Available online at www.sciencedirect.com
ScienceDirect
Remote Sensing of Environment 109 (2007) 314–327
Remote Sensing of Environment
www.elsevier.com/locate/rse

Characterization of pasture biophysical properties and the impact of grazing intensity using remotely sensed data

Izaya Numata [a,*], Dar A. Roberts [a], Oliver A. Chadwick [a], Josh Schimel [b], Fernando R. Sampaio [c], Francisco C. Leonidas [d], João V. Soares [e]

[a] *Department of Geography, University of California, Santa Barbara, CA 93106, USA*
[b] *Department of Ecology, Evolution, and Marine Biology, University of California Santa Barbara, CA 93106, USA*
[c] *Departamento de Agronomia, ULBRA-Centro Universitário Luterano de Ji-Paraná, Ji-Praná, RO, Brazil*
[d] *EMBRAPA/CEPAFRO, Porto Velho, RO, Brazil*
[e] *Instituto Nacional de Pesquisas Espaciais, São José dos Campos, SP, Brazil*

Received 1 September 2006; received in revised form 11 January 2007; accepted 13 January 2007

Abstract

Remote sensing has the potential of improving our ability to map and monitor pasture degradation. Pasture degradation is one of the most important problems in the Amazon, yet the manner in which grazing intensity, edaphic conditions and land-use age impact pasture biophysical properties, and our ability to monitor them using remote sensing is poorly known. We evaluate the connection between field grass biophysical measures and remote sensing, and investigate the impact of grazing intensity on pasture biophysical measures in Rondônia, in the Brazilian Amazon. Above ground biomass, canopy water content and height were measured in different pasture sites during the dry season. Using Landsat Thematic Mapper (TM) data, four spectral vegetation indices and fractions derived from spectral mixture analysis, i.e., Non-Photosynthetic Vegetation (NPV), Green Vegetation (GV), Soil, Shade, and NPV+Soil, were calculated and compared to field grass measures. For grazed pastures under dry conditions, the Normalized Difference Infrared Index (NDII5 and NDII7), had higher correlations with the biophysical measures than the Normalized Difference Vegetation Index (NDVI) and the Soil-Adjusted Vegetation Index (SAVI). NPV had the highest correlations with all field measures, suggesting this fraction is a good indicator of pasture characteristics in Rondônia. Pasture height was correlated to the Shade fraction. A conceptual model was built for pasture biophysical change using three fractions, i.e., NPV, Shade and GV to characterize possible pasture degradation processes in Rondônia. Based upon field measures, grazing intensity had the most significant impact on pasture biophysical properties compared to soil order and land-use age. The impact of grazing on pastures in the dry season could be potentially measured by using remotely sensed measures such as NPV.

Keywords: Pasture degradation; Grass biomass; Spectral mixture analysis; Grazing intensity.

1. Introduction

Managed pastures have been the most important form of land use in the Amazon since early colonization and continue to expand in the region. Many of these areas become degraded after only a few years (Fearnside and Barbosa, 1998). However, quantitative measures of pasture condition and their change in space and time due to pasture degradation have not been reported in the Amazon and our knowledge about the characteristics of grazed pastures is very limited.

Pasture nutritional conditions and changes in soil and plant (grass) vary according to soil order and pasture age (Asner et al., 2004; Numata et al., 2007). In addition to pasture nutritional quality, pasture degradation refers to the reduction of pasture productivity, which is directly determined by a change in pasture biophysical properties such as biomass, leaf area index (LAI), grass density, and canopy height. These measures are a consequence of complex interactions among

---

* Corresponding author. Tel.: +1 805 893 4434; fax: +1 805 893 3146.
E-mail address: numata@geog.ucsb.edu (I. Numata).

0034-4257/$ - see front matter © 2007 Elsevier Inc. All rights reserved.
doi:10.1016/j.rse.2007.01.013

pasture management practices, pasture age, edaphic conditions, and climate (Dias Filho et al., 2000; Serrão & Toledo, 1990). Of these factors, grazing intensity may have the most direct and rapid impact on standing biomass, LAI and vegetation cover in the short term (Lupinacci, 2002; Mwendera et al., 1997).

Animal stocking rates in the Amazonian pastures are usually above the recommended level in order to maximize short term profit (Costa & Rehman, 2005; Fearnside, 1996). As a result, overgrazing causes excess defoliation and grass nutrient loss, resulting in reduced animal production and pasture degradation (Lupinacci, 2002; Boddey et al., 2004). Although the primary effects of grazing intensity on pastures are known, the impacts of grazing intensity have not been quantitatively measured and their importance compared to other factors such as soil order, is not clear.

Remote sensing provides temporal and spatial patterns of ecosystem change and has been used to estimate biophysical characteristics of managed grasslands. In the Amazon, remote sensing has been used primarily to estimate deforestation rates and monitor land-cover change (Alves et al., 1999; Moran, 1993; Roberts et al., 2002; Skole & Tucker, 1993). However, our understanding of the utility of remote sensing for Amazonian pastures is limited and the accuracy and physical meaning of indices derived from remote sensing should be evaluated. Recently, Asner et al. (2004) studied the linkage between pasture biochemical and physical data and remotely derived measures, and found that pasture characteristics measured by Landsat Enhanced Thematic Mapper (ETM+) varied according to soil orders and pasture age. Field pasture LAI and non-photosynthetic material area index (NPAI) were well correlated with remotely sensed indices such as Photosynthetic Vegetation (PV) and Non-photosynthetic vegetation (NPV). Despite these results, some points in Amazonian pasture characterization using remote sensing remain unclear. For example, we do not know the relative importance of pasture age, grazing intensity, and nutrient availability on pasture canopy properties and remotely sensed signatures. We therefore need to expand our understanding of the inter-relationships between these land-use, edaphic, and biogeochemical controls. Here, we investigate the potential of remotely sensed data for pasture characterization and for estimating grass biophysical properties.

Our primary objective was to evaluate the biophysical connections between grazing intensity, pasture age and remotely sensed indices derived from Landsat TM imagery. The specific goals are to: 1) investigate the impacts of grazing intensity on pasture biophysical properties; 2) analyze relationships between pasture field data such as biomass, water and canopy height and remotely sensed data. After determining appropriate remote sensing measures for pasture characterization, a conceptual model will be constructed based upon this analysis. Finally, 3) to analyze the effects of grazing intensity on related remotely sensed data, addressing the question of sensitivity of remote sensing to pasture biophysical changes due to grazing intensity.

2. Methodology

2.1. Study site

The state of Rondônia is located in the southwestern Brazilian Amazon, occupying an area between 8 and 15° S and 60 to 65° W (Fig. 1). Six ranches were used for this study, distributed in Porto Velho, Ariquemes, Ouro Preto, and Presidente Médici. These ranches are beef pastures (extensive management system). Soil orders are related to geology and topography of this region. Oxisols and Ultisols, both dystrophic soils, are found mostly over the Precambrian granitoid and meta-supracrustal rocks with predominantly flat topography in the north of the state, while Alfisols are distributed mainly in central of Rondônia to the south, where they coincide with the presence of intrusive basic and ultrabasic rocks with gently rolling topography (CPRM,1997; EMBRAPA, 1983; Holmes et al., 2004).

2.1.1. Field measurements: grass biophysical properties and soils

Field measurements of grass biophysical properties were conducted in July–August, 2003. Pasture field measurements including biomass, grass water content and canopy height were obtained from study sites that consisted of the same grass species, *Brachiaria brizantha*. Besides grass species, some weed species and burned forest debris were found especially in young pastures (6–10 years old). However, due to periodic burning and other management practices for weed control employed by ranch owners, the amount of residual woody plants and successional plant cover decline as pastures age. Within each study site, the above measurements were taken from a 100 m transect placed on areas with different pasture ages, if more than one age class was present. In total, sixteen transects were used for field measurements of grass biophysical properties in this study. Grass aboveground biomass was clipped from a 50 cm × 50 cm quadrant at 20 m intervals along each 100 m transect gathering six biomass samples per transect. Grass biomass was weighed then oven dried at 70 °C for 36 h. Dried grass biomass was reweighed in order to calculate grass water content. Canopy height was measured at 5 m intervals along the same transects.

Pasture management information was obtained through interviews with ranch owners. Grazing intensity in this study refers exclusively to stocking rate (number of animals per 1 ha). For the dry season in Rondônia, the recommended stocking rate is 1 Animal Unit (450 kg)/ha or 1.2 head/ha (F. C. Leonidas, personal communication). With respect to grazing rotation, the recommended fallow period for pasture after grazing is 20–30 days in Rondônia, but the fallow periods for our study sites varied from 5 to15 days, which is much shorter than is recommended. Although we have information on grazing rotation period for each site at the time of the field survey, the timing of grazing (when cattle come into the area and leave) was not known. Therefore, the impacts of grazing rotation on pasture biophysical changes are not clear in this study. It is assumed, based upon interviews with ranch owners and field

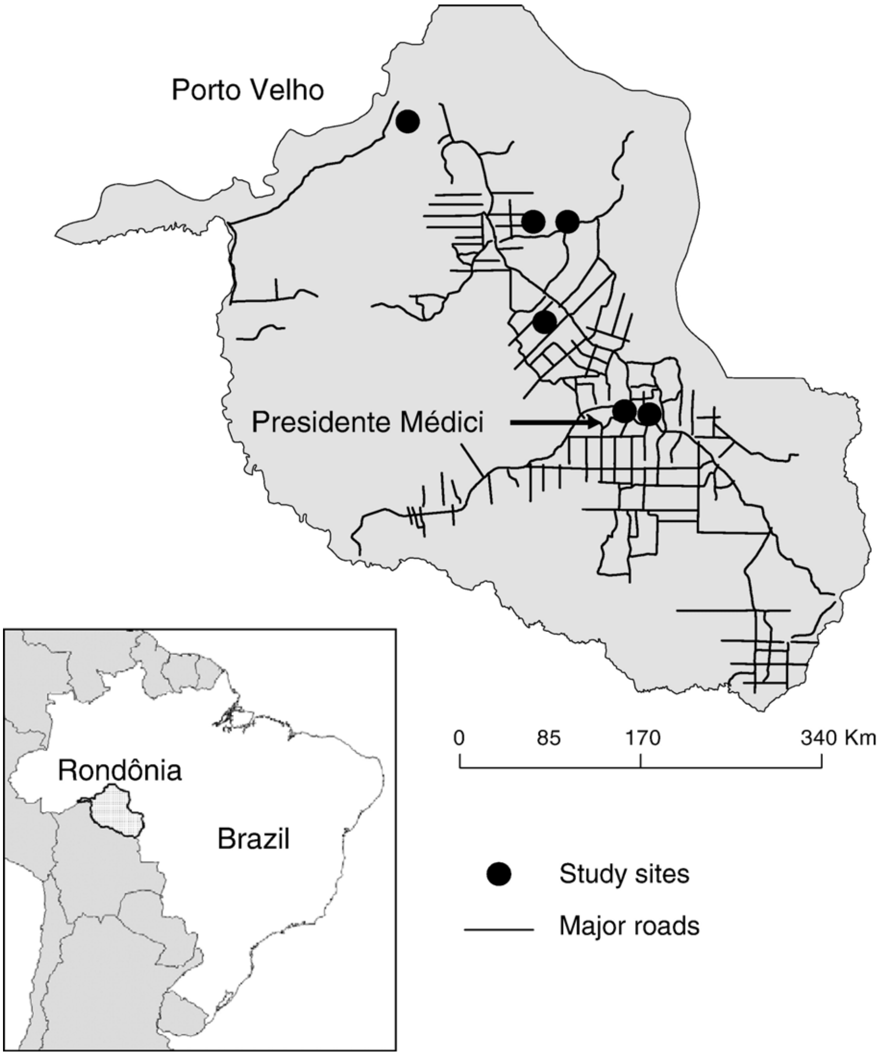


Fig. 1. Study area showing study sites distributed from Porto Velho to Presidente Médici.

measurements, that grazing rotation period in the dry season is positively correlated with stocking rate: the higher the stocking rate, the more biomass will be consumed and the more quickly the rotation will be imposed.

There was no rainfall recorded during the field work and at least three weeks prior to the imagery acquisition dates (SEDAM, 2004). Therefore, the effects of rainfall on field measurements of grass biophysical properties and remotely sensed data were neglected in this study. And the effects of soil moisture on remotely sensed data are likely to be negligible too. Soil sampling was conducted in May and July–August in 2003. Soil samples were collected from 0–30 cm in the areas close to each transect. Soil chemical measures such as pH, soil available P, and Base saturation were measured according to the techniques described in EMBRAPA (1997). Soil reaction (pH) was measured using a standard calomel electrode pH meter. The Melich extractor was used to extract available P and exchangeable K. This extraction procedure utilizes 0.025 N of H_2SO_4, and 0.05 N of HCl to remove labile forms of these nutrients. Phosphorus was determined using spectrophotometry by the method Molybdate Blue while exchangeable K was determined by flame photometry. Exchangeable Ca and Mg were extracted with 1 N KCl, and quantified by titration with EDTA. Exchangeable Al was extracted with 1 N KCl and quantified by titration with 0.025 N NaOH. Base saturation was calculated as:

$$\text{Base saturation} = 100\, S/\text{cation exchange capacity (CEC)} \tag{1}$$

where $S = \text{Ca} + \text{Mg} + \text{K}$ and $\text{CEC} = S + \text{H} + \text{Al}$.

2.1.2. Statistical analysis

To analyze the impact of the variables including soil, land-use age and grazing intensity on biophysical data, one-way analysis of variance (ANOVA) was performed. For the purpose of ANOVA, grazing intensity was divided into three classes based on stocking rate: “high” (> 1.7 head/ha), “medium” (1.2–1.6 head/ha), and low (< 1.1 head/ha). The other variables, soil and age, were also divided into three classes: Soil orders, Alfisols, Ultisols and Oxisols, and three age classes, Young (6–10 years old), Intermediate (11–15 years old) and Old (> 16 years old).

2.1.3. Remote sensing data and preprocessing

Three Landsat Thematic Mapper 5 (TM5) scenes were used in this study: 231/67, 231/68 (07/24/2003), and 232/66 (07/15/2003) (Table 1). Landsat TM5 is a spaceborne multi-spectral sensor that has six spectral bands between 0.45 and 2.22 μm (three visible bands, one near-infrared, and two short wavelength infrared bands). The ground instantaneous field-of-view is 30 m. The Landsat series, starting with the Multispectral Scanner (MSS) launched in 1972 and progressing to Landsat Enhanced Thematic Mapper (ETM+), are the most common remote sensing data used for monitoring Amazonian tropical rain forest since the 1970s.

Images were coregistered to the digital base maps provided by Instituto Nacional de Pesquisas Espaciais (INPE — the Brazilian Space Agency). Landsat TM images were intercalibrated to the corresponding Landsat ETM+ reflectance images using a relative radiometric calibration approach (Roberts et al., 1998a). Invariant targets such as primary forest, second growth forest, bare soil, rock, and water were selected for a pair of reflectance and uncalibrated images. A linear equation was estimated using the pixel mean values extracted from a 4 by 4 pixel area of the invariant targets for each band. These coefficients normalize the uncalibrated images to the corresponding reference reflectance image. Three corresponding Landsat ETM+ images, i.e., 08/11/2001 for 231/67 and 231/68, and 08/01/2001 for 232/66, were radiometrically corrected using the gains and offset provided in the image metafile. Next, an atmospheric correction was performed using software Atmospheric Correction Now 3.0 (ACORN — Imspec, 2003). The tropical model was used for reflectance retrieval. Water vapor was fixed at 35 mm for all three images and image atmospheric visibility was set at 35 km for the 231/67 and 231/68 scenes, and 45 km for the 232/66 scene.

2.1.4. Image analysis

Grass biomass, water content and canopy height were measured from 16 transects and compared to Landsat data. Two types of spectral measures were derived from the imagery: 1) Spectral vegetation indices (VIs) based upon two spectral bands and 2) Spectral Mixture Analysis (SMA).

Four VIs were calculated in this study (Table 2). The first two VIs are the Normalized Difference Vegetation Index (NDVI) and Soil-Adjusted Vegetation Index (SAVI) (Huete, 1988). SAVI better accounts for the effects of variable soil brightness than NDVI. The Normalized Difference Infrared Indices (NDII5 and NDII7) use the bands from the short wavelength infrared (SWIR) region (band 5 — SWIR1 and band 7 — SWIR2, respectively) in place of band 4. These indices are more sensitive to water content (Hardisky et al., 1983; Hill, 2004; Hunt and Rock, 1989).

Table 1
Landsat data used in this study

Path/row	City	Landsat TM	ETM reference
P232/R66	Porto Velho	2003–07–15	2001–08–01
P231/R67	Ji-Paraná	2003–07–24	2001–08–11
P231/R68	Presidente Médici	2003–07–24	2001–08–11

Table 2
Spectral indices used in this study

Spectral indices	Reference
Normalized Difference Vegetation Index $NDVI=(R800-R680)/(R800+R680)$	Rouse et al. (1973)
Soil-Adjusted Vegetation Index $SAVI=(1.5*R800-R680)/(R800+R680+0.5)$	Huete (1988)
Normalized Difference Infrared Index 5 $NDII5=(R800-R1625)/(R800+R1625)$	Hardisky et al. (1983)
Normalized Difference Infrared Index7 $NDII7=(R800-R2220)/(R800+R2220)$	

SMA provides physically meaningful measures of the percentage of the major components within the instantaneous field-of-view, facilitating our interpretation (Adams et al., 1993; Roberts et al., 1993; Settle & Drake, 1993). SMA assumes that the spectra can be modeled as a linear combination of two or more “pure” spectral endmembers (Adams et al., 1993):

$$\rho_\lambda = \sum_{i=1}^{N} f_i * \rho_{i\lambda} + \varepsilon_\lambda \qquad (2)$$

where $\rho_{i\lambda}$ is the reflectance of endmember i for a specific band (λ), f_i is the fraction of the endmember, N is the number of endmembers and ε_λ is the residual error. The sum of the modeled fractions is constrained to 1.

A root mean squared error (RMSE) is calculated for each pixel of the scene to assess model fit (Adams et al., 1993):

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{\lambda=1}^{M} (\varepsilon_\lambda)^2}{M}} \qquad (3)$$

where M is the number of bands. SMA typically assumes single interactions between photons and surfaces, producing linear mixing of the surface fractions and their reflectance. In this study, a 4-endmember model was used including: NPV, GV, Soil, and Shade.

For SMA, a spectral library for NPV, GV, and Soil was built. The library consisted mostly of image endmembers, which were collected from Landsat reflectance images, but some spectra from the field spectrometer were included in the library as well. Field grass spectra were measured using an Analytical Spectral Device (ASD) — full range spectrometer (350 to 2500 nm, Boulder, CO), on loan from the Jet Propulsion Laboratory (JPL). The ASD measurements were conducted for all study sites. The ASD spectra were collected with a 22° field-of-view (FOV) at 5 m intervals along 100 m transect with a 1 m sensor height above grass canopies. All spectral measurements were collected within 2 h of local solar noon under clear-sky conditions. Five replicates were measured for each grass canopy. These spectra were standardized to Spectralon (Labsphere, Inc, North Sutton, NH) measured at approximately 10 min intervals, and converted into reflectance. The spectra from the field spectrometer were convolved to Landsat ETM+ using filter function of the ETM+ sensor.

For the selection of endmembers, we used Multiple Endmember Spectral Mixture Analysis (MESMA) developed by Roberts et al. (1998b). MESMA allows the number and types of endmembers to vary on a pixel basis. A model that meets the criteria of the selection such as lowest RMSE (2.5%), physically reasonable fraction ($0 < f < 1.0$), etc., is considered the best model for the related pixel and selected in MESMA classification output. MESMA generates all possible combinations of models based upon different input endmembers from a spectral library. In this study, as input endmembers we selected five endmembers for soil, nine for GV, and eleven for NPV. This generated 495 models and we also added five already existent models. In total, we had 500 models. See Roberts et al. (1998b) for more details. MESMA was performed for all Landsat data and we selected the best 4-endmember model with NPV, GV, Soil, and Shade (photometric shade), out of 500 models, that was selected in pasture areas. With these selected endmembers (Fig. 2b), simple SMA was performed generating NPV, GV, Soil, Shade fraction images (Fig. 3) and RMSE (not shown).

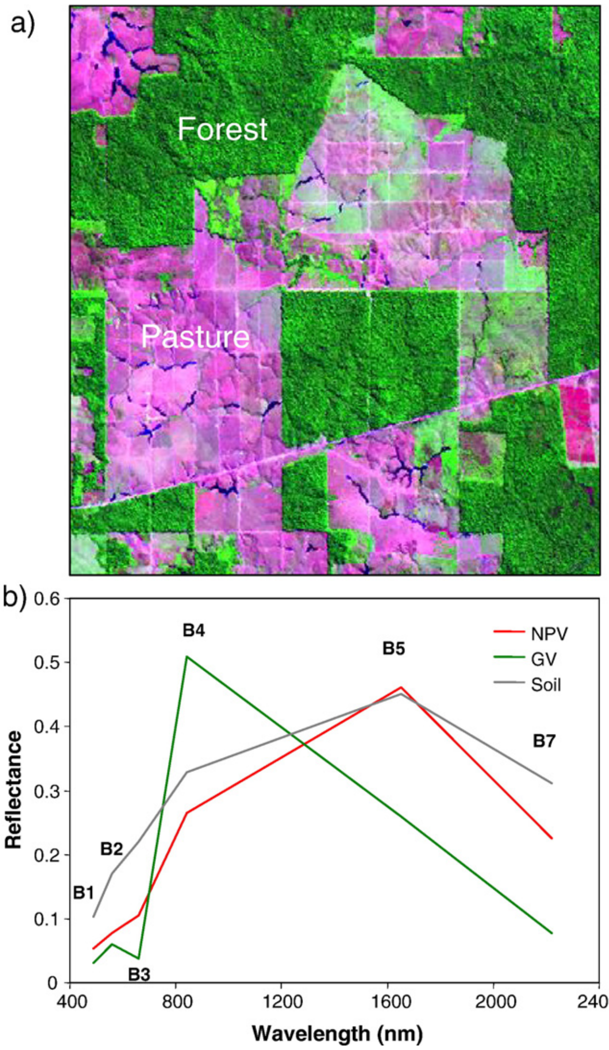


Fig. 2. a) Landsat TM data showing typical land-cover types in the study area. B5, B4, and B3 in RGB; b) Selected Endmembers for Spectral Mixture Analysis: NPV, GV, and Soil.

The vegetation indices and fractions of NPV, GV, Shade and Soil were extracted from four pixels along each transect in the images and then averaged, representing 16 points (transects). Finally, these data were correlated to the relative pasture field data.

3. Results

3.1. Field measurements of grass biophysical properties and the effects of the variables

3.1.1. Stocking rate, soil, and land-use age

Table 3 summarizes field measurements of grass biophysical properties from the 16 transects. Stocking rate in this table refers to general animal stocking rate for each ranch, therefore those transects with the same stocking rate imply that they are from the same ranch (study site). Most of the study sites exceeded the recommended stocking rate of 1.2 head/ha, indicating some degree of overgrazing.

The results of ANOVA reveal that all the factors, i.e., soil, land-use age, and stocking rate are significant for all pasture variables at $P < 0.05$ (Table 4). However, F values indicate that grazing intensity is the most important and influential factor for measurements of grass biophysical properties, followed by soil and age. Direct comparisons of biophysical properties with soil pH, soil available P, and base saturation showed weak relationships, whereas stocking rate had a better relationship ($r^2 = 0.72$, p value < 0.0001, with biomass) (Fig. 4). These results demonstrate the importance of grazing intensity for above ground pasture changes.

3.1.2. Pasture biophysical properties vs. remote sensing

3.1.2.1. Vegetation indices. All four vegetation indices showed positive relationships with pasture measurements (Fig. 5). In general, the correlations were highest for water content and lowest for biomass. The chlorophyll based indices, NDVI and SAVI had poor correlations ($r^2 = 0.05 - 0.13$) compared to the SWIR based indices, i.e., NDII5 and NDII7 ($r^2 = 0.33 - 0.38$). NDVI and SAVI, which rely on the spectral contrast between red and near-infrared bands, are sensitive to leaf-chlorophyll content and LAI in vegetation, whereas NDII5 and NDII7 are more sensitive to leaf water content of vegetation (Hardisky et al., 1983; Hunt and Rock, 1989). Low correlation coefficients between field measurements of grass biophysical properties and chlorophyll based indices can be accounted for by the fact that pastures under dry conditions and intense cattle grazing have small amounts of green leaves, and non-photosynthetic materials such as stems and dry leaves dominate pasture biomass. Since NPV exhibits elevated reflectance in band 3 (Fig. 2b), red and near-infrared based indices are hampered by the small contrast between these two bands in NPV dominated grasses. In the case of NDII5 and NDII7, band 5 and band 7 vary as a function of grass water content in pastures, while band 3 is less sensitive to grass water content.

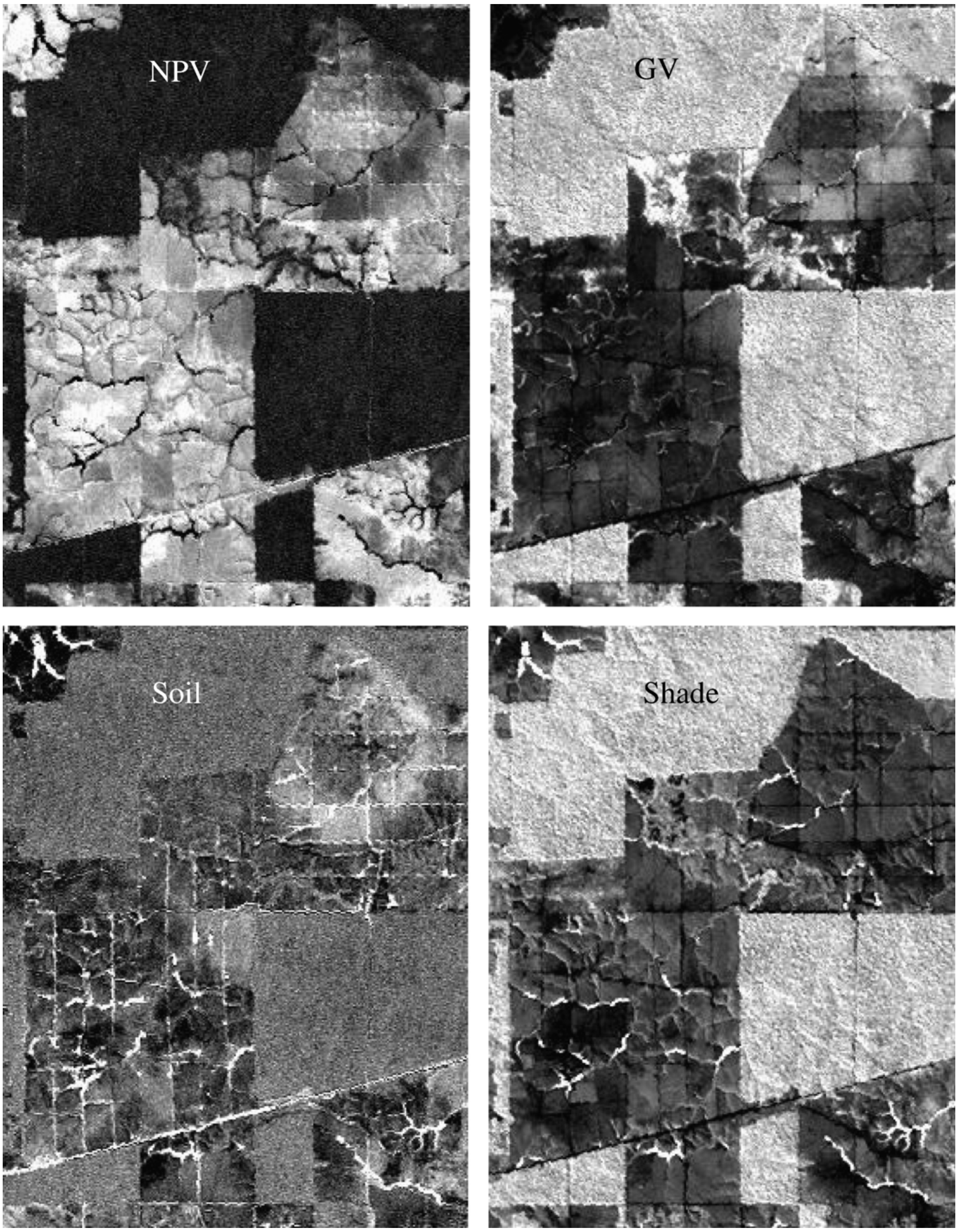


Fig. 3. Fraction images derived from SMA: NPV, GV, Soil, and Shade.

3.1.2.2. Fraction images. The NPV fraction had the highest correlations with biophysical data ($r^2 = 0.68$ with biomass), followed by NPV+ Soil ($r^2 = 0.52$), Shade ($r^2 = 0.50$), and GV ($r^2 = 0.34$) (Fig. 6). Soil fractions had the lowest correlation ($r^2 = 0.01$) (Fig. 6). Like Vegetation indices, water content had higher relationships with fractions compared to biomass. NPV and NPV+Soil were negatively correlated to pasture measurements, whereas GV and Shade showed positive relationships.

Higher and negative relationships of NPV with measurements of grass biophysical properties indicate that less productive and more degraded pastures are characterized by high NPV (around 60%), whereas more productive pastures have low NPV (30–40%). In contrast, GV showed positive relationships with measurements of grass biophysical properties. The more productive pastures (i.e., higher biomass, water content, and height) had GV around 30%, while low GV fractions (less than 10%) were found in the more degraded pastures. This can be explained by the following: Pastures with higher biomass or water content have more standing live biomass with a higher ratio of green leaves to senesced leaves, resulting in low NPV and high GV fractions. Since

Table 3
Summary of field measures and characteristics of study sites

Transect	S.D.[a] (head/ha)	Age[b]	Soil	Biomass (t/ha)	Moisture (t/ha)	Height (cm)
ja	1.09	Yg	Alfisols	9.14	2.60	48 (17)
jb	1.09	Int	Alfisols	9.91	3.37	49 (11)
jc	1.09	Old	Alfisols	7.14	2.62	33 (11)
pa	1.60	Yg	Alfisols	4.02	1.50	26 (7)
pb	1.60	Int	Alfisols	5.84	2.48	28 (10)
pc	1.60	Old	Alfisols	3.80	1.21	23 (10)
na	1.38	Old	Ultisols	5.53	2.45	15 (8)
nb	1.38	Old	Ultisols	4.79	1.95	17 (8)
ta	1.36	Yg	Oxisols	6.40	2.51	36 (17)
tb	1.36	Int	Oxisols	5.49	2.08	21 (11)
tc	1.36	Old	Oxisols	3.58	1.35	21 (10)
ra	2.29	Int	Ultisols	2.43	0.65	5 (4)
rb	2.29	Int	Ultisols	1.18	0.33	5 (4)
sa	1.77	Old	Oxisols	2.57	0.99	14 (12)
sb	1.77	Old	Oxisols	5.50	2.08	17 (10)
sc	1.32	Int	Oxisols	4.31	1.62	25 (18)

[a] Stocking rate.

[b] Age classes are: Yg = young (6 – 10 years), Int = intermediate (11–15 years), Old = old (>16 years).

cattle selectively graze on live and green biomass, the decrease of the amount of above ground biomass by cattle grazing implies the reduction of standing live biomass. As a result, the amount of exposed senesced leaves and exposed litter on the ground increases as the grass canopy is lowered by cattle grazing, contributing to an increase in NPV and a decrease in GV. Since pastures in the dry season are strongly dominated by non-photosynthetic materials as discussed above, the magnitude of GV variability is smaller than NPV variability for pastures and, therefore, grasses are better characterized by NPV than GV. On the other hand, the GV fraction had a higher r^2 than NDVI and SAVI and as high an r^2 as NDII5 and NDII7. Spectral mixture models utilize all spectral information of the six Landsat TM bands, and grazed and dry pastures may be better characterized by GV than typical vegetation indices that involve only two or three bands.

Shade fractions increased as biomass increased. This is probably related to a change in grass stature or canopy height from low to high canopy height accompanied by the increase in biomass. Taller grass canopies cast more shadows, whereas short pasture canopies cast fewer shadows within their canopies. This inference is supported by the fact that the highest r^2 for the shade fraction is found with canopy height ($r^2 = 0.65$).

The soil fraction has been considered a very important measure of pasture degradation or overgrazed areas, especially in semi-arid regions (Asner & Heidebrecht, 2003; Huete et al., 2003; Pickup et al., 1998). In the case of our study, the soil fraction was low and not a good indicator of pasture biophysical properties since most of our study sites have a high vegetation cover including live-senesced biomass and litter and a small amount of bare soil. Our results concur with other studies for Amazonian pastures (Asner et al., 1999; Asner et al., 2004). Another reason for low correlations of this fraction is related to the fact that NPV and Soil are difficult to discriminate using multispectral sensors due to the lack of well expressed ligno-cellulose bands in multi-spectral data such as Landsat (Roberts et al., 1993; van Leeuwen & Huete, 1996). In the case of this study, where NPV is predominant and exposed soil is low, the soil fraction was not well modeled.

Combining NPV and Soil avoids this spectral confusion, and shows a clear decrease as biomass increased. The spectral signatures of pastures with low biomass consist not only of standing biomass, but also of the substrate beneath the pasture canopy such as litter and soil. If the surface of an area is covered by litter, a high NPV fraction can be found, but the soil fraction can be high if the surface is bare soil. A good estimate of these two fractions, NPV and Soil, greatly improves land-cover characterization. (Roberts et al., 1998a; van Leeuwen & Huete, 1996).

Over all, SMA fractions, except Soil, performed better for pasture characterization compared to vegetation indices. These fractions provide intuitive measures for the land surface characteristics (physically meaningful measures of the target) that facilitate our interpretation. Figs. 7 and 8 show examples of the fractional characteristics for two extreme pasture cases in terms of biophysical properties; unproductive/degraded pasture and highly productive pasture. Site r (Table 3 and Fig. 7) has brighter pastures in NPV and NPV + Soil fraction images than Site j (Table 3 and Fig. 8), whereas GV and Shade fractions are higher in Site j compared to Site r (Fig 8).

Grass biophysical change measured by SMA fractions can be summarized by the conceptual model in Fig. 9. More productive pastures can maintain higher biomass, which includes live leaves with higher water content and taller plants. Higher GV (around 20%) and Shade (15–20%) with lower NPV are characteristics of these pastures. On the other hand, heavily grazed and dry pastures have less live leaves with a short height and litter on the ground, which results in a combination of high NPV, low GV, and low Shade. The arrow in Fig. 9 indicates a possible direction of the pasture degradation processes: from highly productive to degraded pastures with low biomass, based upon SMA fractional changes.

Table 4
ANOVA results for biomass, canopy moisture, and height with the factors grazing, soil and age

Indices	*df*	*F* value	Pr (*F*)
Biomass			
Grazing	2	29.81	<0.0001
Soil	2	8.96	<0.001
Age	2	4.07	0.019
Moisture			
Grazing	2	17.393	<0.0001
Soil	2	4.9	0.009
Age	2	3.32	0.04
Height			
Grazing	2	152.57	<0.0001
Soil	2	93.46	<0.0001
Age	2	46.56	<0.001

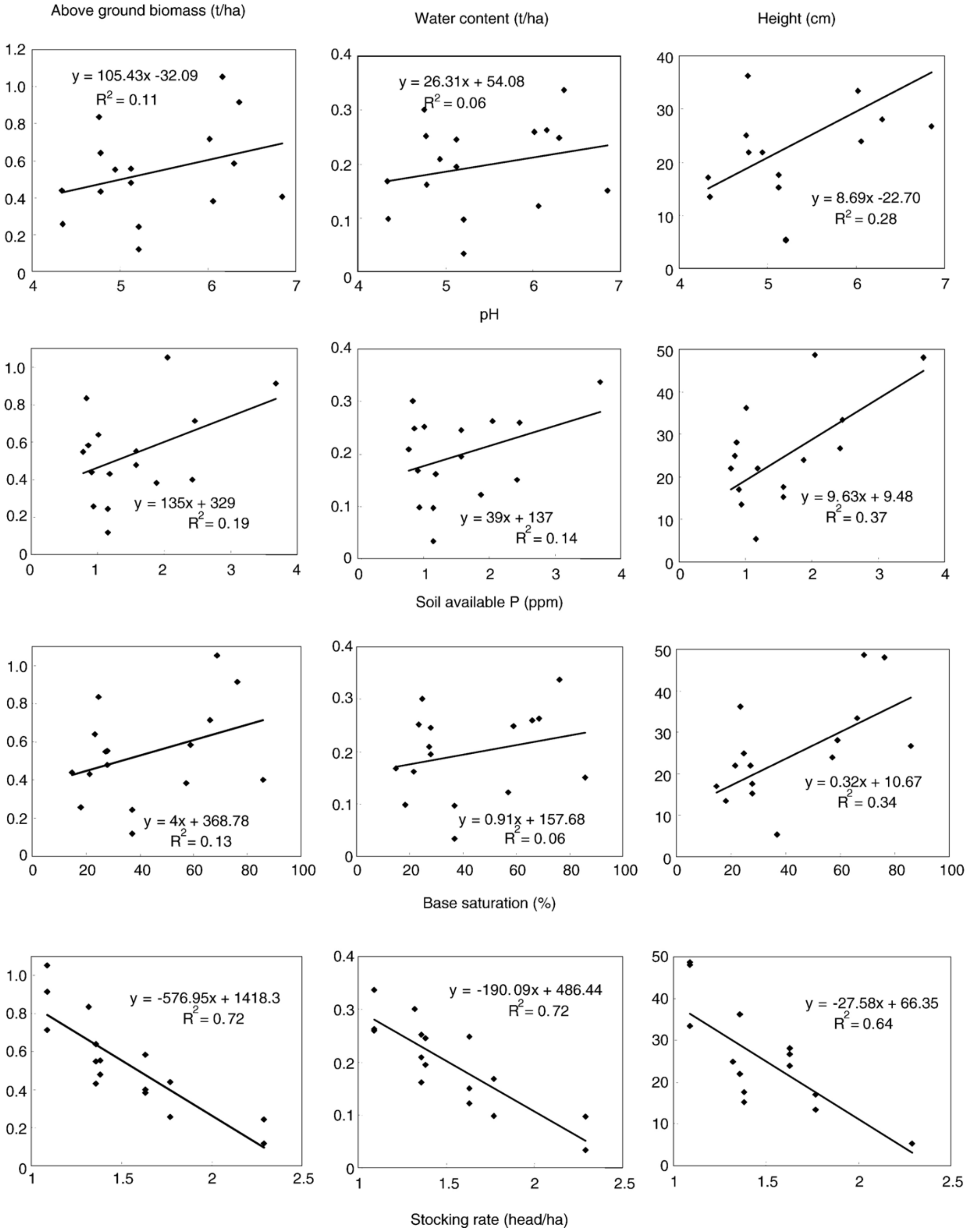
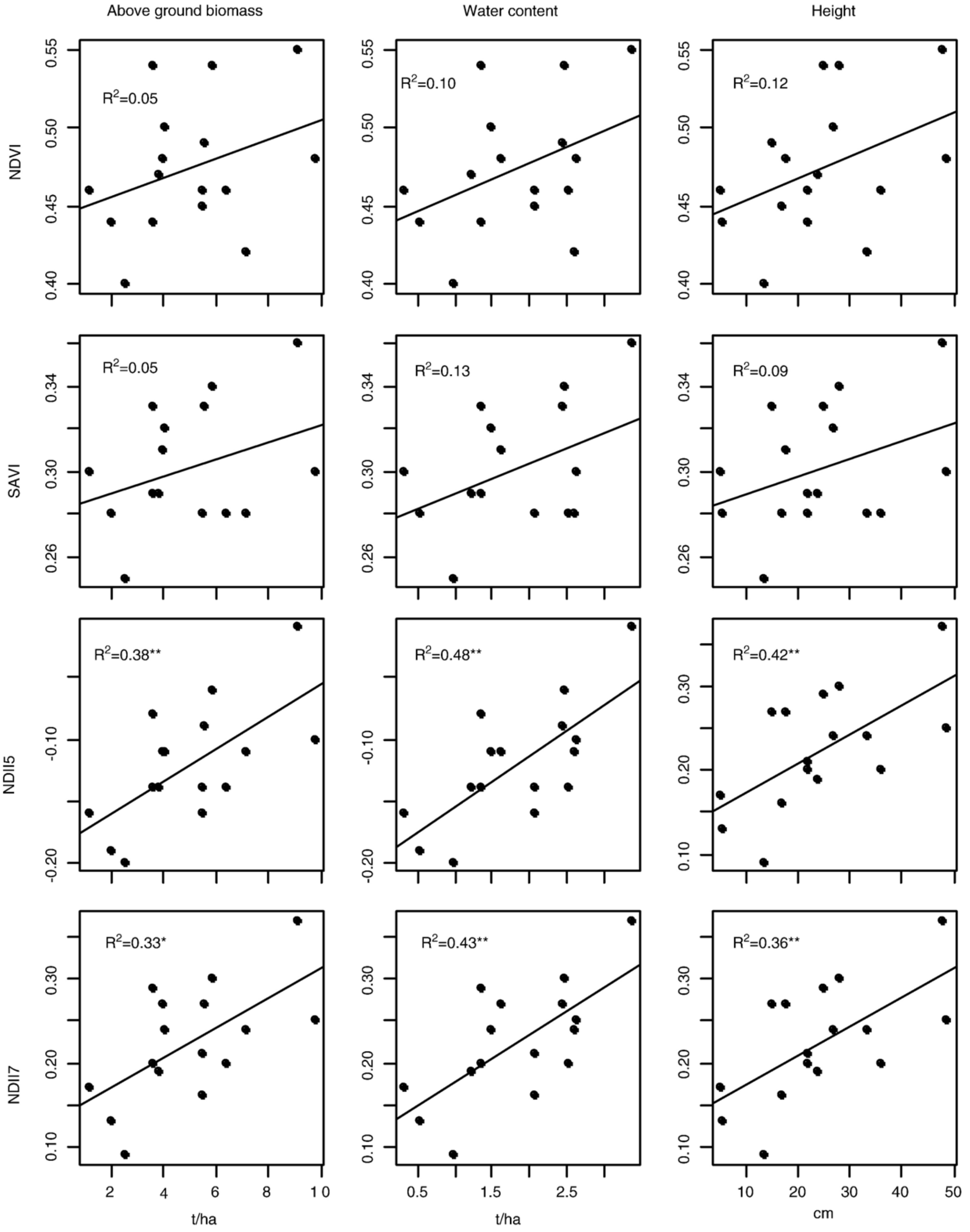


Fig. 4. Relationships of field pasture measures with soil pH, P, base saturation, and stocking rate.

3.2. Grazing intensity vs. remote sensing

Relationships between grazing intensity and remotely sensed data are similar to the ones between field measurements of grass biophysical properties and remote sensing. The results are not surprising given the fact that the remotely sensed data showed reasonable relationships with grass field measures. Also grazing intensity is the most influential factor for grass biomass dynamics. In Table 5, NPV and NPV+Soil showed highly significant and positive correlations with cattle stocking rate ($r^2 = 0.70$ and 0.53, respectively, at $P < 0.001$). NDII5, NDII7, GV and Shade were also significant and negatively correlated at P level < 0.01. These



* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

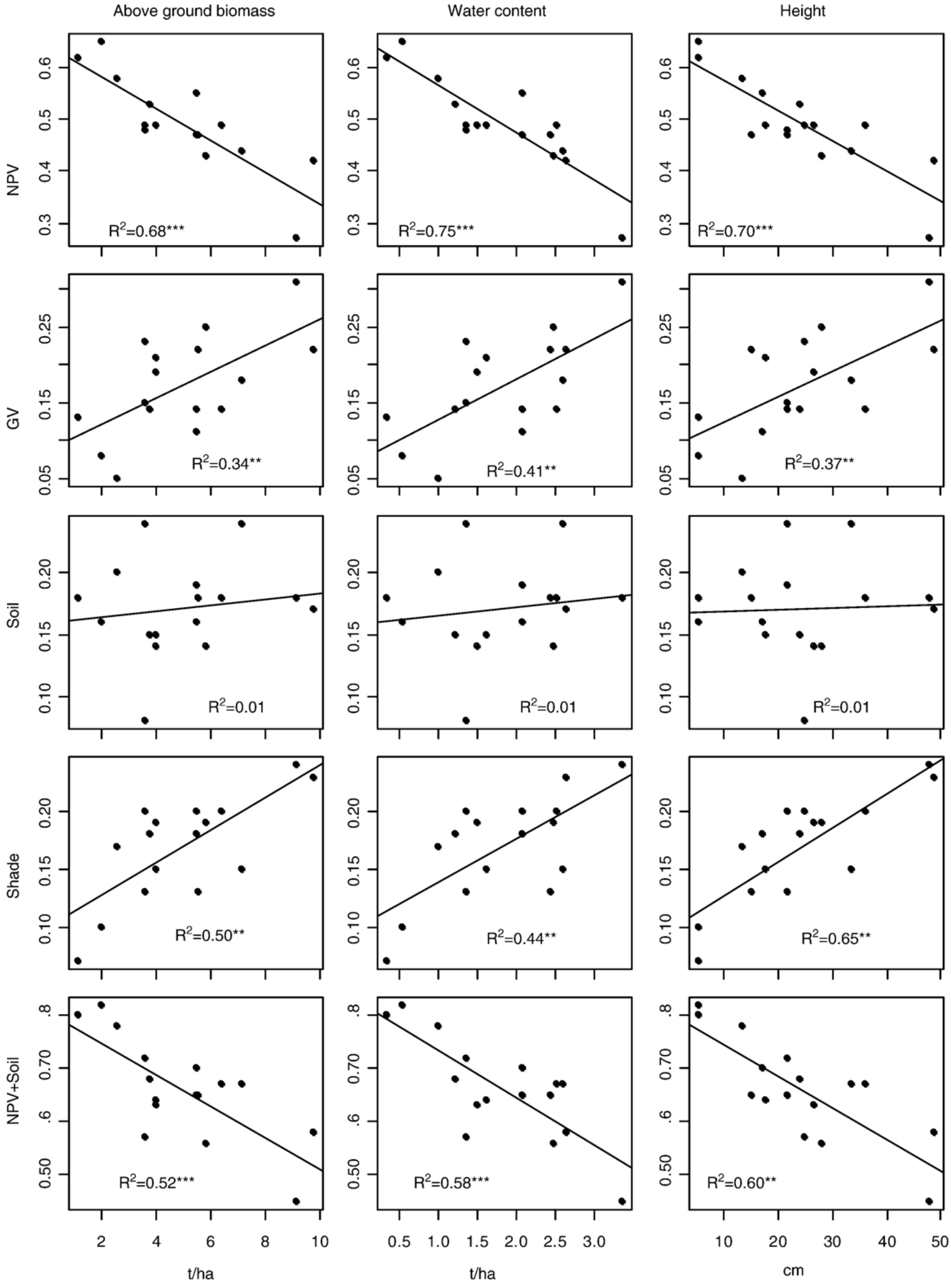
Fig. 5. Scatterplots between field grass measures and vegetation indices.

results suggest that heavily grazed pastures in Rondônia are dominated by NPV, with a short canopy indicated by a low shade fraction, and low canopy moisture indicated by NDII. Grass biophysical changes caused by pasture management may potentially be monitored by remotely sensed data such as NPV during the dry season in Rondônia (Fig. 10).

4. Discussion

4.1. Grazed pasture analysis and remotely sensed measures

NDVI or other chlorophyll based indices have been widely used to characterize grass grazing systems and estimate grass



* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Fig. 6. Scatterplots between field grass measures and SMA fractions.

biomass (Field et al., 1995; Hill et al., 1998; Todd et al., 1998). In general, good relationships have been found between field data and vegetation indices. On the other hand, Hill (2004) argued that a green vegetation index alone may not be sufficiently sensitive enough to detect small spectral changes associated with grazing. For example, previous studies have suggested the use of SWIR bands for grass biomass estimates. Hardisky et al. (1983) observed that NDII showed a better relationship with live biomass (live leaves and stems) and canopy moisture of *Spartina alterniflora* than NDVI. Everitt et

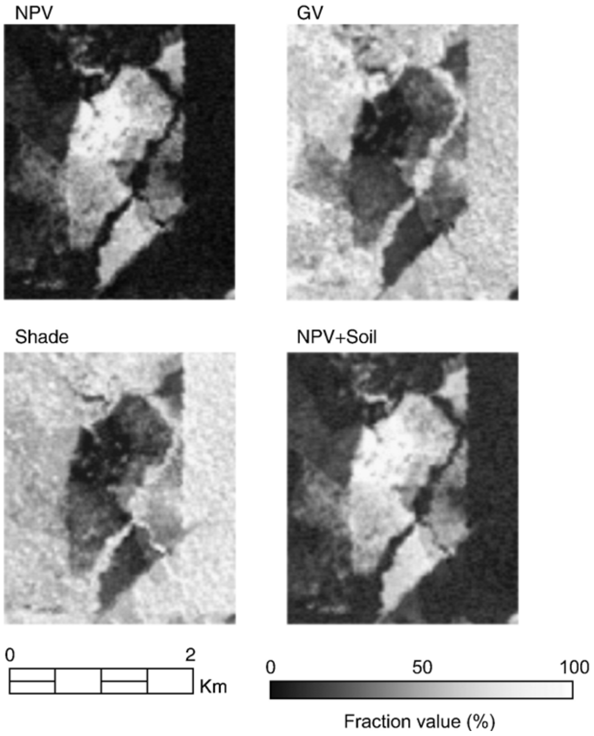


Fig. 7. Example of a low biomass pasture site (Site r).

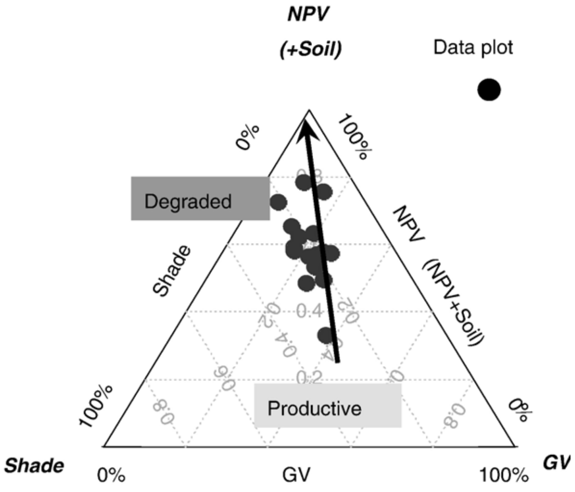


Fig. 9. Conceptual model of pasture change from productive to degraded based on SMA fractions.

al. (1989) obtained good relationships for reflectance in the 2200 nm wavelength and for indices using NIR and SWIR bands in estimate of grass biomass.

The question about which remotely sensed measures are more appropriate for the analysis of grazed pastures may depend upon several factors. One of them is pasture phenology. If remotely sensed data and field measures are from the wet or late wet season, grass biophysical changes due to cattle grazing may

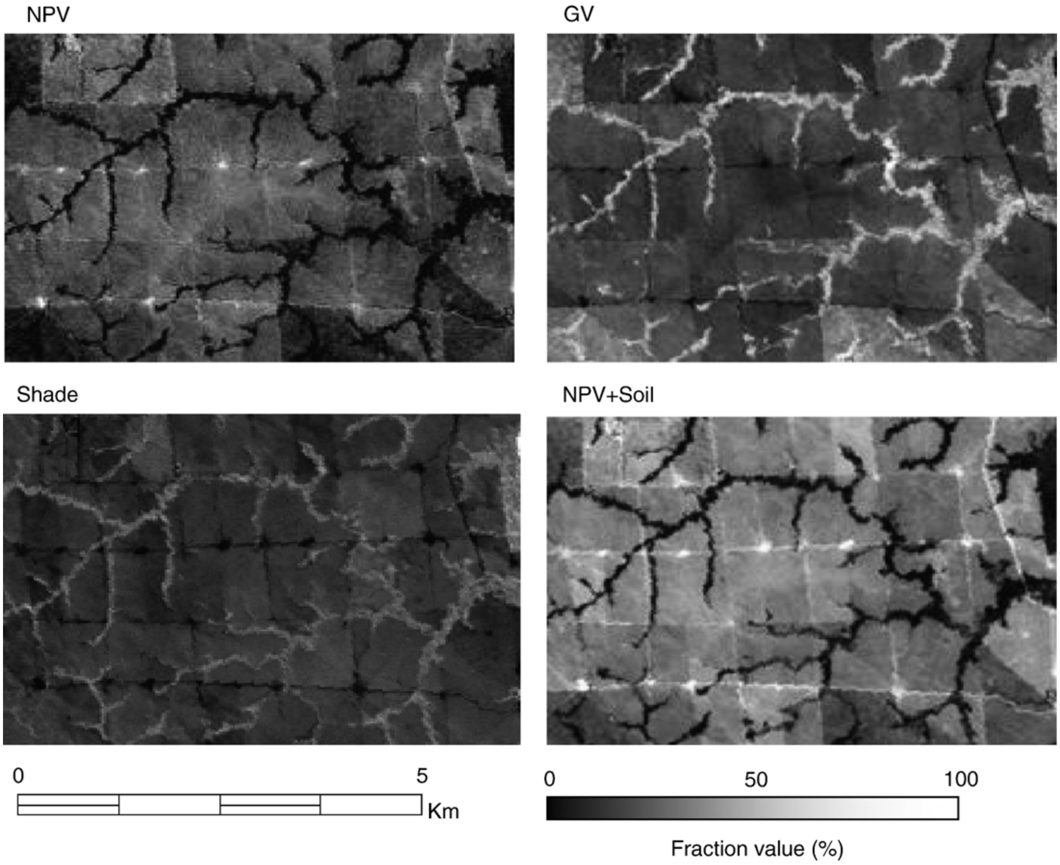


Fig. 8. Example of a high biomass pasture site (Site j).

Table 5
Linear regression of remotely sensed measures against grazing intensity

Variables	R^2	Slope	Intercept	Pr (*t*)
NDVI	0.03	−0.03	0.53	0.26
SAVI	0.04	−0.02	0.34	0.25
NDII5	0.39	−0.08	0.01	<0.01
NDII7	0.40	−0.12	0.41	<0.01
NPV	0.70	0.20	0.18	<0.001
GV	0.33	−0.11	0.35	0.011
Soil	0.02	−0.01	0.19	0.54
Shade	0.43	−0.08	0.29	<0.01
NPV+Soil	0.53	0.19	0.36	<0.001

be better monitored by greenness variation, and greenness indices such as NDVI and GV are more appropriate for either vegetation estimate or grazing effects (Thomson, 1995; Todd et al., 1998; Wessman et al., 1997). In the case of this study, with a mixture of dry and grazed conditions, grass variation depends more on the amount of senesced grass, its brightness (albedo), and water content, rather than greenness variation related to chlorophyll content in vegetation. As a result, non-photosynthetic measures such as NPV and NDII had higher correlations in this analysis. The results of this study on dry-season pasture conditions should represent pasture conditions captured in the satellite imagery in Rondônia, since most of Landsat data are acquired during the dry season in which pastures are dominated with senesced materials.

Another factor is the effect of background substrate. In remotely sensed data, the background signal from pastures is usually litter or bare soil (Asner, 1998; Hill, 2004). Depending upon whether the background is litter or soil, the spectral signature for grass will change and our ability to characterize grass will be affected. For dryer conditions such as the semi-arid regions, absolute quantification of vegetation cover in sparse shrublands using NDVI is weakened by the variability of background soil albedo and high proportions of NPV relative to Plant Vegetation (GV+NPV) (van Leeuwen & Huete, 1996). The soil fraction plays a very important role in characterizing sparse vegetation. In the case of Amazonian pastures, litter seems to be a predominant background substrate that contributes to high NPV from pastures with low biomass. We observed that most of high NPV values are from heavily grazed pastures, which agrees with Asner et al. (2004). In sandy soil conditions, however, degraded pastures may be better characterized by the soil fraction (Asner et al., 2004). In the south region of Rondônia, where there is a large area covered by sandy soils, degraded pastures are usually characterized by the patches of bare soils (Fernando, personal communication) and the soil fraction may play an important role in indicating pasture degradation.

An accurate quantification of NPV or soil fractions from pastures is limited with multispectral sensor data because these fractions are not well discriminated from each other. MODIS 500 m multispectral sensor provides a 1240 band that can contribute to improved characterization of regional pasture biophysical conditions in Rondônia. On the other hand, the separation of NPV from Soil would be more complicated at the coarser spatial resolution, i.e., 500 m. The question regarding how much the amount of soil is required to be discernible from NPV should be addressed by future study of pasture characterization in this region. Soil fractions derived from the hyperspectral sensors have been shown to vary significantly between grazing treatments because of the appearance of bare soils in grazed areas (Asner & Heidebrecht, 2003; Huete et al., 2003; Wessman et al., 1997). The use of hyperspectral data can add more accurate information to improve characterization and estimates of biophysical properties of grazed pastures in the Amazon.

Overall, SMA fractions demonstrated good relationships with grass biophysical properties and provided physically meaningful measures associated with the variation of pasture biomass, water content, and canopy height. In the conceptual model of pasture change built upon SMA fractions, increased grazing intensity can drive pasture degradation.

One of the major sources of errors in this study may be strongly related to scale of field sample size relative to pixel resolution. Our study relied on 0.5 m^2 filed plots to represent a 30 m pixel. This sampling scale may be unrepresentative of pasture properties over Landsat pixel. Hill (2004), for example, states that a scale difference between field plots less than 1.0 m^2 and satellite pixels larger than 400 m^2 introduces sampling errors into the development of biomass prediction. A higher number of field plots should improve relationships between remotely sensed measures and field data.

4.2. Grazing and remote sensing

Previous studies have successfully identified the signals of significant grazing impacts on grass biomass from remotely sensed data, but most have dealt with a clear contrast between grazed and ungrazed treatments only, or with different types of treatments such as burning (Saltz et al., 1999; Wessman et al., 1997; Wylie et al., 2002). Other studies have investigated grazing impacts relative to animal behavior, however, they were based on very small and specific areas such as the impacts of

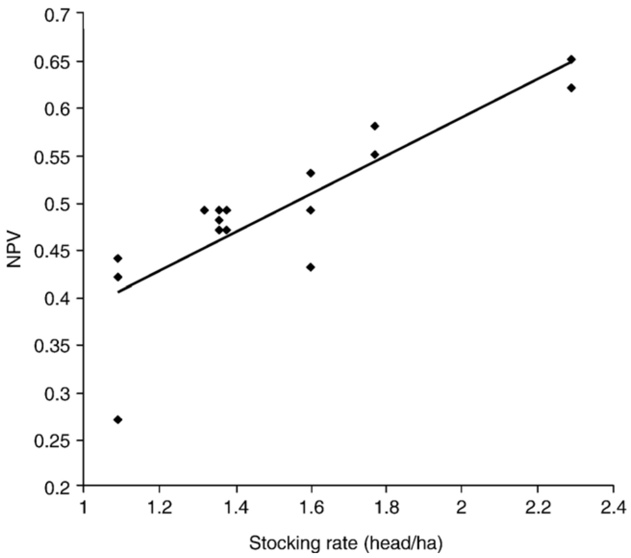


Fig. 10. Relationship between stocking rates and NPV derived from Landsat.

grazing intensity gradient near water (Harris & Asner, 2003; Pickup et al., 1998), which does not indicate general pasture conditions under grazing systems. This study analyzed the effects of grazing intensity on pasture biophysical variables measured in the field and remote sensing along a gradient of stocking density over the study sites. Remotely sensed measures such as NPV quantified the variability in measurements of grass biophysical properties as a function of stocking rates. As expected, grazing intensity and remotely sensed data from pastures showed good relationships. The results may be used to indicate the regions affected by high grazing intensity in Rondônia using remote sensing.

For more specific analyses, however, there are some issues to be considered. First is grazing rotation. Although, this study assumed the minimum effect of grazing rotation, the actual effects of the rotation on grasses inside a study site, for example, are not well understood. Second is pasture types, i.e., beef and dairy, and related grass species. In this study, beef pastures with the grass species *B. brizantha* were analyzed. Addition of dairy pastures with different species such as *Brachiaria decumbens*, the most abundant species in the region after *B. brizantha*, will complete our knowledge about pasture characterization using remote sensing. These points should be addressed in future studies.

5. Conclusions

In this study, we investigated the potential of remote sensing for either quantification of pasture biophysical properties or the analysis of grazing impacts on pasture conditions at the local scale using moderate resolution satellite sensor, i.e., Landsat TM. For grazed pastures under dry conditions, the NIR-SWIR band indices, NDII5 and NDII7, better correlated with field measurements of grass biophysical properties than red-NIR band indices, NDVI and SAVI. SMA fractions provided more intuitive information on pasture conditions. NPV was found to be a good proxy of pasture degradation in Rondônia and successfully showed the impact of grazing on pastures. Other characteristics such as pasture height can also be estimated using the Shade fraction. Grass moisture was better correlated with remotely sensed data than biomass. These results may reflect the main characteristics of Rondônia's pastures, since the satellite data are primarily collected in the dry season.

For more accurate quantification, especially better discrimination of Soil and NPV, higher spectral resolution data such as Aster and Hyperion are needed. In addition, since we used single date satellite images and field data, the consistency of these results should be tested at a different time of the year, investigating whether NPV provides the best estimate for biomass and grazing intensity over longer periods. Temporal analysis using high temporal resolution sensors such as MODIS will be able to address this question.

Acknowledgements

This study was funded by NASA-grants: LBA ECO Phase II — NCC5–681 and the LBA Airborne Program, NCC5–589. We also had technical and logistic support from EMBRAPA-CPAFRO, Agronomy at ULBRA Ji-Paraná, and INCRA Ji-Paraná and INPE. We thank the reviewers of this paper, two anonymous and Dr. Greg Asner, for their invaluable comments and suggestions.

References

Adams, J. B., Smith, M. O., & Johnson, P. E. (1993). Imaging spectroscopy: interpretation based on spectral mixture analysis. In C. M. Pieters, & P. A. J. Englert (Eds.), *Remote Geochemical Analysis: Elemental and Mineralogical Composition* (pp. 145−164). Cambridge, England: Cambridge University Press.

Alves, D. S., Pereira, J. L. G., De Sousa, C. L., Soares, J. V., & Yamaguchi, F. (1999). Characterizing landscape changes in central Rondonia using Landsat TM imagery. *International Journal of Remote Sensing*, *20*, 2877−2882.

Asner, G. P. (1998). Biophysical and biochemical sources of variability in canopy reflectance. *Remote Sensing of Environment*, *64*, 234−253.

Asner, G. P., & Heidebrecht, K. B. (2003). Imaging spectroscopy for desertification studies: comparing AVIRIS and EO-1 Hyperion in Argentina drylands. *IEEE Transactions on Geoscience and Remote Sensing*, *41*, 1283−1296.

Asner, G. P., Townsend, A. R., & Bustamante, M. M. C. (1999). Spectrometry of pasture condition and biogeochemistry in the Central Amazon. *Geophysical Research Letters*, *26*, 2769−2772.

Asner, G. P., Townsend, A. R., Bustamante, M. M. C., Nardoto, G. B., & Olander, L. P. (2004). Pasture degradation in the central Amazon: linking changes in carbon and nutrient cycling with remote sensing. *Global Change Biology*, *10*, 844−862.

Boddey, R. M., Macedo, R., Tarre, R. M., Ferreira, E., de Oliveira, O. C., Rezende, C. D., et al. (2004). Nitrogen cycling in Brachiaria pastures: the key to understanding the process of pasture decline. *Agriculture Ecosystems & Environment*, *103*, 389−403.

Costa, F. P., & Rehman, T. (2005). Unravelling the rationale of 'overgrazing' and stocking rates in the beef production systems of Central Brazil using a bi-criteria compromise programming model. *Agricultural Systems*, *83*, 277−295.

CPRM. 1997. Mapa Geológico do Estado de Rondônia. *in*, Porto Velho, RO.

Dias Filho, M. B., Davidson, E. A., & de Carvalho, C. J. R. (2000). Linking biogeochemical cycles to cattle pasture management and sustainability in the Amazon Basin. In M. McClain, R. L. Victoria, & J. E. Ritchey (Eds.), *The Biogeochemistry of the Amazon Basin.* New York: Oxford Univ. Press.

EMBRAPA. 1983. Mapa de levantamento de reconhecimento de meia intensidade dos solos do estado de Rondônia, 1:500.000. *in*. Comissão Estadual de Planejamento Agrícola, Porto Velho.

EMBRAPA. (1997). Manual de Métodos de Análise de Solo: 2a Edição Rio de Janeiro: Ministério da Agricultura e do Abastecimento.

Everitt, J. H., Escobar, D. E., & Richardson, A. J. (1989). Estimating grassland phytomass production with near-infrared and mid-infrared spectral variables. *Remote Sensing of Environment*, *30*, 257−261.

Fearnside, P. M. (1996). Amazonian deforestation and global warming: carbon stocks in vegetation replacing Brazil's Amazon forest. *Forest Ecology and Management*, *80*, 21−34.

Fearnside, P. M., & Barbosa, I. R. (1998). Soil carbon changes from conversion of forest to pasture in Brazilian Amazonia. *Forest Ecology and Management*, *108*, 147−166.

Field, C. B., Randerson, J. T., & Malmstrom, C. M. (1995). Global net primary production — combining ecology and remote-sensing. *Remote Sensing of Environment*.

Harris, A. T., & Asner, G. P. (2003). Grazing gradient detection with airborne imaging spectroscopy on a semi-arid rangeland.

Hardisky, M. A., Klemas, V., & Smart, R. M. (1983). The influence of soil-salinity, growth form, and leaf moisture on the spectral radiance of *Spartina alterniflora* canopies. *Photogrammetric Engineering and Remote Sensing*, *49*, 77−83.

Hill, M. J. (2004). Grazing agriculture: Managed pasture, grassland, and rangeland. In S. L. Ustin (Ed.), *Manual of Remote SensingRemote sensing* *for natural resource management and environmental monitoring*, *vol. 4*. (pp. 449−530). Hoboken, NJ: John Wiley & Sons.

Hill, M. J., Donald, G. E., Vickery, P. J., Smith, R. C. G. 1998. *NDVI-based phonological indices; predictive potential for grazing systems*. Proceeding for the 9th Australasian Remote Sensing and Photogrammetry Conference, UNSW, Sydney, July, 1998 CDROM.

Holmes, K. W., Roberts, D. A., Sweeney, S., Numata, I., Matricardi, E., Biggs, T. W., et al. (2004). Soil databases and the problem of establishing regional biogeochemical trends. *Global Change Biology*, *10*, 796−814.

Huete, A. R. (1988). A soil-adjusted vegetation index (SAVI). *Remote Sensing of Environment*, *25*, 295−309.

Huete, A. R., Miura, T., & Gao, X. (2003). Lands cover conversion and degradation analyses through coupled soil–plant biophysical parameters derived from Hyperspectral EO-1 Hyperion. *IEEE Transactions on Geoscience and Remote Sensing*, *41*, 1268−1276.

Hunt, E. R., & Rock, B. N. (1989). Detection of changes in leaf water content using near- and middle-infrared reflectance. *Remote Sensing of Environment*, *30*, 43−54.

Imspec (2003). *ACORNTM user's guide.* Analytical Imaging and Geophysics Boulder, CO, USA.

Lupinacci, A. V. (2002). *Reservas orgânicas, índice de área foliar e produção de Forragem em Brachiaria brizantha cv. Marandu submetida a intensidade de pastejo por bovino de corte.* Master Piracicaba: ESALQ/USP.

Moran, E. F. (1993). Deforestation and land use in the Brazilian Amazon. *Human Ecology*, *21*, 1−21.

Mwendera, E. J., Saleem, M. A. M., & Woldu, Z. (1997). Vegetation response to cattle grazing in the Ethiopian highlands. *Agriculture Ecosystems & Environment*, *64*, 43−51.

Numata, I., Chadwick, O. A., Roberts, D. A., Schimel, J. P., Sampaio, F. F., & Leonidas, F. C. (2007). Temporal nutrient variation in soil and vegetation of post-forest pastures as a function of soil order, pasture age, and management, Rondônia, Brazil. *Agriculture Ecosystems & Environment*, *118*, 159−172.

Pickup, G., Bastin, G. N., & Chewings, V. H. (1998). Identifying trends in land degradation in non-equilibrium rangelands. *Journal of Applied Ecology*, *35*, 365−377.

Roberts, D. A., Numata, I., Holmes, K., Batista, G., Krug, T., Monteiro, A., 2002. Large area mapping of land-cover change in Rondonia using multitemporal spectral mixture analysis and decision tree classifiers. *Journal of Geophysical Research-Atmospheres*, *107*, 40–41–40–18.

Roberts, D. A., Batista, G., Pereira, J. L. G., Waller, E., & Nelson, B. (1998). Change identification using multitemporal spectral mixture analysis: applications in eastern Amazônia. In C. Elvidge, & R. Lunetta (Eds.), *Remote Sensing Change Detection: Environmental Monitoring Applications and Methods* (pp. 137−161). Ann Arbor: Ann Arbor Press.

Roberts, D. A., Gardner, M., Church, R., Ustin, S., Scheer, G., & Green, R. O. (1998). Mapping chaparral in the Santa Monica Mountains using multiple endmember spectral mixture models. *Remote Sensing of Environment*, *65*, 267−279.

Roberts, D. A., Smith, M. O., & Adams, J. B. (1993). Green vegetation, nonphotosynthetic vegetation, and soils in AVIRIS data. *Remote Sensing of Environment*, *44*, 255−269.

Rouse, J. W., Haas, R. H., Schell, J. A., & Deering, D. W. (1973). Monitoring vegetation systems in the Great Plains with ERTS. *Proceedings of the third ERTS symposium* (pp. 309−317).

Saltz, D., Schmidt, H., Rowen, M., Karnieli, A., Ward, D., & Schmidt, I. (1999). Assessing grazing impacts by remote sensing in hyper-arid environments. *Journal of Range Management*, *52*, 500−507.

SEDAM (2004). *Boletim Climatologico de Rondônia — Ano 2003*. Porto Velho: Secretaria de Estado de Desenvolvimento Ambiental.

Serrão, E. A. S., & Toledo, J. M. (1990). The search for sustainability in Amazonian pastures. In A. B. Anderson (Ed.), *Alternatives to deforestation: Steps toward sustainable use of the Amazon rain forest* (pp. 195−214). New York: Columbia University Press.

Settle, J. J., & Drake, N. A. (1993). Linear mixing and the estimation of ground cover proportions. *International Journal of Remote Sensing*, *14*, 1159−1177.

Skole, D., & Tucker, C. (1993). Tropical deforestation and habitat fragmentation in the Amazon — satellite data from 1978 to 1988. *Science*, *260*, 1905−1910.

Todd, S. W., Hoffer, R. M., & Milchunas, D. G. (1998). Biomass estimation on grazed and ungrazed rangelands using spectral indices. *International Journal of Remote Sensing*, *19*, 427−438.

Thomson, A. G. (1995). Airborne radiometry and a sheep grazing experiment on dune grassland. *International Journal of Remote Sensing*, *16*, 981−988.

van Leeuwen, W. J. D., & Huete, A. R. (1996). Effects of standing litter on the biophysical interpretation of plant canopies with spectral indices. *Remote Sensing of Environment*, *55*, 123−138.

Wessman, C. A., Bateson, C. A., & Benning, T. L. (1997). Detecting fire and grazing patterns in tallgrass prairie using spectral mixture analysis. *Ecological Applications*, *7*, 493−511.

Wylie, B. K., Meyer, D. J., Tieszen, L. L., & Mannel, S. (2002). Satellite mapping of surface biophysical parameters at the biome scale over the North American grasslands — a case study. *Remote Sensing of Environment*, *79*, 266−278.