.

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