CERRADO VEGETATION USING OPTICAL AND ACTIVE REMOTE SENSING: TWO BRAZILIAN CASE STUDIES.

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ABSTRACT

The amount of phytomass is crucial parameter for the ecology as a whole. Seasonality in *Cerrado* (Brazilian savanna) physiognomies is marked by green leaves lost during the dry period and re-growth during the wet season. The amount of leaves can be estimated either by field determination or by non-destructive methods. Three case studies: one testing passive remote sensing data and Leaf Area Index (LAI) abilities to predict vegetation variation; other comparing a tower registered radiation with Normalized Difference Vegetation Index (NDVI) images; and finally testing SAR L-band ability to estimate above-ground woody biomass (AGWB). *Campo cerrado* physiognomy, showed the highest NDVI variation and *Cerradão*, the lowest NDVI variation from one season to another. PAR albedo variation is from 0.028 to 0.052, from dry to wet season, following the precipitation curves. Solar albedo variation, which includes near infrared radiation, is from 0.08 to 0.17, from dry to wet season. The same seasonal variation proportion was observed with LAI values. An equation to estimate AGWB, using allometric parameters and SAR L-band backscattering, is proposed: the estimation curve with R^2=0.8714, indicates the utility of JERS-1 L band images to estimate AGWB in areas covered by *Cerrado s.s.* and *Cerradão*.

INTRODUCTION

Phytomass is a vegetation parameter that is crucial in ecology as it is the essential basis of the trophic network and is directly affected by climate change. There are two different aspects regarding phytomass: one related to the amount of leaves and the other to the amount and geometry of trunks and branches. In the case of the *Cerrado* biome, the amount of leaves is related to a gradient of vegetation structure from open to densely woody physiognomies and is seasonally-dependent and strongly related to the radiation balance. The quantity of trunk and branch biomass however, varies directly with gradient of vegetation physiognomies. Passive or active remote sensing provides a rapid and non-destructive means of studying or monitoring large scale biomass vegetation, but its usefulness for the analysis of *Cerrado* vegetation has not been rigorously assessed.

The aims of this paper are twofold: to assess the value of remote sensing in estimating the structural components of vegetation and to quantify the relationship between the spectral vegetation index and the radiation balance. In order to compare the ability of estimating green and woody biomass using passive and active sensors, two case studies were analysed seasonally, using two different methods and two different areas. To appraise the practicalities of using a remotely sensed vegetation index to estimate the radiation balance, a further case study was undertaken comparing field and image data from dry and wet seasons with the radiation balance recorded by a tower sensor.

BACKGROUND AND CONTEXT

The *Cerrado* biome (the Brazilian savannas), originally occupied 23% of the national territory. In 1997, Conservation International suggested that this biome was one of the 18 endangered World Hot Spots. At that time more than 70% of the biome had been cleared for agriculture, especially for soybean production. In the Brazilian State of São Paulo, 14% of the area used to be covered by *cerrado*, while today less than 1% remains preserved, mostly in private hands (Kronka *et al., 1993;* SMA-SP, 1999). From a Brazilian conservation point of view, study and monitoring of the *cerrado* has become extremely urgent as a result of the expansion of the agricultural frontier (Silva *et al*., 2005).

According to Coutinho (1978), the *cerrado* vegetation comprises a range of physiognomies, from grassland to arboreal formations. The gradient of density, height and cover of woody species results in different physiognomies with an increasingly woody content from *Campo limpo* to *Campo sujo*, *Campo cerrado*, *Cerrado sensu stricto* (s.s.) and *Cerradão*. *Cerrado sensu lato* (s.l.) usually comprises a patchwork of these physiognomies depending on soil, topography and human impact.

The flora of the *cerrado* consists of approximately 800 species of trees and large number of sub-shrubs, shrubs and herbs. It has typical features of pyrophytic savanna vegetation. The trees are of low contorted form with a thick, corky, fire-resistant bark. Sclerophylly is common and many leaves have thick cuticles, sunken stomata, greatly lignified and sometimes silicified tissues. Xylopodia are well developed in both the woody and herbaceous vegetation (Furley, 1994, 1999; Ratter & Dargie, 1992; Ratter *et al.,* 1996).

In São Paulo State, the focus of the present study, the *cerrado* physiognomies vary from *campo cerrado* to *cerrado sensu stricto* (*s.s*.) to *cerradão* (savanna woodland). Other associated forest types, such as riparian forest and seasonal semi-deciduous forest (SSForest), can also be found particularly in the São Paulo portion of the *cerrado* biome. The *cerradão* canopy is 10 to 15 m high and has regular surface height geometry; on the other hand, the SSForest canopy is 15 to 25 m high and its geometry is relatively rough, mainly because of the presence of emergent trees. The total amount of above-ground woody biomass distinguishes these two vegetation types according to Batalha *et al*. (2001). They also found that cylindrical volume is the best variable to distinguish the *cerrado* physiognomies and can be used to estimate the amount of phytomass. The *cerrado* physiognomies in São Paulo show increasing cylindrical volume values, from *campo cerrado* through *cerradão* (Table 1).

Mesquita Jr. (1998) found a direct relationship between the cylindrical volume and NDVI obtained from satellite images. With cylindrical volumes varying considerably from the woody and herbaceous components (from *campo limpo* to *cerradão*), it is necessary to find the best method to predict the wood and leaf biomass.

The occurrence of dry and wet seasons raises two important questions regarding the vegetation cover in the *cerrado* biome: what is the best method for estimating green and wood biomass using remote sensing methods, and how can passive remote sensing contribute to better understanding of radiation balance? Green biomass and radiation balance are related to the amount of green leaves present in each physiognomic type and vary seasonally. The more woody physiognomies however, differ from one another not only in species composition but also in the amount of total above-ground biomass due to trunks and branches.

Gower *et al.* (1999) made an extensive analysis of the direct and indirect methods used to estimate the leaf area index (LAI), the fraction of absorbed photosynthetically active radiation, and net primary production obtained from remotely sensed products. According to these authors, all of the optical instruments available are liable to underestimate the leaf area index, especially when foliage in the canopy is clumped, as it is in the *cerrado* biome. They also compared the leaf area index obtained from various methods and the vegetation index obtained from satellite images. This experience indicated the potential usefulness of an experiment where simultaneous LAI and NDVI measurements of *cerrado* physiognomies could be compared with the photosynthetically active radiation recorded in the field.

The vegetation index obtained from optical reflectance has been proposed as a good non-destructive method to estimate green biomass, leaf area index or for classification (Bitencourt-Pereira, 1986; Mesquita Jr., 2003). According to Huete *et al.* (1999), optical remote sensing is strongly related to the presence of green leaves and can be measured indirectly with the normalized difference vegetation index (NDVI), which is directly related to leaf area index and biomass. They showed that NDVI correlates exponentially with LAI, saturating around LAI = 4. However, the seasonal variation can lead to misinterpretation when optical remotely sensed data are used to measure vegetation cover parameters. Several Brazilian studies have used optical remote sensing to estimate Brazilian *cerrado* biomass but the results indicate that such techniques are only applicable for some physiognomies because of the seasonality (Bitencourt *et al.*, 1997; Mesquita Jr., 1998; Bitencourt, 2004; Bitencourt *et al.*, 2004). A number of attempts have been made to estimate campo *cerrado* green biomass, with vegetation indices obtained from MSS Landsat data (Bitencourt-Pereira, 1986; Valeriano & Bitencourt-Pereira, 1988), and some studies have attempted to quantify *cerrado* s.s. total biomass through vegetation indices obtained from TM Landsat data (Santos, 1988).

The (active) microwave L-band signal can penetrate into a vegetation canopy and respond to the structure volume. That fact could improve the prospects for vegetation analysis. In recent years microwave images have become useful to ecologists because their signals are more related to aspects of geometry, such as branches and trunks, than to the presence of leaves. The distance between trees can also be measured with that microwave. Another advantage is the fact that they are less dependent on weather conditions allowing images even during the wet season. The potential of Synthetic Aperture Radar (SAR) images like JERS-1 (L band) for the study of *cerrado* physiognomies has been explored by Santos *et al.* (1998, 2000, 2002) and the possibility of estimating woody biomass from active remote sensors were explored by Kasischke *et al.* (1997) and Santos *et al*. (1998). Imhoff (1995) showed that the correlation between biomass and backscatter is due to the increased scattering volume that occurs from the forest canopy as the above-ground biomass increases. He contends that the level of saturation in estimating above-ground biomass is limited by the microwave wavelength. He correlated field biomass with C, L and P-bands backscattering respectively, and found that the C-band saturates with less biomass, followed by the L-band and the P-band. Thus, it is expected that P-band images will be better for estimating biomass because they saturate at a higher biomass. Santos *et al.* (2003) also explored the use of airborne SAR P-band in estimating above-ground biomass in tropical rain forest, opening a new perspective toward estimating biomass of dense physiognomies.

Radiation balance in each type of vegetation can be measured daily using field sensors located in towers. However, due to the high costs of having a tower in each separate physiognomic type, optical remote sensing was used here to estimate the variation in green biomass within the seasonal radiation balance.

LOCATION AND METHODS

Study areas

The study areas are *cerrado* remnants taken from the Forest Inventory of São Paulo State (Kronka *et al.,* 1993) They contain the full range of *cerrado* physiognomies, as well as some patches of associated types of vegetation. Fig. 1 illustrates their location as well as the extent of the *cerrado* domain in Brazil and São Paulo State.

The first area is a conservation unit (CU), named Pé-de-Gigante, located in Santa Rita do Passa Quatro municipality (47°37'W and 21°37'S), covering approximately 1,225 ha (Mesquita Jr., 1998 and 2003; Batalha *et al*., 2001; Bitencourt *et al*., 2004). The second area is a set of natural vegetation remnants, within private properties, located in Campos Novos Paulista municipality (50°00' W and 22°30' S) with an area of approximately 1,766 ha (Kuntschick & Bitencourt, 2003; Bitencourt *et al*., 2004).

Insert Fig. 1 here

Both field areas were used to perform three investigations: estimates of (i) Green Leaf and (ii) Above-Ground Woody Biomass, using either passive (Landsat and Ikonos) or active (JERS-1) remotely sensed data; and (iii) to relate the reflectance vegetation index with Radiation Balance data obtained in the field. To estimate green leaf and investigate radiation balance it is necessary take seasonality into account together with the structure of each *cerrado* physiognomy. Pé-de-Gigante CU is appropriate, not only because there is a tower collecting daily data, but also because the vegetation is well studied. To estimate above ground woody biomass (AGWB) it was necessary to select appropriate woody *cerrado* physignomies.

The Pé-de-Gigante CU was created in 1970, with 1,225 ha spread over altitudes ranging from 590 to 740 m. The present vegetation comprises all of the *cerrado* physiognomic types. Climatically, the region is classified as tropical with wet summer and dry winters, which corresponds to Cwa of Koeppen's Climatic Classification. The mean annual precipitation is 1,475 mm year^{-1} and the mean monthly temperature is around 23 ºC, with little variation. According to Mesquita Jr. (1998), there are 600 ha of *cerrado s.s.*; 404 ha of *cerrado s.s.* with a thin herbaceous stratum; 49 ha of *cerradão*; and 114 ha of *campo cerrado*, plus other associated physiognomic types of vegetation. The amount of green leaves in each physiognomic unit was estimated using two methods: firstly, reflectance transformed into classes of a vegetation index and secondly, leaf area index obtained in the field using a non-destructive method. The results were compared to the daily radiation collected (from a tower) in the same period to see whether vegetation indices could be used to estimate radiation balance.

The Campos Novos Paulista remnants, were used collectively to find the relationship between AGWB of *cerrado* s.s. and *cerradão*, using the regression analysis between backscattering signal (σ) within L band SAR images and AGWB obtained from an appropriate allometric biomass equation.

Passive System: Green Leaf Estimates

In order to obtain the seasonal variation in NDVI (normalised difference vegetation index between near infrared and red bands), a series of five TM Landsat images was used. Four images from 1995 (June 03, July 07, August 22, November 10) and one image from January 29, 1996 were analysed. All images were compensated for atmospheric effects and solar angle, and then converted from digital numbers to reflectance (Mesquita Jr., 1998 and 2003). Fig. 2 shows the spatial distribution of the physiognomic types in the conservation unit. The polygons defining the area of probable occurrence of the *cerrado* physiognomies were obtained from the average NDVI, from dry to wet season, for each class. The vegetation structure was measured within an area of 2.7 ha with all physiognomic types. Thus, in 30 permanent plots of 30x30 m all trees were measured, giving data on diameter at ground level, total height, crown height and diameter, species type, and the X and Y coordinates of the individual tree positions. Fig. 3 illustrates the arrangement of all trees in the sample area with a diameter at ground level greater than 10cm and the arrangement of the permanent plots. Each circle represents the projection of the circular crown diameter. The plot arrangement shows the physiognomic (crown density) gradient from savanna woodland (*cerradão*) to the predominantly grassy type of vegetation (*campo cerrado*).

The pixel size is 30m for optical Landsat bands, and 4 m for Ikonos multispectral bands. Thus, each permanent plot was designed with a maximum size of 30 x 30m, to be comparable with other satellite images. All permanent plots were arranged in three connected lines, from East to West. This arrangement provides for geographical alignment of both lines of pixels and terrain permanent plots. Because all images are always geo-coded with some sub-pixel uncertainty, the vertices of the terrain polygon were used to obtain the average NDVI value related to each permanent plot.

The LAI estimations took place during dry and wet seasons (June 2001 and January 2002) using two Plant Canopy Analysers (Li-Cor LAI-2000). In each field trip, 25 records were taken in each permanent plot (a total of 750 records for each period) and they were used to calculate the mean LAI within each plot. It had been earlier suggested (Gower *et al.,* 1999), that 22 records would be enough to calculate the mean LAI of each plot. The LAI values were compared with the NDVI average of Ikonos-Multispectral image from April 21, 2001.

Insert Figs 2 & 3 here

Passive system: Radiation Balance

The relationship between vegetation cover and radiation rests on the fact that leaves are responsible for capturing most of the solar energy at the Earth's surface, particularly in the visible PAR (photosynthetically active radiation) band (0.4µm – 0.7µm). It is expected that the amount of solar energy absorbed by the vegetation cover changes seasonally, especially in biomes like *cerrado*, which has two prominent seasons (one dry and one wet). Thus, using optical remote sensing data, it is possible to measure the photosynthetically-active vegetation and compare it with the amount of energy registered in the field. The spectral vegetation indices, obtained from satellite, are numerical models that have a direct relation with green biomass per area since they result from the spectral responses of the vegetation in the red and near infrared bands. The spectral response of the vegetation in the red band is due to the presence of chlorophyll and the spectral response of the vegetation in the near infrared band is due to leaf structure. Since vegetation indices are proportional to green leaf density and the *cerrado* physiognomies range from grassland to forest, it is possible to map these physiognomies using vegetation indices.

LAI can also be used to estimate total amount of leaves, which can vary from 1 to 8, with 1 corresponding to desert vegetation and from 6 to 8 corresponding to rain forest. Daughtry (1990) reviewed several direct or indirect methods to measure the LAI, and the correlation of this information with remote sensing data. His work showed that LAI can be used to estimate the total amount of leaves of each tree of all vegetation cover. Considering the relationship between LAI and NDVI, we want see if it is possible to correlate solar and PAR albedo, obtained in the field, with NDVI classes obtained with optical remote sensing.

This present study utilized a tower installed in *cerrado* s.s., with sensors for PAR and solar albedo as illustrated in Fig. 4. A quantum system (LiCor – 190AS sensor) was used to measure the PAR (0.4μm to 0.7μm) albedo. A pyranometer was used to measure the total radiation of the solar spectrum ($0.28\ \mu$m to $2.8\ \mu$m), with a LiCor – 200AS sensor.

Fig. 4 shows the plan of the vegetation physiognomy and the tower. The radiation collection period was the whole of 2001. The vegetation classes were abstracted from a map published in Mesquita Jr. (1998) and LAI data for each class were collected in the field, in June, 2001 and in January, 2002. The NDVI, the vegetation index used in the analysis, is obtained from the reflectance of red and infrared bands from two satellites: Landsat-TM and Ikonos-Multispectral. The sphere of detection of the tower sensors is smaller than 50m diameter, covering the *cerrado s.s.* physiognomy around the tower. Considering that the spatial resolution of Landsat-TM is 30x30ms and Ikonos-Multispectral is 4x4m, it is acceptable to compare the energy registered in the images and by the tower.

Insert Fig 4 here

Active microwave system: Estimates of above ground woody biomass

Microwave radiation is emitted from the JERS-1 radar antenna, which also receives the backscattered signal from the earth's surface. The sigma signal (σ) value is the ratio of the received backscattered energy over the emitted energy. Usually σ values are expressed in decibels (dB) units. The pixel values in the original image are in digital numbers (DN). These values can be converted to σ through equation 1 (Rosenqvist, 1997; Shimada, 2001).

$$\sigma = 10.\log_{10}\left(\frac{\Sigma\left(DN^2\right)}{n}\right) + CF$$

Equation 1

DN = digital number of a pixel in a 16 bit image

σ = the ratio of received backscattered energy over emitted energy

n = number of pixels sampled

CF = calibration factor (Table 2).

Generally, the σ values are dependent on the geometry of the signal emitted by the antenna and the type of its backscatter produced by the target on the ground. The JERS-1 SAR signal interacts with earth's surface roughness on a magnitude of half of the wavelength (λ =23 cm) and mostly with objects oriented according to the VV (vertical emission – vertical reception) signal polarization (i.e. tree trunks).

A number of parameters are important in understanding the response of the target on the Earth's surface. They include geometry of satellite and antenna (satellite ephemeris and antenna angle) in relation to surface and target (corner reflection and specular reflection). When the satellite is in a descendent orbit (North to South), the antenna views the west side, when it is in an ascendant orbit (South to North) the antenna views East. According to the date of the image, it is possible to determine its orbit and the antenna angle (http://www.eus.eoc.nasda.go.jp/). This information, together with relief data, can be used to identify the patterns of corner reflection, layover and shadow in the signal received. Images acquired when the satellite orbit is descendent will have high reflection caused by east hill surfaces over high slope relief (corner effect and incident angle close to zero), and for ascendant orbit the opposite applies. According to Luckman *et al*. (1998), the satellite orbit is important to an understanding of the signal reflected by the target in the JERS-1 SAR images. For these reasons it is also important to make the conversion using the factors given in Table 2.

Two SAR images from the JERS-1 satellite were used to calibrate field data with the satellite backscattering response. The data were supplied by the Japan Aerospace Exploration Agency (JAXA). All digital processing was performed using all or some of the following software: ERDAS Imagine, ERMapper, and ENVI. The work was undertaken in *cerrado* remnants located in two farms, within the Campos Novos Paulista Municipality. The *cerrado* remnants are currently surrounded by pasture and, to a lesser degree, by cultivation.

A JERS-1 image acquired on December 20, 1995 (path/row 389/-338) was used for the above test. An ETM+ Landsat-7 image (221/076) was also used to select the sample sites within the study area. The optical image was acquired on June 26, 2002 and was geo-coded with ground control points obtained either in the field using a GPS receiver or obtained from a 1:50,000 topographical map (IBGE, 1975). A preliminary classification of the vegetation types from both farms was performed using the NDVI image. Based on this classification, a rapid floristic survey was made in the area (Durigan *et al.,* 2003a,b; Ratter *et al*., 2000a,b., 2003), in order to improve the information on vegetation type and conservation conditions. As a result, a structural physiognomic zoning map comprising ten vegetation classes was constructed to aid the sampling process. In each zone, biophysical data were measured and, based on these data, above-ground wood biomass (AGWB) values were computed. The vegetation was sampled using the point centred quadrant method (Mueller-Dombois & Ellenberg, 1974). Ten sample sites were chosen to analyse the vegetation in the field. In each site, 20 quadrants (with four trees each) were measured. Other parameters, measured for each tree, comprised diameter at breast height (DHB), distance from the central tree and height. The AGWB estimate was made through the application of allometric equations (Equation 2) developed by Abdala *et al.* (1998):

$$\log(y) = 0.9967 \log(x) + 2.587 \qquad \text{Equation 2}$$

where **y** = total individual weight (g) and **x** = cylindrical volume (dm^3). The equation was developed for *cerrado s.s* and *cerradão* vegetation types, located in the central portion of the *cerrado* domain. The AGWB values of these sampled points were related to the **σ** data recorded in the radar images.

The SAR image was read, subset and geo-coded to UTM projection, using the software ENVI 3.5. The image was filtered with a 3x3 Frost type filter in order to reduce the effect of the speckle noise. Fig. 5 shows the location of the 10 sample sites, inside or outside the *cerrado* remnants polygons (in grey) obtained from Kronka *et al.*(1993). The backscattering **σ** values considered for each sample site, are the average values found inside the samples polygons (in black), also shown in the Fig. 5.

Insert Fig 5 here

The 10 sample sites comprised:

- **Sample site 1** corresponding to an old area covered by *cerradão*, outside the *cerrado* remnant and partially deforested for raising cattle.
- **Sample site 2** was an area with similar covering, but with a greater number of remnant trees.
- **Sample site 3** was covered by an open type of *cerrado s.s*. In this site the trees were smaller and more numerous than in the previous sample site.
- **Sample site 4** was covered by an ecotone which ranged from *cerradão* to SSForest. There were many trees re-growing from axial buds at the bottom of the trunk. A total of 80 trees were sampled in this area. Among them, 17 showed the phenomenon of multiple axial re-growth. This area was connected with others covered by pasture and cattle invaded it continuously, harming regeneration.

- **Sample site 5** was covered by *cerradão*, with significant accumulation of litter on the ground. This site provided evidence that fires were not frequent in this area, as in many similar areas.
- **Sample site 6** corresponded to a well preserved *cerradão* tract close to the edge of the remnant. The area was clear cut 30 years ago, but since then it has been protected from cattle. For this reason an advanced regeneration process was evident.
- **Sample site 7** corresponded to a well preserved central tract of *cerradão* with little influence from edge effects.
- **Sample site 8** had a *cerradão* vegetation cover and was located to the south of the drainage line.
- **Sample site 9** was also covered by *cerradão* and was located alongside the drainage, between sites 8 and 10.
- **Sample site 10** was covered by *cerradão* and located in the North part of the forested drainage strip.

RESULTS

Green Leaf Estimates

The results of the overall LAI mean values, for dry and wet seasons, are presented in Table 3. In each sample plot all plants were identified, providing information on the predominant *cerrado* sub-groups. Thus, besides the LAI mean values resulting from 25 records in each plot, there is also data on the predominant physiognomy. The lowest mean values of LAI are observed in *campo cerrado* (A 1,3 and 4; B 3 and 4; C 3 and 4), followed by *cerrado*.s.s.(A 5 and 6; B 1, 5, 6 and 9; C 1, 5, 6 and 10), and *cerradão* (A 7, 8, 9 and 10; B 7 and 8; C 7, 8 and 9). Table 4 illustrates the mean LAI values found for each physiognomic group. C*ampo cerrado* showed a slightly greater variation between seasons, from 1.15 to 2.32, when compared to *cerradão,* which varied from 1.89 to 2.85. All physiognomies show LAI values below 4, indicating that the NDVI is sufficiently good for prediction.

The relationship between the NDVI obtained from an Ikonos-Multispectral image and the mean LAI obtained in the field for each permanent plot is shown in Fig. 6. The LAI data were collected in June 2001. In that year, it was still raining in May and had not dried out by June (Fig.7).

Insert Fig 6 here

The Ikonos image corresponds to the pre-dry period, which should be the best period to discriminate between the *cerrado* physiognomies using NDVI images obtained with TM-Landsat (Mesquita Jr., 1998). However, some differences were expected with the Ikonos-Multispectral NDVI image because the pixel size in that image is 4x4 m as opposed to 30x30 m. in TM-Landsat. The increased spatial resolution of the Ikonos images may also increase reflectance side effects due to exposed soil, litter and shadow.

The gradient of physiognomic groups shows a significant seasonal variation in NDVIs, from dry to wet season: *campo cerrado* from 0.35 to 0.67; *cerrado s.s.* from 0.41 to 0.69; and *cerradão* from 0.48 to 0.71 (Table 5). *Campo cerrado* showed a NDVI variation around 50%, reducing toward 30% as the physiognomy changes to *cerrado s.s.* and *cerradão.*

Radiation Balance

Fig. 7 shows the solar and PAR albedo data collected from the tower as well as the precipitation per month during 2001. The inversion observed from July to October reflects the lack of precipitation observed from June to August. PAR albedo increased from 0.028 to 0.052 from February to September (around 50%) and decreased again to 0.028 from October to December, due to the reduction in the amount of green leaves that absorbed energy in that portion of the electromagnetic spectrum.

Insert Fig 7 here

Solar albedo, which includes near-infrared radiation, showed a decrease from 0.08 to 0.17 (> 50%) during the dry season. The reason for this is also related to the loss of green leaves, which are responsible for high reflectance in the near-infrared region. After September, the regrowth of green leaves increased the measured solar albedo.

The LAI variation may include dead leaves still held in the vegetation, giving some uncertainty. The NDVI variation is mostly due to the green leaves, but may also be affected by the presence of exposed soil, dead biomass and shadow. Both LAI and NDVI values showed the same trends from dry to wet seasons. The vegetation index image is better because it can give a rapid and efficient description of the green vegetation distribution, with the same level of uncertainty offered by the LAI measurements. Thus, the use of NDVI images is as acceptable as LAI, so commonly used to estimate green leaves and, consequently, the radiation balance (Daughtry, 1990; Gower *et al.*, 1999).

Active microwave system: above-ground wood biomass estimate

The field data are summarised in Table 6, compiled from the analysis of 80 trees observations in each of the 10 samples sites, comprising a total of 800 trees sampled. The backscattering values showed a direct correlation with the AGWB: low AGWB values indicate low σ values, corroborating the literature (Kasischke *et al*., 1997; Santos *et al*.,1998). Sample sites 1 and 2 are both outside the *cerrado* remnants (Kronka *et al.*,1993). The trees found there belong to *cerradão,* with cylindrical volume of 664 and 473 dm^3 respectively. Their total biomass levels are the smallest of the *cerrado* formations studied, due to the mean distance between trees (38.3 and 18.2m, respectively). The σ are the smallest amongst them. Site 3 comprises a *cerrado s.s.* with trees 11.2m apart, with AGWB still low, and σ a little lower than the previous one. Sites 4 to 10 are all *cerradão* but with different structural conditions due to their conservation stage. Although site 4 shows species belonging to the transition between *cerradão* and SSForest, the mean cylindrical volume is 98.97 dm^3, the AGWB is 5 times bigger than the previous site because the mean distance between trees is 3 times smaller, with σ similar to the *cerrado s.s.*. Sites 5 and 6, containing species typical of *cerradão,* are quite similar in terms of cylindrical volume, mean distance between trees, and σ mean values lower than the previous one, with AGWB levels varying from 33.43 to 62.67 t ha^{-1}. Site 5 is badly preserved (BP) and site 6 lies near the edge (NE) of the remnant. They both quite similar in terms of cylindrical volume, AGWB, distance between trees, and σ values. Site 7, which is far from the edge (FE) contains higher cylindrical volume, AGWB, distance between trees and σ values, when compared with the previous sites. According to IBGE (1975), that study area is a pasture.

The only exception is a strip located alongside a drainage channel that runs approximately from North to South. In this area, the only portion that appeared to be covered by forest twenty five years ago, was covered by *cerradão* with some evidence of past fire (charcoal-covered cork found in some individuals). For that reason, three sites were sampled to the north, centre and south. Site 8 is a denser form of *cerradão* (cylindrical volume 167.29 dm^3 and 2.23m of distance between trees), showing higher AGWB and σ mean values. Finally, sites 9 and 10, which are located along the drainage line (AD), give the highest AGWB, corroborated by the cylindrical volume, with σ mean values among the highest values. The cylindrical volume values (due to the woody portion only) were used not only to calculate AGWB but can also be associated with the conservation status: sites 1 and 2 were managed to maintain only the biggest trees. The σ mean values is directly proportional to AGWB, until around 130 $t.ha^{-1}$, and inversely proportional to the distance between trees (the more sparse the trees, the smaller is the L band backscattering).

Fig. 8 shows an asymptotic curve relating AGWB, obtained from allometric parameters, with σ mean values obtained from the JERS-1 image. The AGWB, from less dense physiognomies, is followed by the lowest σ values increment and the AGWB, from denser physiognomies, and showed a smaller increment in σ values.

Insert Fig 8 here

The equation derived from the regression analyses (Equation 3) shows a very good correlation ($R^2 = 0.8714$), making it useful for estimating AGWB in other *cerrado* areas.

$$\mathbf{Y = 1.5135 \ln (dB \text{ or } \sigma) - 14.924} \qquad \text{Equation 3}$$

DISCUSSION

Passive Remote Sensing:

NDVI x LAI - The relationship between NDVI and LAI substantiates the hypothesis that the NDVI values increase as LAI values increase, providing the LAI is below 4 (Huete *et al.*, 1999). Further, the NDVI and LAI variations, from *campo cerrado* to *cerradão,* observed here showed similar pattern as the one found by Mesquita Jr. (2003). In other words, low arboreal cylindrical volume means also low NDVI and low LAI.

The gradient of physiognomies showed a significant seasonal variation in NDVI, with up to double their values between the dry and wet seasons. The *campo cerrado,* with lower cylindrical volume values, showed the highest NDVI variation and, conversely, the *cerradão,* with higher cylindrical volume values, showed the lowest NDVI variation. This variation can be associated with the fact that most of the herbaceous stratum suffers as the water supply becomes scarce during the dry season. Perennial trees on the other hand, can access deeper water supplies and maintain their greenness over a longer period.

Radiation Balance x NDVI - The solar and PAR albedo data collected from the tower seem to follow the mean precipitation per month. The inversion in albedo curves observed from July and October, reflects the lack of precipitation registered from June and August. PAR albedo increased during the dry season from 0.028 to 0.052 (> 50%) due to the reduction in the amount of green leaves (low LAI and NDVI) responsible for absorbed energy in that portion of the electromagnetic spectrum.

Solar albedo, which includes near infrared radiation, showed a decrease from 0.08 to 0.17 (> 50%) from dry to wet seasons. The reason for this is also related to the loss of green leaves, which are responsible for high reflectance in the near infrared region. After September, new green leaf growth increased the solar albedo measured.

Similar variations were observed in both LAI and NDVI values, from the dry to the wet seasons. LAI variation may include standing dead leaves, which may reduce its precision but NDVI variation is mostly due to the green leaves, although it may be affected by the presence of exposed soil, standing dead biomass, and shadow. Another advantage of the vegetation index obtained from reflectance images is a rapid and efficient description of the green vegetation distribution. Thus, the use of NDVI images is as acceptable as the LAI, which is commonly used to estimate green leaves and consequently the radiation balance.

In the Mesquita Jr. (1998) study, the NDVI variation over the year (from wet to dry to wet season) showed similar behaviour to the solar albedo measured by the tower sensors. This observation suggests an acceptable capability of NDVI images to predict LAI and radiation balance:- the higher the NDVI or LAI, the higher the solar albedo and the lower the PAR albedo.

Active remote sensing

SAR image x aboveground woody biomass - The results suggest a stable tendency but up to 70 $t.ha^{-1}$ of biomass, the backscattering values start to increase in lower rate. The increasing AGWB at sites 6 to 10 does not have the same backscattering variation as in sites 1 to 5. The behaviour of the curve supports the usefulness of the L band radar images, specifically of the JERS-1 microwaves sensor, to estimate forest AGWB up to a threshold value of 100 $t.ha^{-1}$, in areas covered by *cerrado s.s*. and *cerradão*. The microwaves interact with the trunks of trees and the returned signal is related to the amount of AGWB. However, the signal is influenced by both living and dead trees. It is therefore, necessary to take the total AGWB into account.

Santos *et al*. (2002) also used JERS-1 SAR images to quantify AGWB in the contact zone between rainforest and *cerrado* in the Brazilian States of Roraima and Mato Grosso. Although that study showed higher AGWB values, the shape of the curve was similar to that in the present study, suggesting that if SAR data is able to estimate rain forest biomass, it also can estimate *cerrado s.l.* vegetation because this vegetation formation is less dense than forest.

The validity of the present work may be jeopardised by the fact that the JERS-1 image was acquired by the satellite six years before the field work was undertaken. During this period of time changes in the vegetation are likely to have occurred. However, during the vegetation survey under the BIOTA/FAPESP project in 1999, the *cerrado* vegetation inside the remnants (Kronka *et al.,* 1993) was considered to be very well preserved, which supports the results found. Thus, the results suggest that L-band radar imagery is suitable for AGWB quantification in *cerrado* areas.

CONCLUSIONS

The multiwavelength approach used in this paper allows the characterisation of the vegetation by indirect measurements. The results obtained with the NDVI series of Landsat images provide a comprehensive understanding of the vegetation structure. This approach allows us to infer the vegetation dynamic processes detected from the tower, allowing an extrapolation to the whole conservation unit. The tower results provide very high temporal resolution information about the vegetation dynamics throughout the year, which can be related to seasonal variation. The variation in the amount of green leaves in the *cerrado* gradient of vegetation physiognomies can be rapidly and efficiently estimated using a spectral vegetation index (NDVI) obtained from optical remote sensing. The measurements of solar albedo also correlated with other physical environmental parameters that can be used as a component of high order environmental models. The radiation balance from dry to wet season, measured in the field, varied in the same proportion as the LAI and NDVI changes, obtained respectively from Plant Canopy Analyser and from NDVI images. The spectral response of the green leaves closely matched the results from remotely sensed data, a feature which has not been reported in the literature so far. NDVI values are directly related to LAI (where $LAI<4$) and to photosynthetically active radiation, which can be used to estimate net primary production. But as NDVI is only related to green leaves, a different method is necessary to estimate branch and trunk biomass. The above-ground woody biomass (AGWB) showed a very good correlation (R^2 = 0.8714) with the data from the SAR L-band image. The estimation equation (equation 2) found here, which uses allometric parameters of 800 trees, provides a reliable non-destructive technique for predicting above ground biomass in areas with similar vegetation density. L-band SAR data have given better results than optical vegetation index images, for both *cerradão* and *cerrado s.s.* SAR images may be used to map the spatial distribution of different classes of cerrado vegetation and to estimate the amount of carbon stocked in the biomass. There is still discussion about the upper limit of biomass that can be detected from L band SAR images, which may lie somewhere between 100 and 120 $t.ha^{-1}$. The ecological importance of phytomass estimation makes it essential to look for new non-destructive methods. The SAR images are especially helpful because the microwaves are independent of weather conditions (transparent to clouds and rain). In the near future other SAR bands will become available, such as P band, which is expected to estimate phytomass with more precision. Also in the future, there is the option of band polarisation, which will further improve the non-destructive estimation of phytomass.

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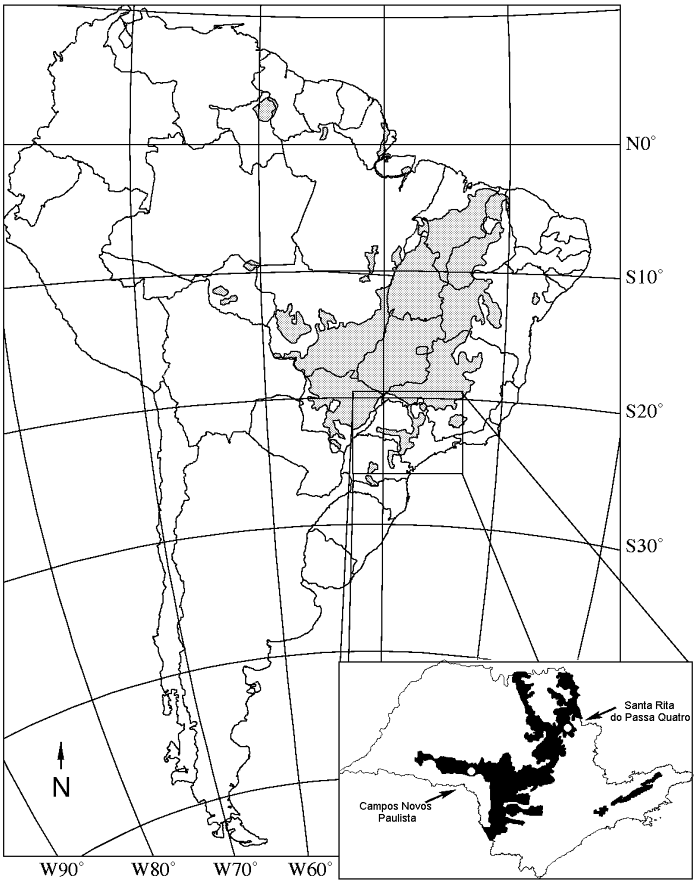


Figure 1 The distribution of the *cerrado* domain in South America. The inset map shows the extent of *cerrado* in the State of São Paulo (IBGE, 1993) and the location of both study areas.

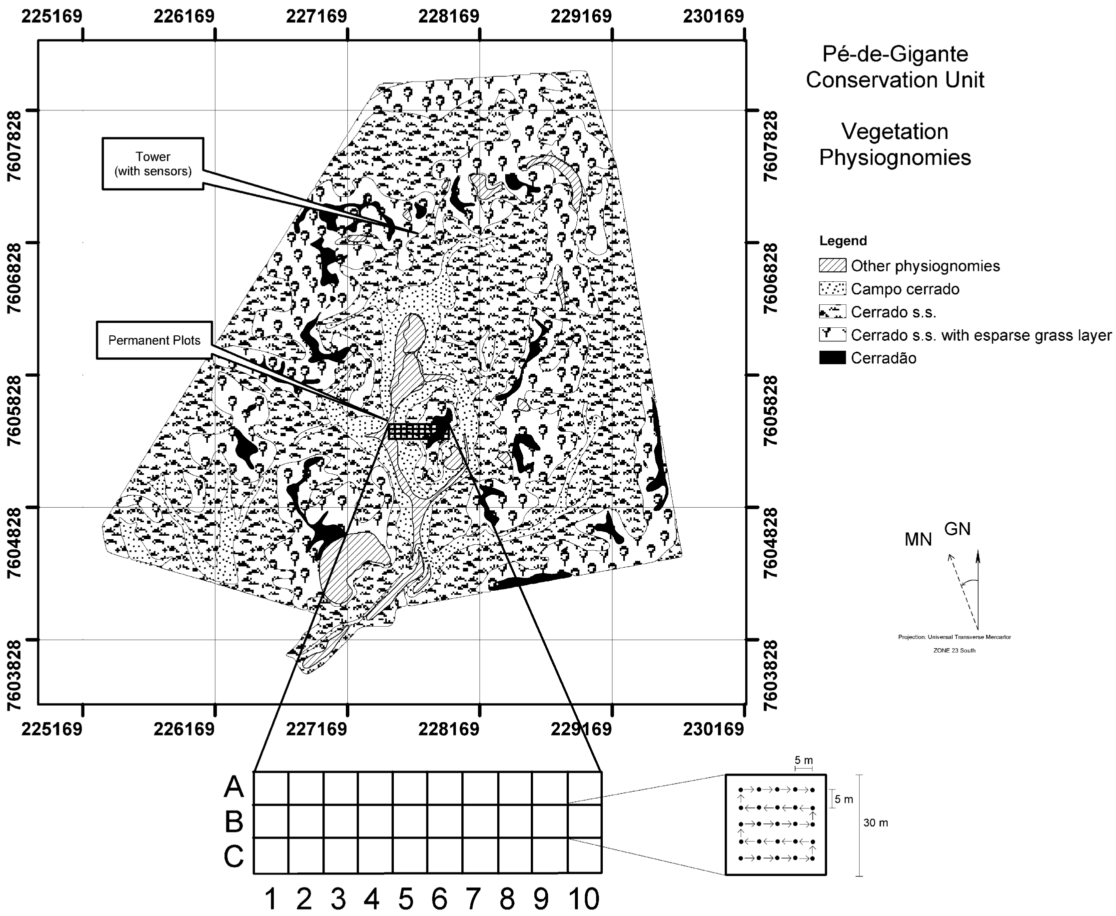


Figure 2 (a) map of the Conservation Unit where the green leaf estimates and radiation balance studies took place; (b) the scheme of the permanent plots where the LAI was estimated and (c) the field sample arrangement.

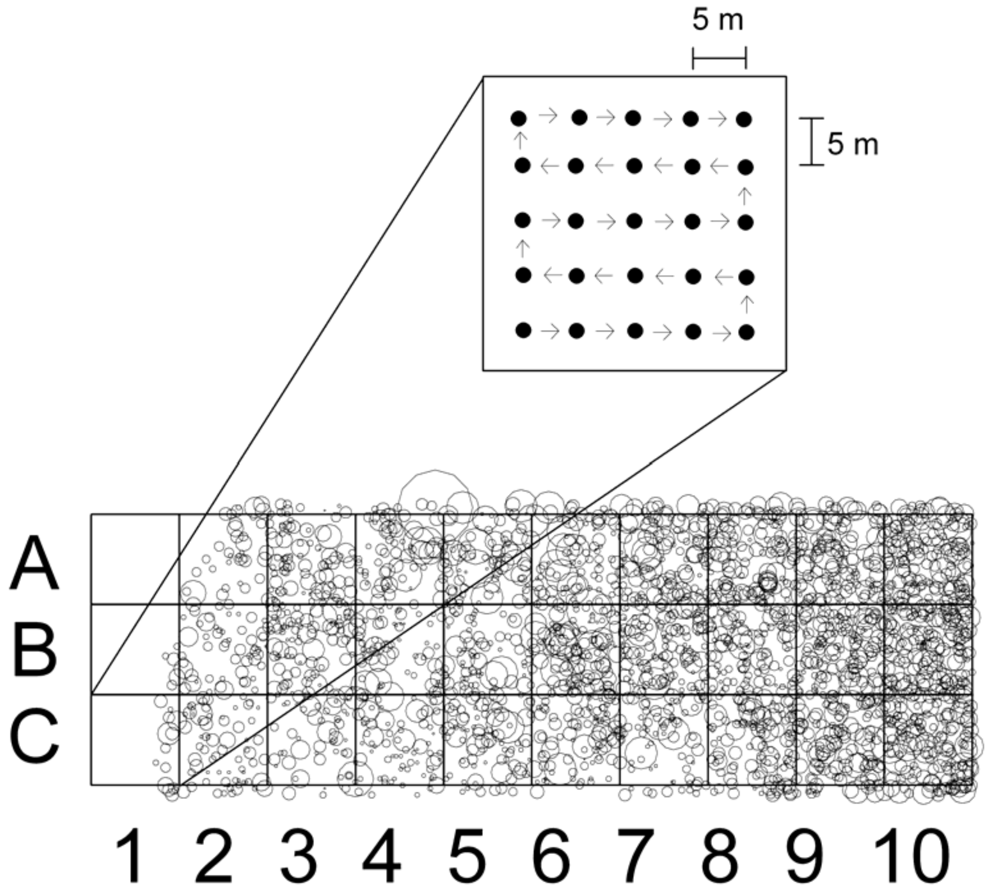


Figure 3 Detail of the field procedure to collect LAI values, in 30 permanent plots of 30 x 30m. Each permanent plot represents the actual vegetation cover identified in the field.

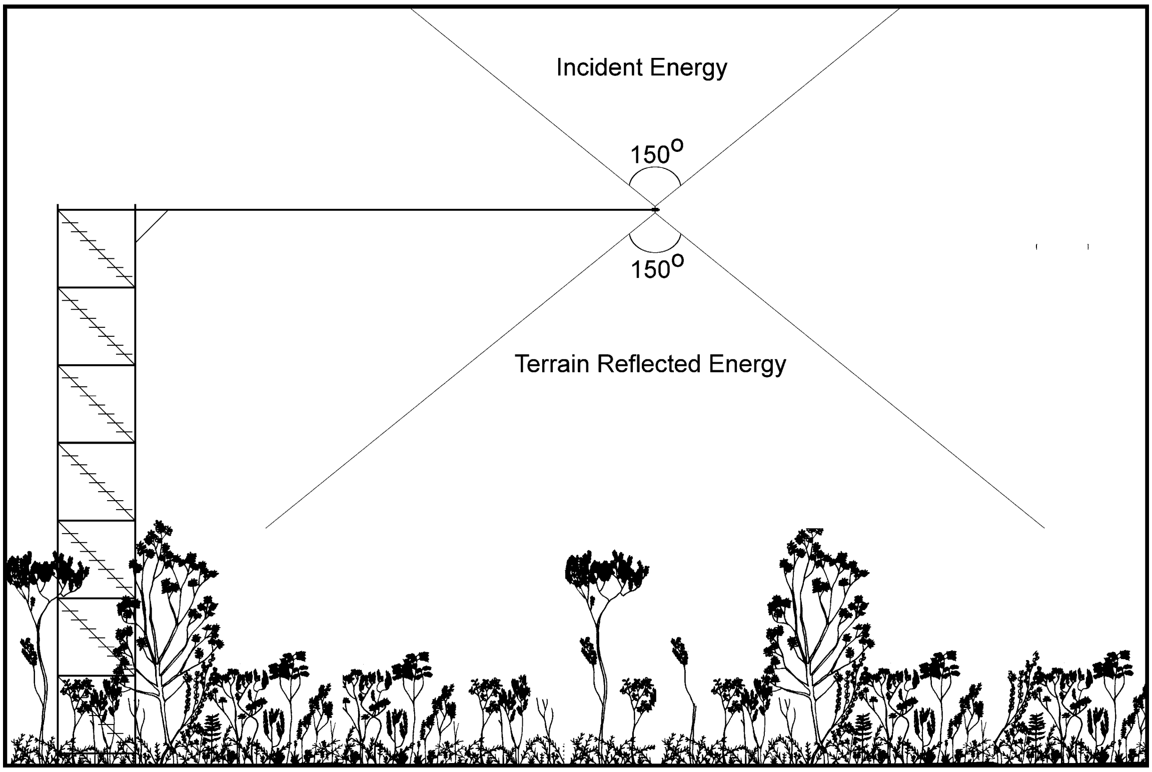


Figure 4 The design of the tower in relation to the vegetation profile.

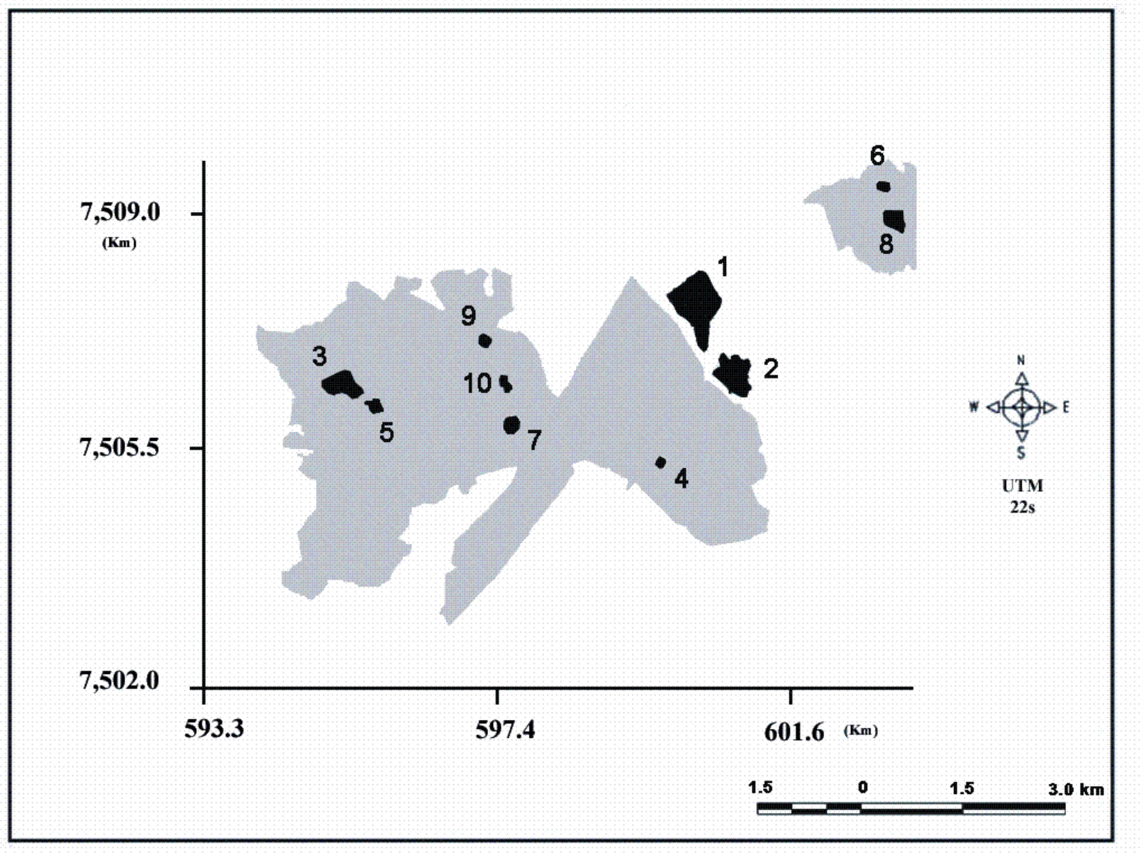
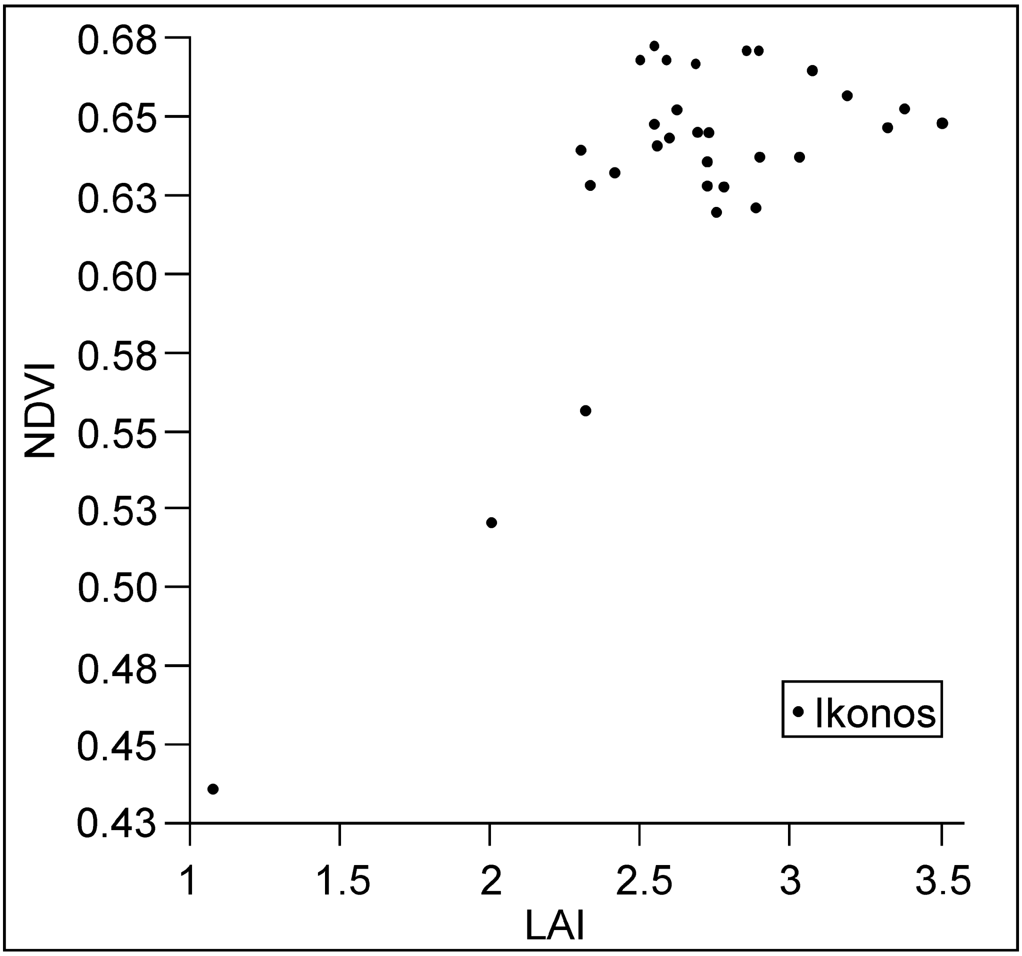


Figure 5 The study area showing the studied 10 sampled sites (in grey polygons) and the sample plot areas (in black polygons) from where the JERS-1 image backscattering and AGWB data were collected.



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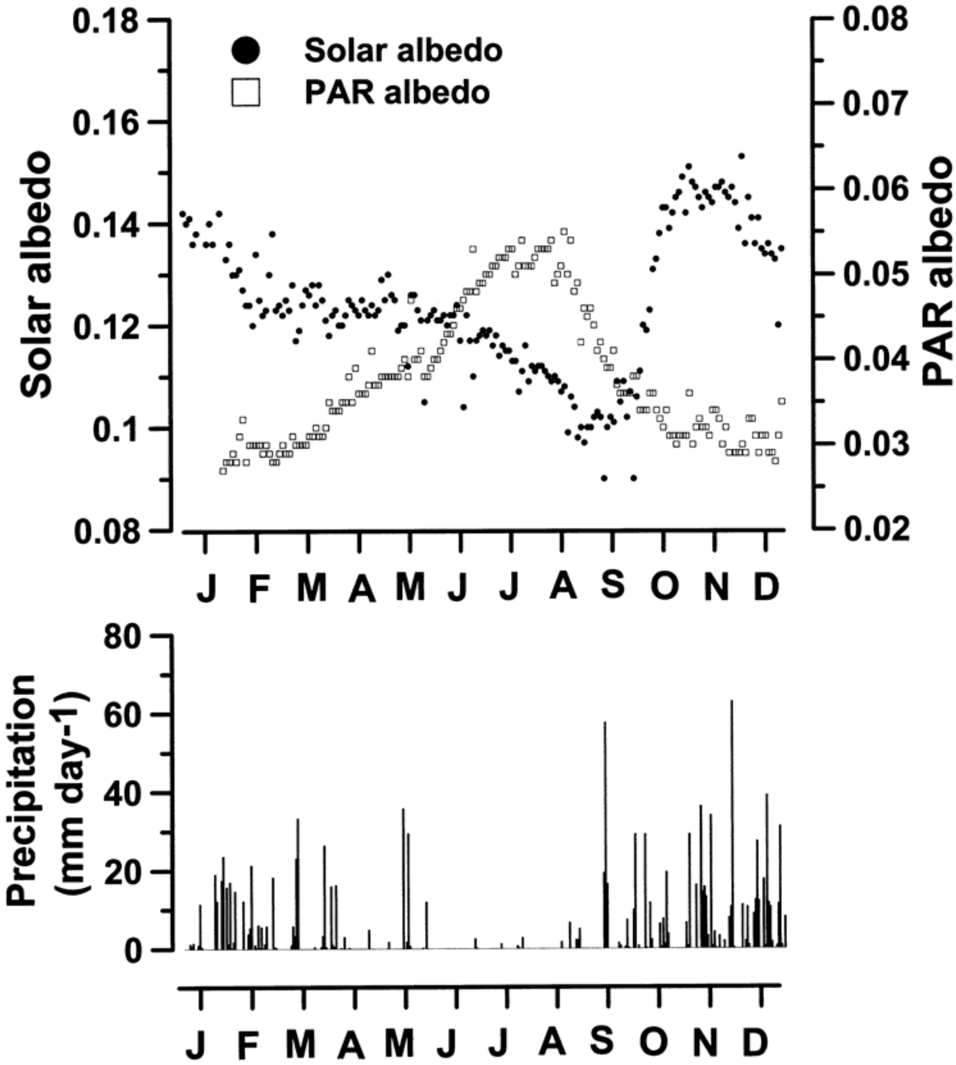

Figure 7 Solar and PAR albedo curves and precipitation data, all collected at the tower, during the year 2001.

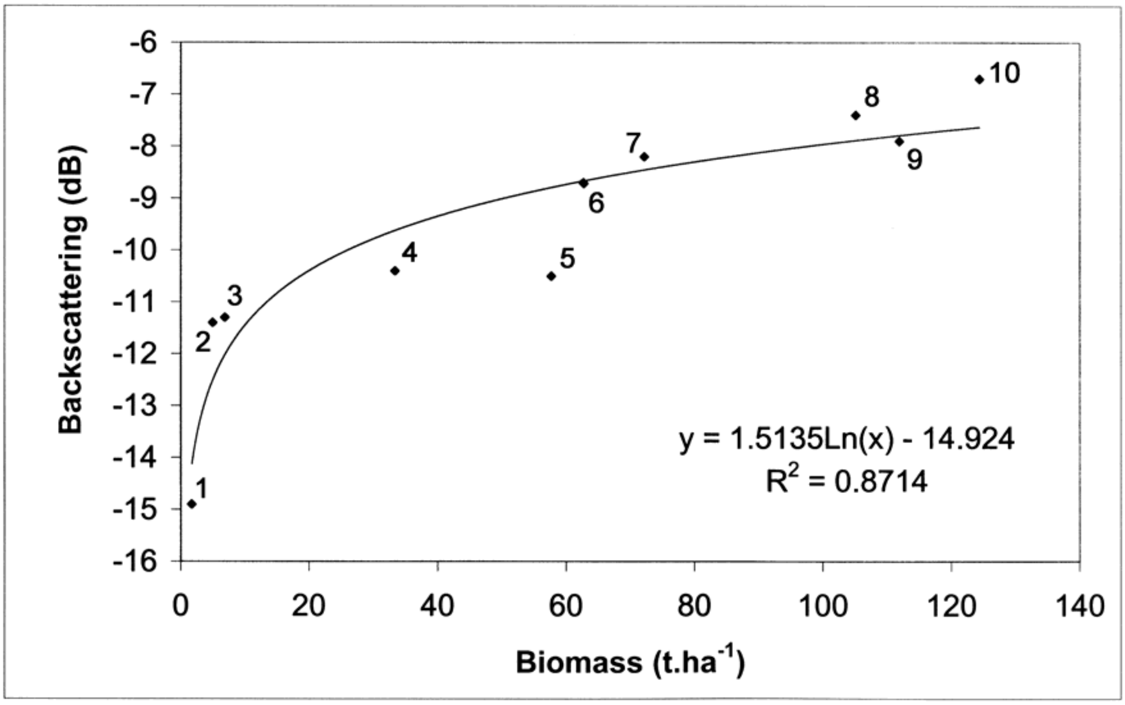

Figure 8 Curve showing the relationship between the forest AGWB values and the σ values in units of dB in the JERS-1 image.

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Table 1

Structural descriptors for woody and herbaceous cylindrical volume, in three *cerrado* physiognomies. Values are mean ± standard deviation, for $p<0.001$.(adapted from Batalha *et al.*, 2001).

Descriptor	*Campo cerrado* N=714	*Cerrado s.s.* N=399	*Cerradão* N=301
Woody component: Cylindrical volume ($m^3 . h^{-1}$)	69.11±29.3	164.79±62.5	428.47±369.2
Herbaceous component: Cylindrical volume ($m^3 . h^{-1}$)	95.98±86.8	38.39±37.2	4.47±7.7

Table 2

Calibration factors according to the date interval when the images JERS-1/SAR were processed.

Processing Date	Calibration Factor (dB)
Until February 14, 1993	-70,00
After February 15, 1993	-68,50
After November 01, 1996	-68,20
After April 01, 2000	-85,34

Source: NASDA (EORC - Orderdesk)

Tables 3

The LAI values for each permanent plot, in both field seasons: June and January, plus the predominant physiognomies based on the plant species found; 25 measurements in each plot; and key - Cc = *campo cerrado*; Css = *cerrado s.s.*; and Cd = *cerradão.*

Plots and Periods	Rows	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
JUNE	*A*	0.91 Cc	1.25 Css	1.09 Cc	1.13 Cc	1.50 Css	2.32 Css	2.00 Cd	1.88 Cd	1.81 Cd	1.74 Cd
	B	1.50 Css	1.47 Css	1.21 Cc	1.17 Cc	1.73 Css	2.09 Css	2.04 Cd	2.07 Cd	1.52 Css	2.18 Css
	C	1.96 Css	1.99 Css	1.13 Cc	1.43 Cc	1.65 Css	1.95 Css	1.72 Cd	2.02 Cd	1.73 Cd	2.49 Css
JANUARY	*A*	1.09	3.03	2.59	2.73	2.31	2.90	3.07	2.90	2.72	2.78
	B	2.00	3.32	2.54	2.55	2.71	3.19	3.38	2.51	2.54	2.63
	C	2.33	3.50	2.34	2.43	2.72	2.75	2.90	2.85	2.58	2.68

Table 4

The Mean LAI value for each *cerrado* physiognomy, in June 2001 and January 2002: Cc = *campo cerrado*; Cs = *cerrado s.s.*; and Cd = *cerradão,* N represents the measurement number in each period.

Physiognomies	June 2001	January 2002
*Campo cerrado (*N=175)	1.15	2.32
Cerrado s.s.(N=350)	1.83	2.76
*Cerradão (*N=225)	1.89	2.85

Table 5

The average NDVI values, inside each polygon defined in Fig.2, corresponding to probable *cerrado* physiognomies, from dry to wet season (from June/1995 to January/1996).

Probable *cerrado* physiognomy	June 1995	July 1995	August 1995	Nov. 1995	Jan. 1996	Amplitude Variation
campo cerrado	0.49	0.48	0.35	0.60	0.67	0.32
cerrado s.s.	0.54	0.53	0.41	0.63	0.69	0.28
cerradão	0.58	0.57	0.48	0.66	0.71	0.22

Table 6

Sample sites with each predominate physiognomy, mean cylindrical volume; above-ground wood biomass (AGWB); mean distance among trees; and mean backscattering values (**σ**).

Sample sites	**Predominate physiognomies**	**Cylindrical Vol. (dm^3)**	**AGWB(*) ($t . ha^{-1}$)**	**Mean distance (m)**	**σ (dB)**
1	*Cerradão* trees	664.18	3.32	38.29	-14.53
2	*Cerradão* trees	472.81	4.89	18.82	-10.99
3	*Cerrado s.s.*	226.74	6.60	11.20	-9.79
4	*Cerradão* - SSForest	98.97	32.24	3.30	- 9.03
5	*Cerradão* BP	167.29	55.80	3.30	- 8.93
6	*Cerradão* NE	138.02	60.53	3.20	- 8.49
7	*Cerradão* FE	240.45	90.08	2.20	- 7.90
8	*Cerradão*	168.02	69.89	3.55	- 7.04
9	*Cerradão* AD	290.75	108.27	3.13	- 7.48
10	*Cerradão* AD	335.12	120.35	3.55	- 7.18

(*) Abdala *et al.* (1998)