EARTH Interactions

Analysis of Cerrado Physiognomies and Conversion in the MODIS Seasonal–Temporal Domain

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ABSTRACT: The "cerrado" biome in central Brazil is rapidly being converted into pasture and agricultural crops with important consequences for local and regional climate change and regional carbon fluxes between the atmosphere and land surface. Satellite remote sensing provides an opportunity to monitor the highly diverse and complex cerrado biome, encompassing grassland, shrubland, woodland and gallery forests, and converted areas. In this study, the potential of *Terra* Moderate Resolution Imaging Spectroradiometer (MODIS) data is analyzed to discriminate among these diverse cerrado physiognomies and converted pastures based on their seasonal dynamics and phenology. Four years (2000–03) of MODIS 16-day composited, 250-m resolution vegetation index (VI) data were extracted over a series of biophysically sampled field study sites representing the major cerrado types. The temporal VI profiles over the cerrado formations exhibited high seasonal contrasts with a pronounced dry season from June to August and a wet growing season from

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November to March. The converted pasture areas showed the highest seasonal contrasts while the gallery forest formation had the lowest contrast. Seasonal VI variations were negatively correlated with woody canopy crown cover and provided a method to discriminate among converted cerrado areas, gallery forests, and the woody and herbaceous cerrado formations. The grassland and shrub cerrado formations, however, were difficult to separate based on their seasonal VI profiles. Maximum discrimination among the cerrado types occurred during the dry season where a positive linear relationship was found between VI and green cover. The annual integrated VI values showed the gallery forests and cerrado woodland as having the highest, and hence most annual productivity, while the more herbaceous shrub and grassland cerrado types were least productive. The cumulative VI profiles of converted cerrado, pasture areas varied distinctly in shape due to their strong dry season inactivity. Furthermore, the annual integrated VI values of the converted pastures differed significantly between the normalized difference vegetation index (NDVI) and the enhanced vegetation index (EVI) MODIS VI products, resulting in large discrepancies in productivity estimates relative to the native cerrado sites. This study shows that the MODIS seasonal–temporal VI profiles are highly useful in monitoring the cerrado biome and conversion-related activities.

KEYWORDS: Cerrado, MODIS, Phenology, Temporal domain, Remote sensing

1. Introduction

The cerrado is the largest neotropical savanna region in South America, extending throughout Brazil, Paraguay, and Bolivia. This biome is among the richest in biodiversity and consists of a large variety of vegetation communities with a full range of physiognomic categories ranging from grassland to forest formations. There have been more than 500 woody plant species (Feifili et al. 1998) and at least 4700 herbaceous species (Mendonca et al. 1998) found in the cerrado region. Ribeiro and Walter (Ribeiro and Walter 1998) divided the major cerrado formations into a dominant herbaceous/shrub stratum (savanna grassland and shrub savanna) and a woody-dominated stratum (wooded savanna and savanna woodland). However the classification of the cerrado is very complex owing to conspicuous differences in origin, physiognomy, and ecological characteristics. Over central Brazil, the cerrado biome region has a tropical climate with an “Aw” Köppen classification. The mean annual precipitation is 1500 mm and ranges from 750 to 2000 mm with a mean temperature always above 18°C (Dambrós et al. 1981).

The soils in the cerrado region are predominantly oxisols that are well drained, clay rich, low nutrient, and acidic with high Fe- and Al-oxide contents (Askew et al. 1970; Motta et al. 2002; Goodland and Ferri 1979; Sarmiento 1984; Heridasan et al. 1987; Furley and Ratter 1988). The upland areas have more nutrient-rich and reddish soils supporting dense cerrado or woodland while the lower elevations are made up of less well-drained and yellowish soils supporting native grassland (Eiten 1982). Elevation ranges between 300 and 1600 m, dominated by cerrado vegetation with gallery forests along rivers and streams. Fire is an important determinant of the cerrado vegetation. They are generally surface fires, which primarily consume the herbaceous layer as most of cerrado woody plants are fire resistant.

The cerrado biome has a very strong wet–dry seasonality (Castro et al. 1994) with most of the precipitation occurring in the rainy season from October to March with very little rain during the dry period from May to August. Medina (Medina 1982) studied the phenology of many savanna plants and found perennial C_4 grasses with a growing season length from July to November with peak development in September–October corresponding to the onset of spring rainfall. In contrast, the woody plants are more or less evergreen throughout the year, with a flush of new leaves near the end of the dry season and maximum development during the rainy season.

Most of the cerrado biome has been either completely converted or modified in significant ways, especially for agriculture and pasture. Nepstad et al. (Nepstad et al. 1997) found that the rate of cerrado conversion exceeded the rate of tropical Amazon forest conversion. These large-scale cerrado conversions have occurred in the last 50 yr, following the construction of the capital city of Brasilia and have been accompanied by increased fire incidence and nonnative, invasive species (Henriques and Hay 2002). Despite this alarming rate of conversion, there have been few attempts in quantifying and monitoring land-use changes throughout this threatened biome and only 1% of the cerrado region is now protected in parks or reserves.

Many studies have shown the utility of remote sensing data to investigate vegetation dynamics and phenology (Schwartz 1998; Reed et al. 1994; Goward et al. 1994; Schwartz and Reed 1999; Zhang et al. 2003; Tieszan et al. 1997). Vegetation indices (VIs), in particular, have been used to enhance and quantify the "green" photosynthetic signal and enable meaningful spatial and temporal intercomparisons of vegetation activity. They have been effectively used in monitoring vegetation seasonal dynamics, phenology, change detection, and land-cover classification (Townshend et al. 1991; Townshend 1994; Price 2003). They are also useful in deriving biophysical vegetation properties such as fractional vegetation cover, biomass, leaf area index (LAI), fraction of absorbed photosynthetic active radiation (fPAR; Asrar et al. 1984; Asrar et al. 1992; Baret 1995; Sellers 1985), and net primary production (NPP; Tucker and Sellers 1986; Running and Nemani 1988).

The Moderate Resolution Imaging Spectroradiometer (MODIS) on board the *Terra* platform was launched on 18 December 1999 as part of the National Aeronautics and Space Administration (NASA) Earth Observing System (EOS). The VI products generated from this sensor include the normalized difference vegetation index (NDVI) and the enhanced vegetation index (EVI) and are designed to monitor spatial and temporal patterns of photosynthetic activity on a consistent and global basis at 1-km, 500-m, and 250-m resolutions and 16-day compositing periods. The NDVI is sufficiently stable to permit meaningful comparisons of seasonal, interannual, and long-term variations of vegetation structure, phenology, and biophysical parameters:

$$\mathrm{NDVI} = \frac{\rho_{\mathrm{NIR}} - \rho_{\mathrm{red}}}{\rho_{\mathrm{NIR}} + \rho_{\mathrm{red}}}, \tag{1}$$

where ρ_{red} and ρ_{NIR} are the surface bidirectional reflectance factors for MODIS bands 1 (620–670 nm) and 2 (841–876 nm).

The MODIS EVI was developed to optimize the vegetation signal with improved sensitivity in high biomass regions and reduced atmospheric and soil background noise. The EVI has been reported to be more responsive to canopy structural variations, including leaf area index, canopy type, plant physiognomy, and canopy architecture (Huete et al. 2002):

$$\mathrm{EVI} = \frac{\rho_{\mathrm{NIR}} - \rho_{\mathrm{red}}}{\rho_{\mathrm{NIR}} + C_1\rho_{\mathrm{red}} - C_2\rho_{\mathrm{blue}} + L}(G), \tag{2}$$

where ρ_{NIR}, ρ_{red}, and ρ_{blue} are reflectances in MODIS bands 1, 2, and 3 (459–479 nm); C_1 and C_2 are the atmosphere resistance coefficients; L is a canopy background brightness correction factor; and G is the gain factor. The coefficients for MODIS are $L = 1$, $C_1 = 6$, $C_2 = 7.5$, and G (gain factor) $= 2.5$ (Huete et al. 1994; Huete et al. 1997).

Ferreira et al. (Ferreira et al. 2003) studied the various cerrado formations at Brasilia National Park with Analytical Spectral Devices (ASD) data collected from the MODIS Land (MODLAND) Surface Radiation and Snow and Ice Product Teams Quick Airborne Looks (MQUALS) platform in May (wet season) and July (dry season) 2000. They convolved the fine spectral resolution data into Landsat ETM+, Advanced Very High Resolution Radiometer (AVHRR), and MODIS bandpasses and computed VIs to analyze the wet and dry season spectral properties of various cerrado classes. They found only slight differences in VI values among the cerrado physiognomies despite a large range of “greenness” conditions. However, three major cerrado formations—herbaceous dominant, woody dominated, and gallery forest—could be distinguished using both the dry and wet season data. Although they found the VI products that convolved into the Landsat ETM+ bands were the most sensitive in depicting the dry and wet seasonal contrast of the cerrado formations, they reported that the MODIS VI products would also be adequate for monitoring the seasonal dynamics of the cerrado (Ferreira et al. 2004; Ferreira and Huete 2004).

The purpose of this study was to assess the potential of temporal MODIS data to discriminate the diverse cerrado physiognomies and converted pasture areas based on their seasonal profiles and phenology. Four years (2000–03) of MODIS 16-day composited, 250-m resolution VI data were extracted over a series of study sites that were biophysically sampled. We hypothesized that the MODIS VI products would be able to discern converted from native cerrado and the more woody physiognomies from the relatively herbaceous physiognomies based on differences in their phenology and greenness persistence through the dry and wet seasons. Our goal is to develop a satellite-based, cerrado-monitoring scheme of the physiognomic composites, health, and conversion of the cerrado biome. The monitoring of the cerrado biome is important to ecosystem function, carbon and water dynamics, and climate change studies.

2. Study sites and methods

The study area of interest is located near Brasilia in the northern Federal District, Brazil, where there are two, preserved cerrado sites: Brasilia National Park (BNP) and Águas Emendadas (AE) Ecological Station. BNP (15°40′S, 47°35′W) is the largest Large-Scale Biosphere–Atmosphere (LBA) experiment in the Amazon core site in the cerrado biome with an area comprising approximately 300 km^2 at an elevation of 1150 m (Figure 1). The AE (15°33′S, 47°40′W) comprises 100 km^2 at an elevation of 1100 m (Figure 1). Both protected cerrado areas are dominated by herbaceous, woody, and forested physiognomies. We also investigated the seasonal behavior of the surrounding areas that include converted cerrado (pasture and agriculture) and unprotected upland cerrado north of BNP (Figure 1).

Field measurements were conducted in BNP, AE, and the Rio de Janeiro Farm (RJ) during the period from 10 to 18 June 2002. Three north–south transects of 250-m length were set up at BNP over shrub cerrado (SC), wooded cerrado (WC), and cerrado woodland (CW) sites. Three transects were also established at AE over humid cerrado grassland (CG), WC, and CW sites. Two transects were also set up at the RJ, near Sao Gabriel, Goias (about 150 km north of Brasilia; −15.24299°S,−047.69597°W). This highly productive pasture has been investigated by the Brazilian agency Embrapa and consists of well-managed 10-yr-old pastures.

Biophysical measurements along the transects included percent cover data (green vegetation, dry vegetation, soil, herbaceous, litter, wood), the leaf and plant area index (LAI–PAI), the fraction of absorbed photosynthetically active radiation

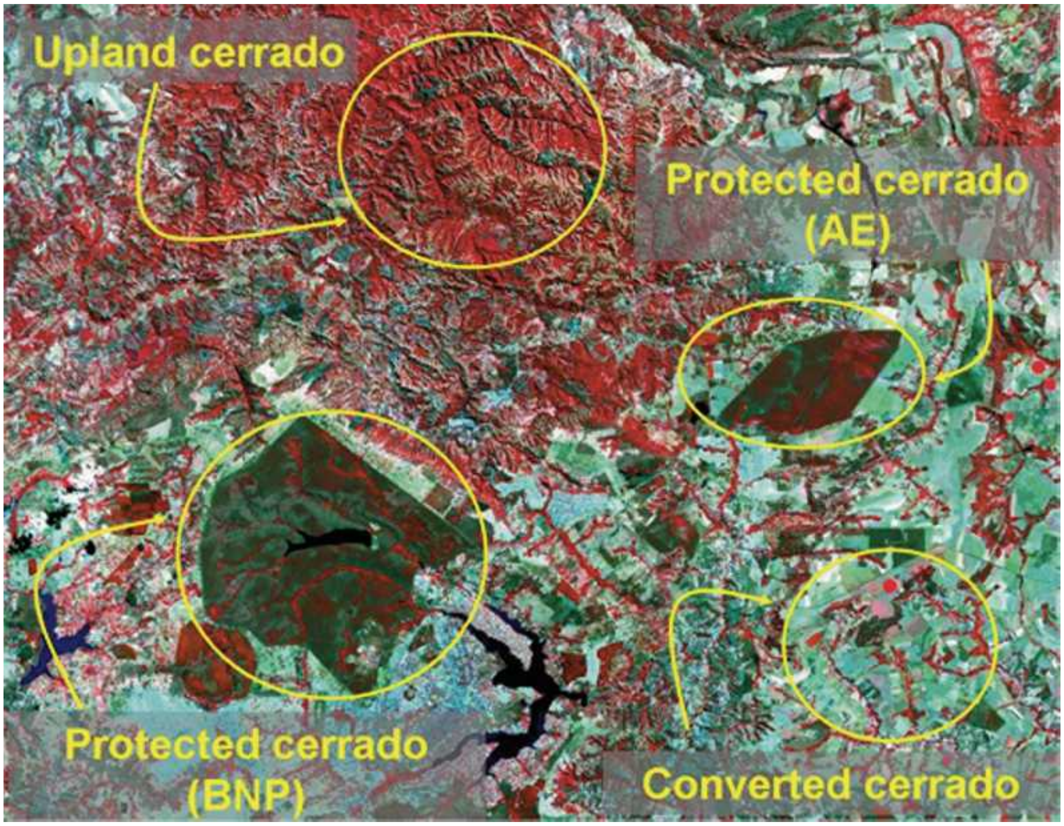


Figure 1. The cerrado study sites and surrounding regions near Brasilia (color composite image (bands 4, 3, and 2) from Landsat ETM+ image 20 Jul 2001).

(fAPAR), shrub and tree heights, and soil characterization data. The LAI-2000 was used for the LAI–PAI measurements and an Accupar ceptometer was used for conducting fAPAR measurements. Tree and shrub height measurements were made for all plants taller than 30 cm along a 10-m swath along the transects. Percent cover components were measured by using the point sampling method at an interval of 20 cm for the first 100 m of the transect and 1-m intervals for the remaining portion of the transect.

Rainfall data for the years 2000–03 were obtained from the Santa Maria meteorological station, BNP, and the 30-yr average (1961–90) rainfall data was obtained from the Global Historical Climatology Network (GHCN; Figure 2). Precipitation amounts are high in January–March (summer rain), and October–December (spring rain) with a dry period from April to October (Figure 2). In general, the 30-yr average precipitation was higher compared with the 4 yr of rainfall examined here.

The *Terra* MODIS VI products with quality assurance (QA) information were utilized to study the seasonal patterns and variability of the cerrado formations. The MODIS VI, 16-day composites at 250-m resolution from 18 February 2000 to 19 December 2003 were extracted and QA filtered to reduce cloud-contaminated pixels. The filtered VI values were averaged over each study site to generate the temporal profiles representing the various cerrado formations, gallery forest, and converted pasture sites. No smoothing nor postprocessing of the temporal profiles were performed.

Six different land-cover types were examined with the MODIS time series data, including four major cerrado physiognomies: CG, SC, WC, CW, gallery forest (GF), and cerrado-converted pasture (PA). Three replicate sites were chosen for each land-cover type, overlapping our field transects, site visits, and detailed vegetation maps (e.g., BNP, Figure 3). In addition, MODIS VI values were also extracted over large portions of BNP (140 km^2), AE (52 km^2), upland cerrado

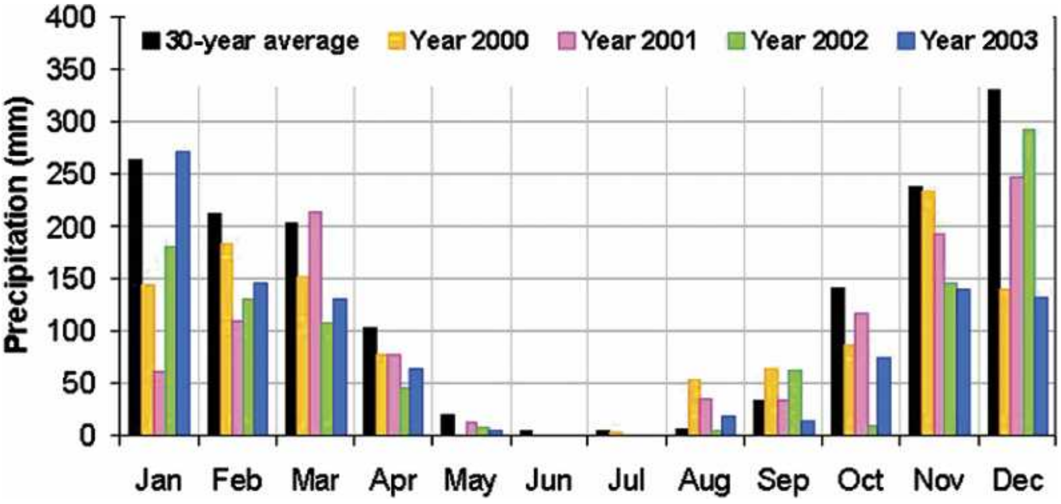
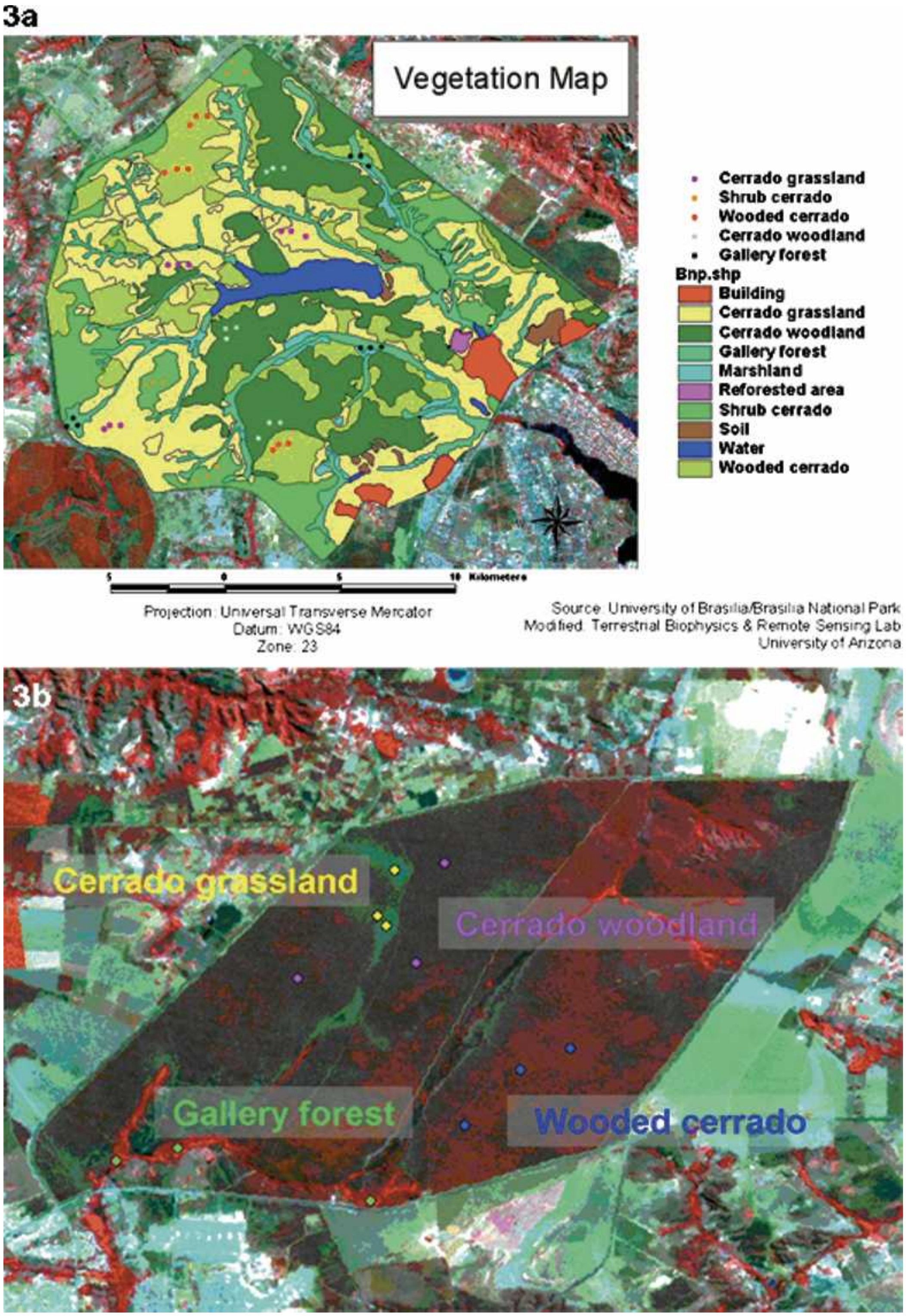


Figure 2. Monthly rainfall data for years 2000–03 at the Santa Maria station, BNP, along with the 30-yr average (1961–90).



Source: University of Brasilia/Brasilia National Park
Modified: Terrestrial Biophysics & Remote Sensing Lab
University of Arizona

Figure 3. MODIS VI extraction sites overlaid on a vegetation map of (a) BNP and (b) AE.

(150 km^2), and converted cerrado (100 km^2) to assess large-scale differences in their seasonal vegetation dynamics (Figure 1).

3. Results

3.1. Large area comparisons

The large area extracts of MODIS VI values from protected cerrado (BNP and AE), upland cerrado, and converted cerrado provided an overall comparison of their seasonal vegetation dynamics (Figure 4). The four examined areas exhibited well-pronounced seasonal NDVI and EVI profiles with the highest values in the wet season and lowest VI values in the dry season. The VI profiles followed the precipitation patterns observed in Figure 2 with a vegetation response lag of approximately 1 month. Whereas July was the lowest rainfall month in the dry season (May–August), the lowest VI values occurred in August (Figure 4). Similarly, December was the peak rainfall month in the wet season (November–March) while peak VI values occurred in February (Figure 4).

The upland, more dense and woody cerrado region had the highest VI values throughout the year while the protected cerrado (BNP and AE) sites showed

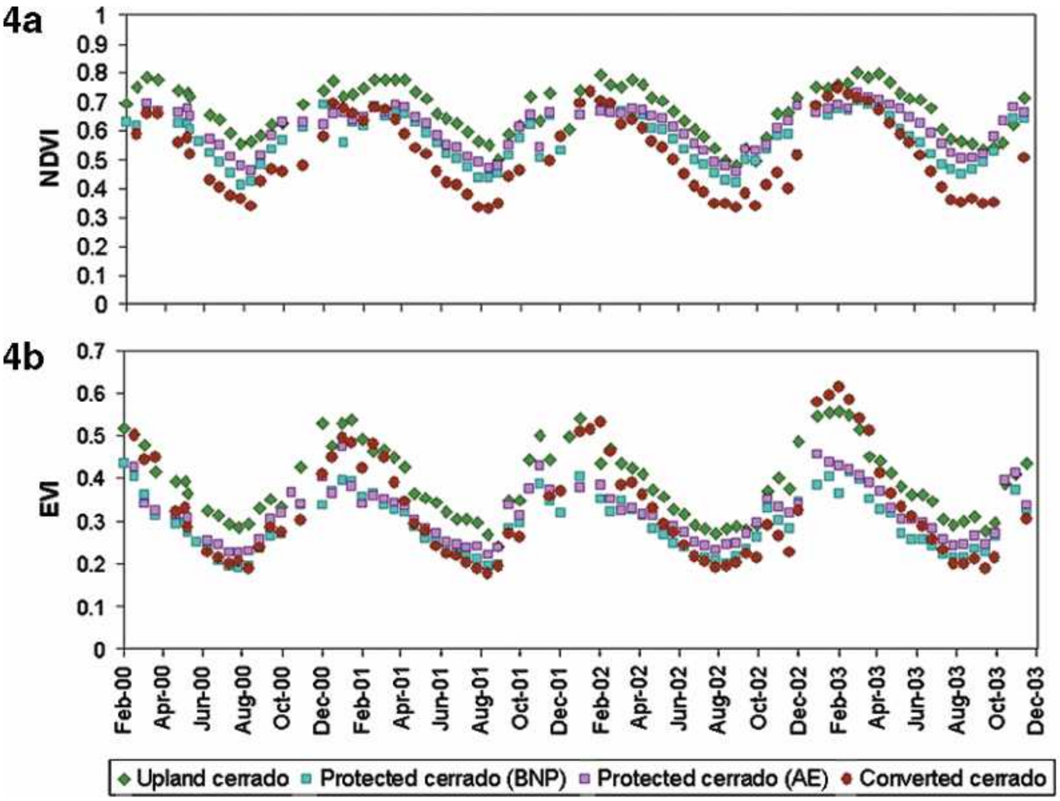


Figure 4. Four years of seasonal (a) NDVI and (b) EVI data at BNP, AE, an upland cerrado region, and converted areas.

intermediate VI values. The converted area showed the highest contrast between wet and dry seasons, particularly in the EVI profile with values varying from ~0.20 (dry season) to ~0.60 in the wet season. The converted area had EVI values that resembled the upland cerrado during the peak growing season and values that were more similar to the protected cerrado sites in the dry season (Figure 4b). The same converted sites had the lowest NDVI values in the dry season with intermediate values in the wet season (Figure 4).

3.2. Seasonal variations within cerrado physiognomies

Phenologic variations within the various cerrado physiognomic classes were analyzed with the MODIS 250-m VI seasonal profiles (Figure 5). Four dominant cerrado classes (cerrado grassland, shrub cerrado, wooded cerrado, and cerrado woodland) and gallery forest at BNP (Figure 5a) and three cerrado types (cerrado grassland, wooded cerrado, and cerrado woodland) and gallery forest at AE (Figure 5b) were analyzed along with various surrounding pasture sites. Phenology characteristics, such as “green-up,” the peak of the growing season, and dry down phases were clearly evident in the MODIS VI seasonal profiles for all four major cerrado physiognomies, as well as gallery forest and converted pasture (Figure 5). For both geographic locations (BNP and AE), all classes had maximum VI values during the rainy season and lowest values during the dry season. The seasonal profiles showed a decrease in VI values at the onset of the dry season as well as an increase in VI following the initiation of the rainy season with a time lag of about 2 months (Figure 5). There was a broad NDVI “green peak” period of the growing season, from December to March, in contrast to a sharper and more well-defined EVI green peak (January–February). A similar, but reverse, pattern can be observed in the dry season with a sharper NDVI dry period, August–September, compared with the broader EVI dry period (Figure 5). The gallery forest EVI profiles revealed more seasonal variations compared with the NDVI profile, an indication that NDVI values were approaching saturation (i.e., NDVI values above 0.8).

Differences in the VI seasonal profiles were apparent among pasture, gallery forest, and cerrado classes, but only minor variations were observed within the four cerrado physiognomic classes themselves (Figure 5). The NDVI values of these four cerrado physiognomies were intermediate between those of the gallery forest and pasture sites with the cerrado woodland sites (most woody) having the highest NDVI values and the cerrado grassland the lowest NDVI values (most herbaceous). This was also evident, but weaker, among the EVI seasonal profiles.

To further investigate the differences among the cerrado formations, we averaged the four annual cycles of VI data into single seasonal profiles for each land-cover type (Figure 6). The NDVI values of the pasture and gallery forest sites were easily discriminable from all the native cerrado classes during the dry season, but were not as well discriminable in the wet season (Figure 6a). Overall, NDVI variations among the land-cover types were greatest in the dry season and minimal in the wet season. In contrast, the EVI showed more variations across the land-cover types in the wet season, with values ranging from ~0.32 (shrub and grass cerrado) to ~0.68 (pasture; Figure 6b). EVI variations across all the land-cover types were of similar magnitude in the dry season, with the lowest variations occurring in April.

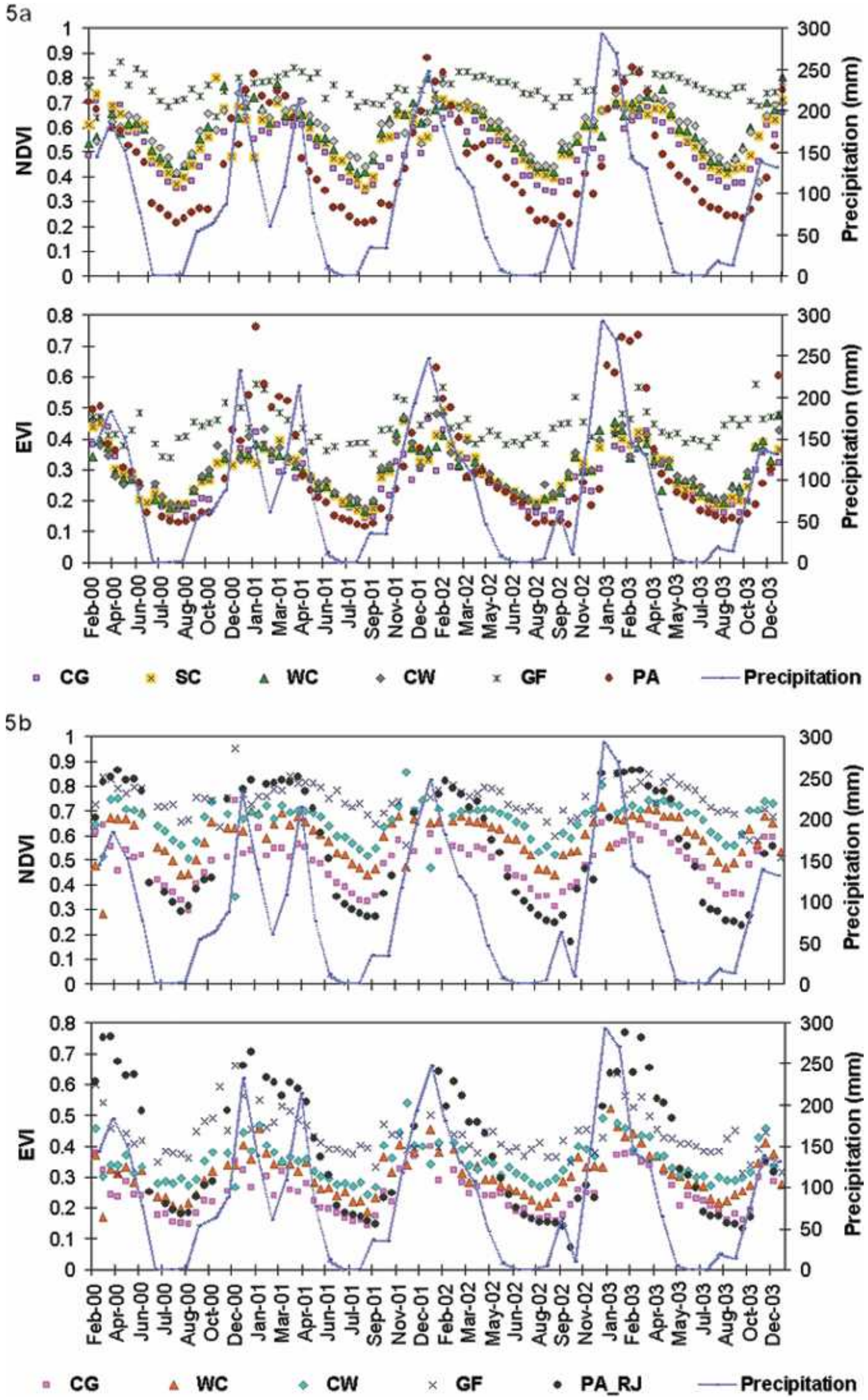


Figure 5. The VI temporal profiles of the four cerrado formations at (a) BNP and (b) AE and pasture sites in the surrounding areas. The sites include CG, SC, WC, CW, GF, and PA (site names expanded in text) including the pasture sites at Rio de Janeiro Farm (PA_RJ).

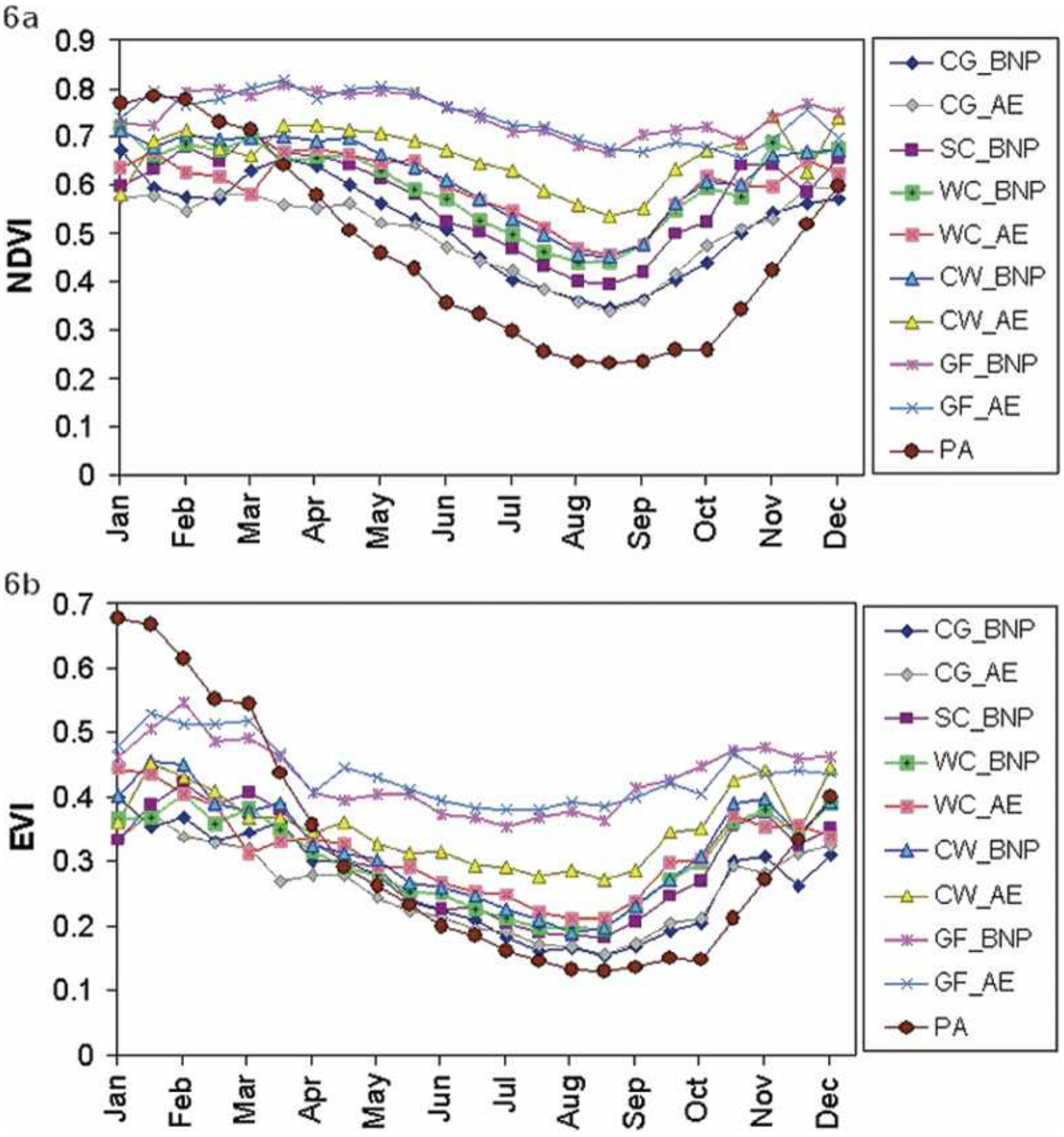


Figure 6. Average seasonal profiles of years 2000–03 MODIS (a) NDVI and (b) EVI at BNP, AE, and PA in surrounding areas (site names same as in Figure 5).

The pasture sites analyzed here were discernible from all other vegetation types in the wet period of the EVI profiles, and in the dry period of the NDVI profiles (Figure 6). The gallery forest sites were readily discriminable in the dry period of both VIs. Among the four cerrado physiognomies, the cerrado grassland sites had the lowest VI values and strongest seasonal contrast, while the cerrado woodland sites had the highest VI values and weakest contrast. However, many of the woody physiognomies, including shrub cerrado, wooded cerrado, and cerrado woodland, had seasonal profiles that were more difficult to distinguish in both VI profiles (Figure 6). Furthermore, the rate of green-up in August and September was slower in the case of pasture and cerrado grassland than the other cerrado types. This may be a result of the flush in new leaf growth that occurs with the woody plant species at the end of the dry season.

Seasonal contrast metrics, such as "normalized" maximum and minimum VI values, revealed the very strong contrast of the pasture sites and weak contrast of the gallery forest sites (Figure 7). The cerrado physiognomies were less variable and showed nearly continuous decrease in contrast between the extreme pasture and gallery forest cases. The cerrado grassland had the highest contrast with the more woody cerrado classes showing lower and less distinguishable seasonal contrasts. The cerrado woodland at AE, however, had a very low contrast, approaching that of the gallery forest (Figure 7). Both normalized measures of contrast had similar patterns across all sites, with EVI contrast values significantly exceeding the NDVI contrast values.

The averaged seasonal profiles were analyzed further by plotting the maximum minus minimum VI values (dynamic range) against their dry season, minimum VI values (Figure 8). Separately, each of these metrics of seasonality provided some measure of discrimination among the land-cover types. When plotted together, one observes an overall curvilinear relationship between land-cover seasonal contrast values and dry season values. With decreasing minimum VI values, the seasonal variations of the land-cover type became stronger (Figure 8). The gallery forest had the lowest seasonal contrast while the four cerrado physiognomies had nearly identical seasonal VI contrasts of 0.30 (NDVI) and 0.25 (EVI), except for the AE cerrado woodland, which had seasonal contrasts approaching those of the gallery forest.

In Figure 8, we can observe that the dry season, minimum VI values provided more separability among the four cerrado physiognomies than their dry–wet VI seasonal contrasts. The slopes of the plotted land-cover points to the origin provide a combined measure of both seasonal contrast and minimum VI value with steeper slopes representing higher seasonal dynamics. The more dynamic pasture sites had the steepest slopes, while the gallery forest sites had the lowest slopes. The slopes of the cerrado formations, exhibited more variation with the more woody physiognomies showing lower slopes than the herbaceous ones, particular in the NDVI plot (Figure 8).

The seasonality of the shrub cerrado, wooded cerrado, and cerrado woodland physiognomies were also investigated by normalizing their 4-yr average VI profiles by that from the cerrado grassland (no wood) to assess the effect of woody vegetation on the seasonal profile response. The normalized equations employed were as follows:

$$\mathrm{NDVIsc}^* = \mathrm{NDVIsc}/\mathrm{NDVIcg}, \tag{3}$$

$$\mathrm{NDVIwc}^* = \mathrm{NDVIwc}/\mathrm{NDVIcg}, \tag{4}$$

$$\mathrm{NDVIcw}^* = \mathrm{NDVIcw}/\mathrm{NDVIcg}, \tag{5}$$

in which normalization was carried out for each composite period of an annual cycle.

We found the normalized shrub cerrado, wooded cerrado, and cerrado woodland NDVI seasonal patterns to be distinct from the cerrado grassland profile, particu-

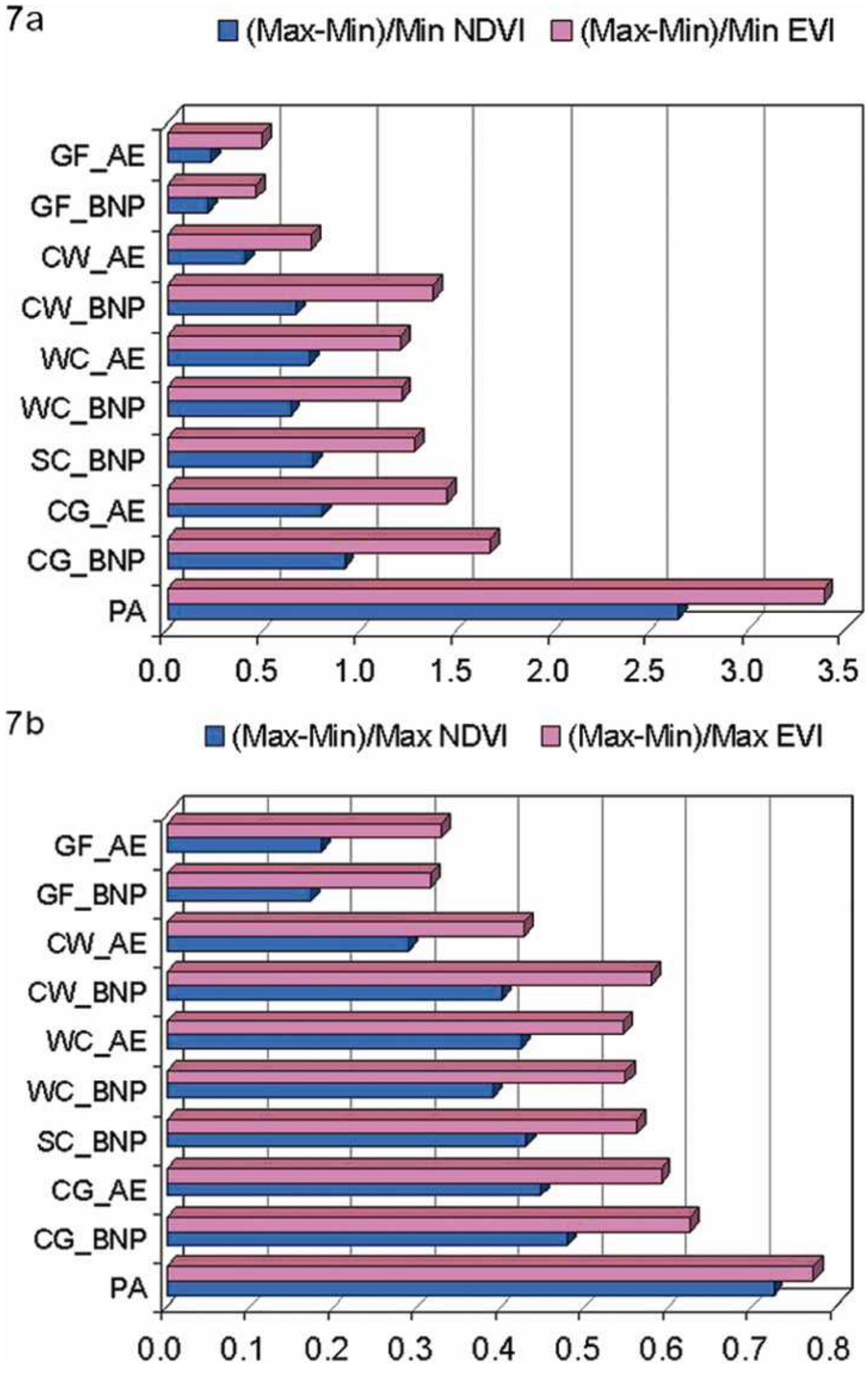


Figure 7. NDVI and EVI seasonal contrasts normalized by (a) minimum VI and (b) maximum VI for all study sites.

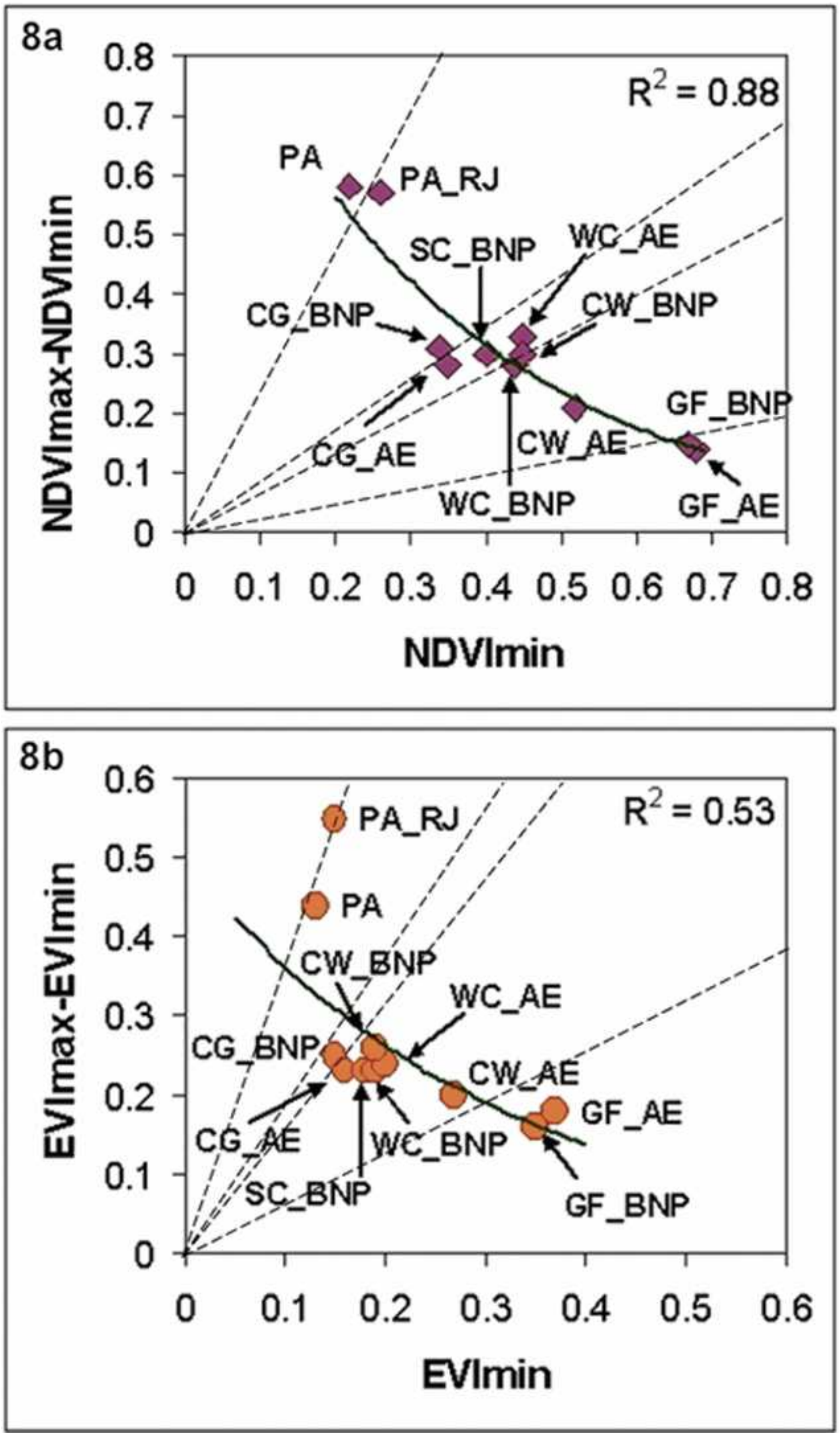


Figure 8. Relationship between (a) seasonal VI contrast (maximum − minimum) and (b) dry season, minimum VI for all the land-cover types analyzed. The slope lines illustrate variations in the combined measure of seasonal dynamics of all sites (site names same as in Figure 5).

larly during the dry season and green-up periods from September to November (Figure 9). The more herbaceous, shrub cerrado site had the weakest deviation relative to the grassland while the more woody-dominated cerrado types exhibited strong deviations that were distinct from grassland (Figure 9). The dry-down phase from March to August provided increasing separation of the woody physiognomies to each other as well as relative to the more rapidly drying "cerrado grassland" reference. This shows the buffering effect of the woody vegetation to the dynamic dry–wet cycles of the cerrado biome.

3.3. Biophysical analyses

The biophysical field data collected over the BNP, AE, and RJ study sites were correlated with MODIS VI data for the vegetation field sampling period in June 2002. The MODIS VIs were positively correlated with percent green cover during this dry season campaign (Figures 10a,b). This confirms that the VIs were primarily a measure of greenness amount (e.g., green cover) and not canopy physiognomy (e.g., tree, shrub, grass). The strong linear EVI and slightly curvilinear NDVI relationship found between green cover and VIs across the land-cover types also indicated that many of the cerrado types were not separable with the VIs because their range in green cover was too small. Furthermore, green cover variations within a single cerrado physiognomy could easily exceed variations across distinct physiognomies, as in the case of the CW sites at BNP and AE (Figures 10a,b). This shows the difficulty in using spatial variations in VI values alone to discriminate cerrado land-cover types, and shows the need to incorporate temporal (phenology) information.

On the other hand, we found a strong negative correlation between dry and wet seasonal VI contrast and percent woody crown cover for the native cerrado and

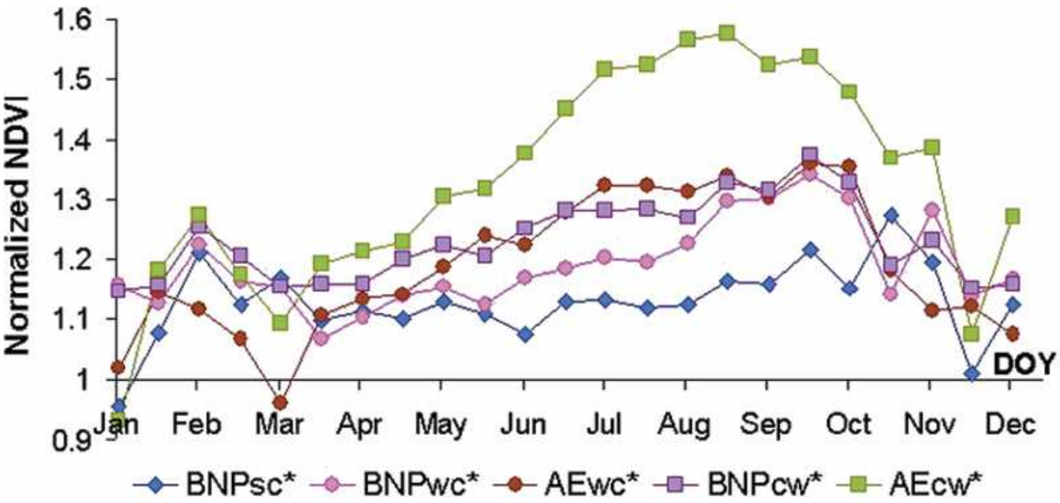


Figure 9. Normalized NDVI seasonal curves of BNP and AE shrub cerrado ($_{SC}$*), wooded cerrado ($_{WC}$*), and cerrado woodland ($_{CW}$*) obtained by dividing their 4-yr average (2000–03) seasonal response by that of the cerrado grassland.

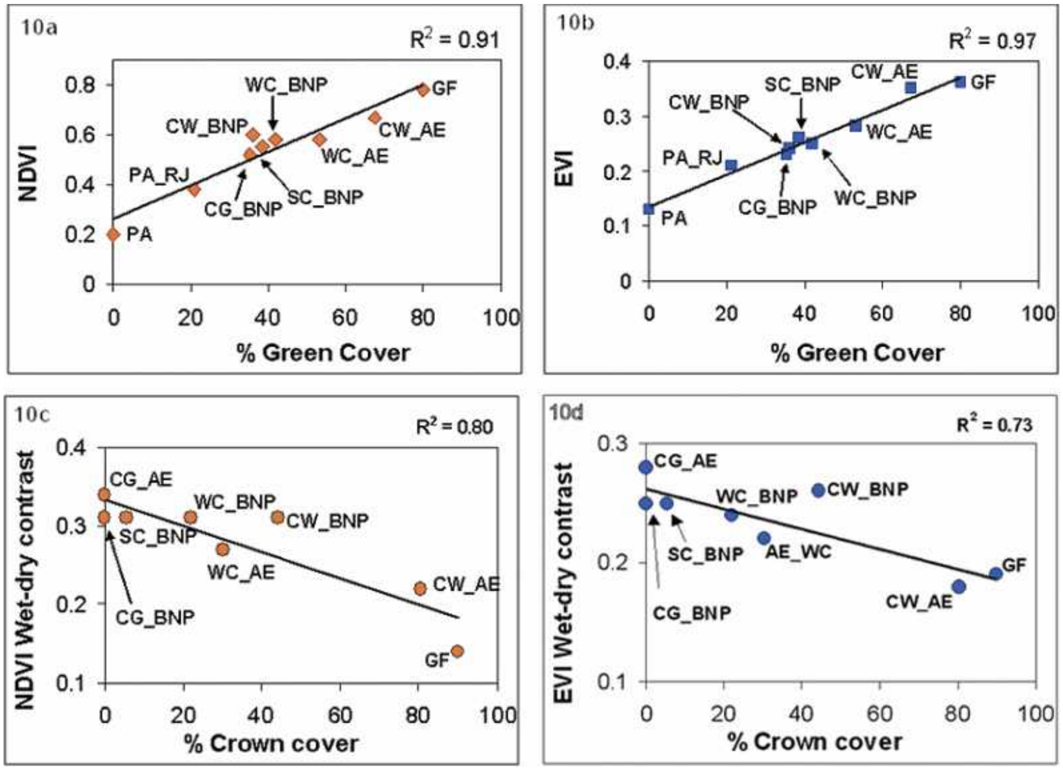


Figure 10. The relationship of percent green cover with MODIS VIs for (top) Jun 2002 and (bottom) percent woody canopy crown cover with dry–wet seasonal contrasts (site names same as in Figure 5).

gallery forest sites (Figures 10c,d). As the amount of woody crown cover increased across the cerrado physiognomies, the dry and wet seasonal contrast in VI values decreased with the gallery forest sites showing the least contrasts and the cerrado grassland sites exhibiting the highest seasonal contrasts. The converted pasture sites were not included on this graph as their seasonal contrast values, for near-zero crown cover, were twice those of the cerrado grassland sites (~0.55 to 0.60 for NDVI and EVI, respectively). As with the percent green cover relationships, seasonal VI contrast values showed larger variations within a physiognomic class (i.e., CW) than across the cerrado classes. However, one can readily note that the cerrado woodland site at AE had a canopy crown cover level near that of the gallery forest and therefore behaved more like the gallery forest sites than the cerrado woodland site at BNP (Figures 10b,c). This further shows the complexity in classifying cerrado physiognomic classes. In summary, we found that as the woody canopy crown cover increased from the herbaceous to more woody cerrado physiognomies, percent green cover (dry season) increased and seasonal VI contrast decreased.

In Figure 11, we directly compared similar physiognomic classes across geographic sites (BNP and AE). The cerrado grasslands from the two areas were nearly identical over the 4 yr. The two wooded cerrado sites and two gallery forest

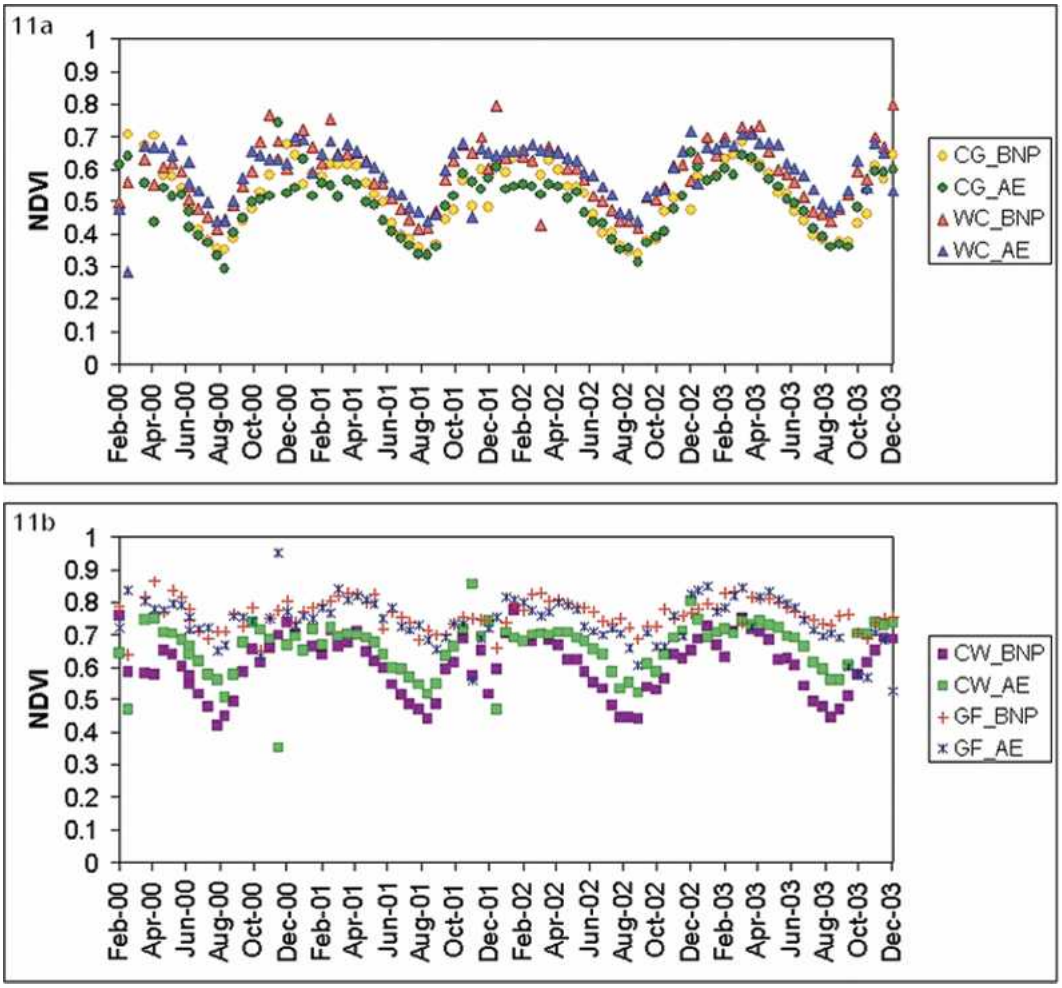


Figure 11. Cross-site comparisons (BNP and AE) of NDVI seasonal profiles for similar cerrado physiognomies: (a) CG and WC and (b) CW and GF.

sites were also similar over the 4 yr (Figure 11a). The cerrado woodland sites, on the other hand, varied greatly between the two areas, equivalent to the variations across grassland and wooded cerrado physiognomies (Figure 11b). This could be explained by the very high woody canopy crown cover at the AE site that resulted in a seasonal profile between that of the cerrado woodland at BNP and the gallery forest sites.

The cumulative VI response curves integrate VI temporal variations over the whole growing cycle and are widely used as proxies in net primary production models. Overall, the native cerrado formations had similar, "sigmoidal" profile shapes that reflected a slowdown in growth (dry season) midway through the year (Figure 12). This was more apparent in the EVI response curves. The more woody cerrado physiognomies yielded the higher magnitude cumulative VI profiles, indicating higher productivities in comparison with the more herbaceous cerrado

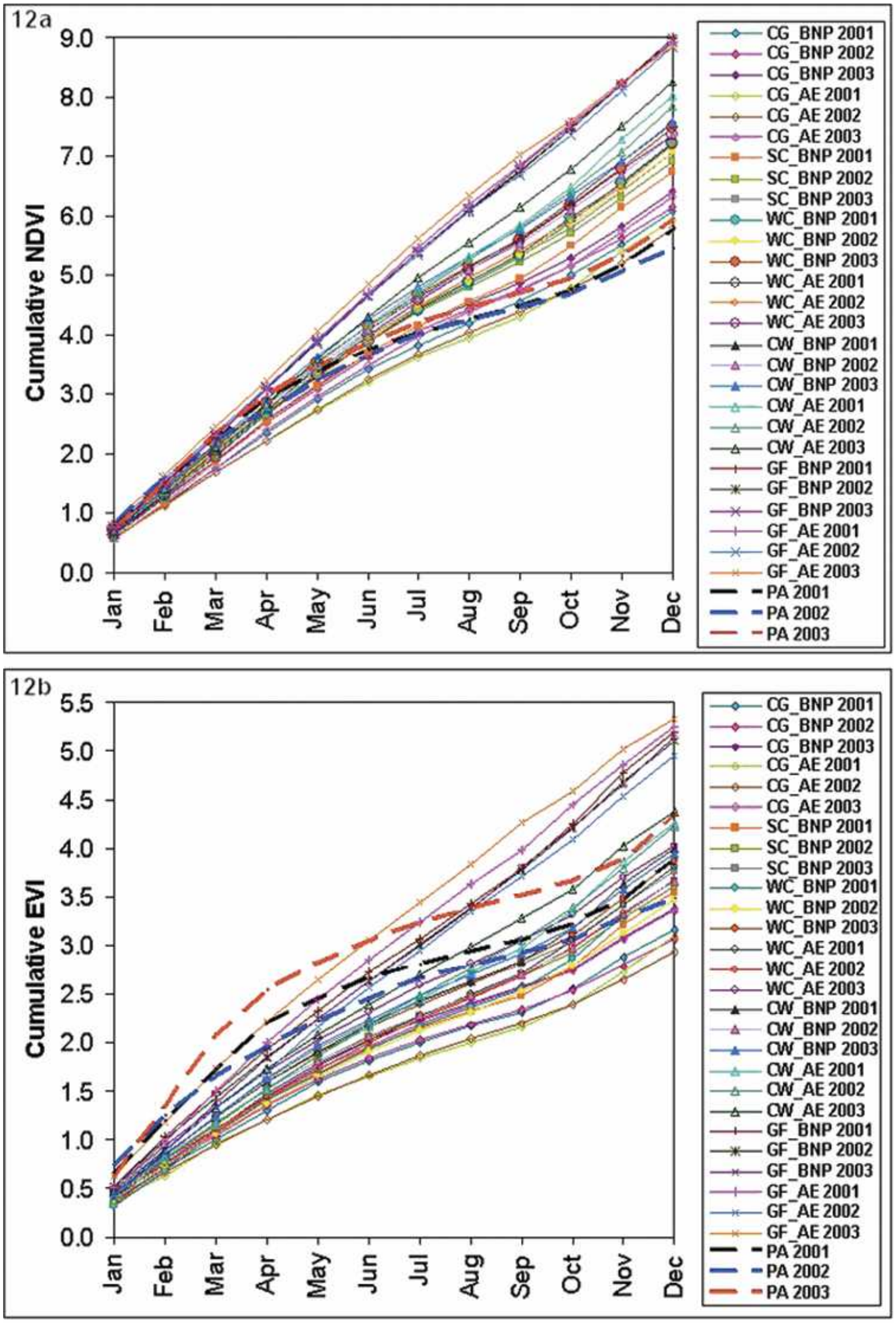


Figure 12. The cumulative response curves of (a) NDVI and (b) EVI for all cerrado (CG, SC, WC, CW), PA, and GF study sites in BNP and AE for 2001, 2002, and 2003.

types (Figure 12). The gallery forests had the highest values, followed by the cerrado woodland sites, woody cerrado, and shrub and grassland cerrado types. The gallery forests also had near-linear response curves in both VIs, indicating a strong insensitivity to the dry season.

The converted pasture sites, however, produced cumulative VI profile shapes that were markedly different from those of the native cerrado formations, a result of their stronger dry season response (flattened shape) and higher growth rates at the beginning and end of the year (wet season). There was a large discrepancy, however, between the final integrated NDVI and EVI cumulative responses, such that the pasture sites had low productivity NDVI values that were similar to those of the cerrado grassland, while the pasture sites had high productivity EVI values that were more similar to those of the cerrado woodland (Figure 12b).

The NDVI cumulative response curves also showed minimal interannual variations while the EVI curves showed more variations in the response curves and production over the 3 yr. This can be related to variable rainfall dynamics, such as the high January 2003 rainy period resulting in the steep increase in pasture EVI responses in February–March 2003, or the high March 2001 rainfall resulting in a steep increase in pasture EVI response in March–April 2001 (Figure 2).

4. Conclusions and discussion

The “cerrado” biome in central Brazil has been largely converted into agriculture and pasture. This conversion has important implications for local and regional climate change and for changes in carbon fluxes between the atmosphere and the land surface. Thus, a study of seasonal cerrado dynamics and phenology of the diverse cerrado biome encompassing woodland, grassland, gallery forest, and converted areas was conducted using 4 yr, 2000–03, of *Terra* MODIS vegetation index (VI) data. We used a series of field study sites, representing the major cerrado types, to relate MODIS NDVI and EVI seasonal patterns and profiles with land-cover physiognomy and biophysical field measurements.

We found the MODIS vegetation index time series data to be useful in studying both the seasonal dynamics of the cerrado physiognomies and cerrado land conversions. All of the cerrado classes and converted pasture sites showed strong VI seasonal profiles depicting seasonal trends in photosynthetic activity. The VI seasonal profiles had well-pronounced dry and wet period variations with high vegetation activity in the growing season (November to April) and decreasing VI values during the dry-down and dry phases (May to September), and the VIs responded to the monthly rainfall profiles fairly well with a 1–2-month lag in response.

The MODIS VIs were found to be well correlated with vegetation biophysical properties, particularly percent green cover, across a wide range of cerrado physiognomic classes (herbaceous to woodland). In fact, the MODIS VIs appeared to primarily respond to the greenness amount (green cover) of the site and not canopy structure nor physiognomy (tree, shrub, grass). Hence if percent green cover values overlapped between two cerrado physiognomies, then the VIs would not be able to distinguish between these cerrado types. The MODIS VI seasonal profiles thus represented a combined “community” phenology of herbaceous understory vegetation and woody vegetation with open overstory canopies. The woody cerrado component largely presented an evergreen signal that increased with new leaf growth at end of dry season (August) just prior to the rains. This was difficult to differentiate, however, from the green grass growth that occurs at the onset of rain activity in September, given the 16-day temporal resolution of the composited data.

Despite the lack of sensitivity of the VI to canopy structure and physiognomy, the dry–wet seasonal contrast variations in the VI profiles were sensitive and showed strong negative correlations with woody canopy crown cover across the various land-cover types, providing a method to discriminate among converted cerrado areas, gallery forests, and the woody and herbaceous cerrado formations. The converted pasture areas showed the highest VI seasonal contrasts while the gallery forest formations had the lowest contrasts. The contrast variations within the cerrado physiognomies themselves were not as pronounced as those of the forest and pasture types, but enabled the more woody cerrado types to be differentiated from the herbaceous-dominant types.

The two MODIS VIs (NDVI and EVI), each provided unique and useful information in the analysis of cerrado seasonal patterns and dynamics. Whereas NDVI provided significant variations across all the study sites in the dry season, the EVI provided more variations among the cerrado types in the wet season, a period in which the NDVI yielded less information. While the pasture sites were discernible from all other vegetation classes in the dry season with the NDVI, pastures were more discernible in the wet season using the EVI. Annual integrated VI values showed gallery forests and cerrado woodland to be the most productive with shrub and grassland cerrado the least productive. The annual integrated VI profiles of the converted pastures, however, differed significantly between the two MODIS VIs such that the pastures were found to be very productive in the EVI data (similar to the cerrado woodland) and were least productive in the NDVI data (similar to the shrub and grassland cerrado). These discrepancies in the annual integrated VI values are in need of more attention, especially when considering the impacts and consequences of cerrado conversion to pasture on productivity and carbon cycling.

In summary, we found that moderate resolution satellite remote sensing, such as MODIS, offers valuable and useful information for monitoring the highly diverse and complex cerrado biome and associated cerrado conversions. Although there were limitations, much information on phenology and seasonal cerrado dynamics were retrievable from the seasonal time series MODIS data. Coupling satellite time series data with vegetation biophysical properties, canopy structure, and physiognomies will greatly improve our understanding of climate variability and anthropogenic impacts on the cerrado biome.

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