Regional Characterization of Pasture Changes through Time and Space in Rondônia, Brazil

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ABSTRACT: Although pasture degradation has been a regional concern in Amazonian ecosystems, our ability to characterize and monitor pasture degradation under different environmental and human-related conditions is still limited. Regional analysis of pasture dynamic patterns was conducted using high-frequency temporal satellite data and ancillary data to better understand pasture degradation under varied soil, environmental, and pasture management conditions in the state of Rondônia, Brazil. The 10-day normalized difference vegetation index (NDVI) composite derived from Moderate Resolution Imaging Spectroradiometer (MODIS) 250-m resolution was used to characterize different grass phenological patterns for 32 counties in Rondônia between 2001 and 2003. Six pasture greenness classes showed that high greenness pasture classes dominated in young pastures, while low greenness pasture classes were least common. As pastures aged, the proportion of high greenness pasture classes decreased and the proportion of low greenness pastures increased, indicating a decrease in forage productivity over time in Rondônia. The magnitude of productivity decline depended on environmental constraints and land use systems. To refine this analysis, trajectories of pasture change were determined using spectral mixture analysis applied to Landsat time series data from 1988 to 2001 with the focus on two counties that show contrasting patterns of potential of grass production: Pimenteira, representing the "degraded" pasture category, and Governador Jorge Teixeira, as the "productive" pasture category. The results revealed a clear pasture degradation pattern in Pimenteira, related to low soil fertility and dry climate conditions, while Governador Jorge Teixeira, with better soil fertility and intermediate precipitation, did not show signs of pasture degradation through time.

KEYWORDS: Regional pasture analysis; Pasture greenness; Time series; MODIS; NDVI

1. Introduction

Since the early colonization of the Amazon, pasture has been the most extensive land use, covering 60%–80% of the total cleared area (Fearnside 1996), and its expansion has been accelerating (IBGE 2002; IBGE 2005; Simon and Garagorry 2005; Soares-Filho et al. 2006). In the state of Rondônia, Brazil, in the southwest Amazon, cattle stocks increased more than 100% between 1998 and 2005, and beef and milk production increased 220% and 65%, respectively (IBGE 2005). In part the increase is related to intensification of production systems (Pedlowski et al. 1997), but most of the increase still comes from forest conversion (Simon and Garagorry 2005). Rapid expansion of pasture on Rondônia's nutrient-poor soils raises concern about the sustainability of grass production (Serrão and Toledo 1990; Dias Filho et al. 2000). The spatial variability of diverse edaphic and climatic conditions and variable grazing pressures combine to produce a variety of pasture degradation patterns. Previous research found that grass nutrient status is influenced by soil fertility (Dias Filho et al. 2000; Asner et al. 2004), whereas pasture physical properties are controlled most strongly by pasture grazing intensity (Mwendera et al. 1997; Lupinacci 2002). Their impacts, however, are not well known at regional scales.

Remote sensing is ideal for monitoring spatially explicit temporal changes in pasture properties. Temporal vegetation indices derived from remote sensing such as the normalized difference vegetation index (NDVI) provide appropriate measures to analyze changes in vegetation cover leaf area index (LAI) and biomass, and estimate annual net primary production (NPP; Myneni et al. 1995; Todd et al. 1998; Gower et al. 1999; Huete et al. 2006). Unlike a single-date satellite image that provides a snapshot (or time-specific measure) of vegetation conditions, interannual remotely sensed data can characterize year-to-year variation and processes associated with pasture degradation, such as a long-term decline in photosynthetic cover. Furthermore, high temporal resolution data such as Moderate Resolution Imaging Spectrometer (MODIS) data allow us to identify more detailed phenological patterns of pastures within a year that may be associated with degradation. Monitoring change in photosynthetically active grass biomass through different seasons and years provides an index of pasture productivity because this material varies primarily as a function of biomass and LAI that can, in turn, be related to forage production.

In Rondônia's seasonal climate, grasses senesce in the dry season and can become highly degraded if over utilized. With the onset of the rainy season, grasses add photosynthetically active material at a rate and to an extent that is related to both the edaphic condition of the site and to the extent of damage sustained during the dry season. Different patterns of grass greenness change can occur due to pasture status managements and environment over Rondônia. For example, degraded pastures with low biomass or LAI have low recovery of biomass from dry to wet season, resulting in muted change in greenness, whereas productive pastures with high biomass exhibit substantial change in greenness (Gower et al. 1999; Hill 2004). Detecting different temporal patterns of greenness change using remote sensing and their relationships with edaphic, climate, and management factors at a statewide scale will provide insights into pasture degradation processes in Rondônia.

In this study, we analyzed pasture patterns and pasture degradation processes for 32 counties in the state of Rondônia. Three goals were addressed in this analysis.

- First, characterization of pasture degradation processes based upon NDVI time series data in combination with environmental and census data.
- Second, identification of regions at high risk of pasture degradation due to specific soil, environmental, or management conditions.
- Finally, assessment of the specific trajectories of pasture physical change using Landsat times series.

Two types of temporal analysis were conducted: 1) change in pasture greenness with high temporal frequency data from MODIS and 2) pasture physical change detection with spectral mixture analysis (SMA) derived from Landsat time series data.

2. Study region

The state of Rondônia is located in the southwestern Brazilian Amazon, occupying an area between 8° and 15°S and 60° to 65°W (Figure 1). The climate is humid tropical, Awi, according to the Köppen classification, with a well-defined dry season during July and August. Annual precipitation is around 2250 mm. The average temperature is 24°C, while relative humidity varies between 80% and 85% (RADAM BRASIL 1978). Soil orders are related to geology and topography of

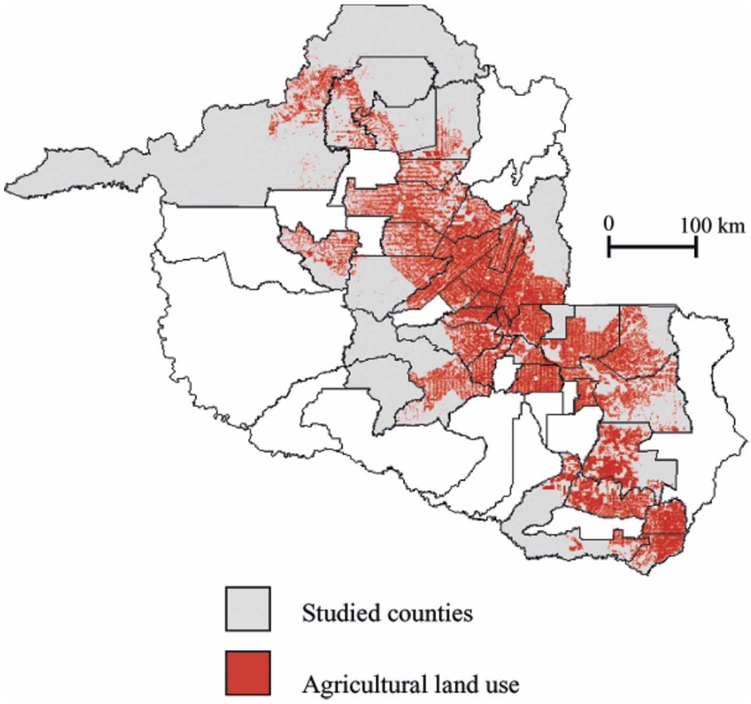

Figure 1. Study region: State of Rondonia. Thirty-two counties were selected for this study (gray polygons).

this region. Oxisols and Ultisols, dystrophic soils, are found mostly over the Precambrian granitoid and metasuparacrustal rocks with predominantly flat topography in the north of the state, while Alfisols are distributed mainly in central Rondônia toward the south, where they coincide with the presence of intrusive basic and ultrabasic rocks with gently rolling topography (EMBRAPA 1983; CPRM 1997; Holmes et al. 2004). The natural vegetation consists of dense tropical forest and open tropical forest (INPE 2002).

Land cover conversion has been primarily concentrated along the federal road BR368 and adjacent roads. Cattle pasture is the predominant land use type across the state. These areas are designated primarily for beef and milk production. Pasture sizes vary from less than 20 ha to more than 5000 ha according to pasture type. Dairy pastures are mostly found in the small producer settlements in the central region bounded by the settlements such as Ouro Preto and Ji-Paraná, while beef pastures cover extensive areas located to the north and south and distributed within the central region. Other land uses in Rondônia include perennial crops such as coffee and cacao, and annual crops such as corn, rice, manioc, and beans (Pedlowski et al. 1997; IBGE 2003).

3. Methods

This study used remote sensing, a geographic information system, and agricultural census data. Remote sensing spatiotemporal analysis for pasture dynamics included the following components: 1) preprocessing of the MODIS NDVI 10-day composite, 2) production of land use map using Landsat classified images, 3) compilation of the major controlling variables, and 4) data analysis.

3.1. MODIS 10-day-composite NDVI data

The dataset of the NDVI 10-day composites was derived from the MODIS 250-m daily reflectance data (MOD09GQK) for the period between 2001 and 2003. Spectral bands included red (645.5 nm, band 1) and near infrared (856.5 nm, band 2). Mosaicking and reprojection of the four tiles of the MODIS data (H9–10 and V11–12) was accomplished using the MODIS Reprojection Tool (MRT) version 3.2 (http://edcdaac.usgs.gov/landdaac/tools/modis/index.asp). The reprojected dataset was subset to provide coverage for the study region only.

Once all daily reflectance images were subset, they were composited into 10-day composites. Band 1 (red), which provides a clear contrast between cloud and noncloud areas, was used to mask cloudy areas out of the 10-day composite. After cloud masking, the compositing date was selected based on the median of the red band. The same date was used for the composite of band 2 (NIR).

NDVI was calculated for each 10-day composite:

$$\mathrm{NDVI} = (\mathrm{B2} - \mathrm{B1})/(\mathrm{B2} + \mathrm{B1}), \tag{1}$$

where B1 is MODIS band 1 (red) and B2 is MODIS band 2 (NIR).

Despite masking for clouds, cloud effects were not entirely removed from the time series data. To minimize cloud effects on the NDVI time series, we used the local minimum fitting (LMF) algorithm developed by Sawada and Sawada (Sawada and Sawada 2002). This algorithm uses a trigonometric regression function after having gone through a minimum value filter. The LMF processed NDVI time series data are illustrated in Figure 2. For more details, see Sawada and Sawada (Sawada and Sawada 2002). Although LMF minimized cloud effects on the NDVI time series, noise remained during the rainy season. Therefore, analysis was restricted to the period between April and the end of October, which covers from the late rainy season to the dry season and the early rainy season.

3.2. Land use base map from Landsat time series

Since there is no information available about the extent of current land use for Rondônia, the Landsat classified images, consisting of seven scenes, were used to estimate land use area for 2002. Land use in this study considered only areas classified as agriculture crops or pasture. Landsat data have 30-m spatial resolution; much finer, and more accurate, compared to the MODIS 250-m data. A land use map (excluding forest, second growth forest, river, rock, urban, savanna, and non-agricultural–pastoral areas) was generated from the Landsat classified images using a decision-tree-based classification technique (Roberts et al. 2002). To eliminate temporally variant land cover types such as burned areas, green pasture, and recently deforested and secondary forest areas, a time series window between 1999 and 2003 was used to determine the consistent land use areas over this period. The details about Landsat classification and reclassification techniques for land cover mapping of Rondônia are described by Roberts et al. (Roberts et al. 2002). This land use map was used as a base map showing the current spatially explicit land

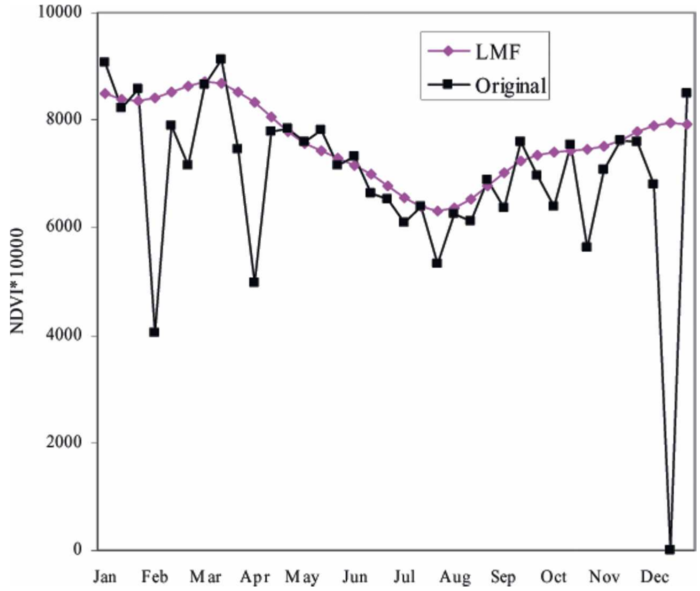

Figure 2. Smoothed MODIS NDVI time series data after the application of LMF.

use areas in Rondônia. In addition, estimated pasture areas for 2002 were calculated at the county level, by subtracting agriculture crop areas (annual and perennial), derived from the census data (IBGE 2003) from the land use map.

3.3. Controlling variables

Four controlling variables for Rondônia's pasture greenness change patterns were used: land use age, soil order, average annual precipitation, and stocking rate. The land use age map was generated from the Landsat time series dataset (Table 1). The dataset comprised the same seven scenes used for the land use map, covering a period between 1985 and 2003. The time series of shade fraction images derived from spectral mixture analysis was used to generate the age map based upon the technique described by Numata et al. (Numata et al. 2003). Four age classes were included in this analysis: 1–5, 6–10, 11–15, and >16 yr old (Figure 3a).

The available soil and rainfall maps of Rondônia are quite generalized but

Table 1. Landsat scenes and time series dataset used for land use age map.

Path/row	Region	Dates
232/66	Porto Velho	Jul 1986, Jul 1992, Jul 1997, Sep 2002
232/67	Ariquemes	Aug 1986, Jun 1992, Jun 1997, Aug 2002
231/67	Ji-Paraná	Oct 1986, Jul 1991, Jun 1997, Aug 2002
231/68	Pimenta Bueno	Oct 1986, Jul 1992, Jul 1997, Aug 2002
230/68	Cacoal	Jul 1986, Jul 1992, Jun 1997, Aug 2002
230/69	Chupinguaia	Jul 1986, Jul 1991, Oct 1996, Jun 2002
229/69	Vilhena	Jul 1986, Jun 1992, Jul 1996, Aug 2002

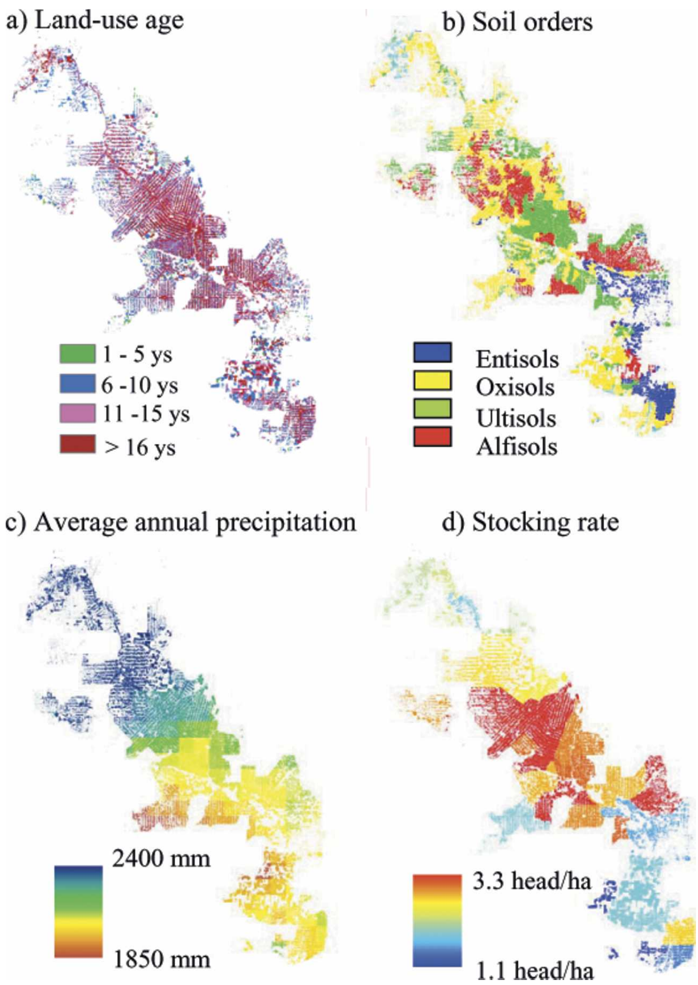

Figure 3. Maps of controlling variables: (a) land use age, (b) soil orders, (c) average annual precipitation, and (d) stocking rate.

capture the important environmental variations across the region. The 1:500 000 scale EMBRAPA (EMBRAPA 1983) soil map for Rondônia was used to identify the coverage for four major soil orders according to the U.S. soil taxonomy system (USDA 1999): Entisols, Oxisols, Ultisols, and Alfisols (Figure 3b). An average annual precipitation map with a 10 km × 10 km spatial grid was derived from available rainfall data collected over the state of Rondônia between 1987 and 1995 (Figure 3c). Rainfall data collected from rainfall stations were spatialized by using Kriging (see Dunne 1999).

Stocking rate in this study refers to grazing intensity over pasture, which is an important driving factor for pasture sustainability. To calculate this, the Instituto Brasileiro de Geografia e Eestatistica agricultural census data were used. The census data are organized at the county scale. The rate was calculated as below:

$$\text{Stocking rate} = \text{number of cattle (head)/pasture area (ha)}. \quad (2)$$

The number of cows was determined from the census data relative to the year 2002, and the pasture area was estimated for each county by subtracting agricultural area from the land use area calculated from the Landsat classified images (Figure 3d).

3.4. Analyses of patterns of pasture greenness change through space and time

Since the land use map covers only seven Landsat scenes, uncovered counties were eliminated. In addition, those counties in which pasture area was less than 85% of the total land use area were not included in the analysis. This left 32 counties for pasture analysis (Figure 1). In this way, the analysis was conducted assuming that all areas studied are dominated by pasture-based systems with other agricultural activities making up 15% of the remaining area at most. The land use map with the 32 counties was used as a mask to determine the common study areas for all the other variables (Figure 3). Although the county of Porto Velho, Brazil, is not entirely covered by the available Landsat scenes, it was included in the analysis because it is the oldest county that provides historical land use study (mostly pasture). Total land use area for this county was estimated by combining Landsat data and MODIS 250-m data.

To determine major pasture greenness patterns in Rondônia, preprocessed NDVI images were classified by the Iterative Self-Organizing DATA Classifier (ISODATA) unsupervised classification algorithm (Jensen 1996). ISODATA unsupervised classification is an iterative procedure. First, it calculates a vector of arbitrary initial clusters evenly distributed in the data space, and then it classifies each pixel to the closest cluster (minimum distance approach) and recalculates new cluster means with all pixels belonging to the class. The last two procedures are iteratively repeated until changes between each iteration fall below a specified threshold (Jensen 1996). ISODATA classification was performed with 10 iterations, yielding six pasture classes.

To evaluate the effects of controlling variables on different pasture classes derived from ISODATA classification and the driving variables, a generalized linear model with Poisson distribution was used. The model is designed to estimate the parameters of a multivariate explanatory model in which the dependent variable is categorical and the independent variables are either continuous or categorical (Cristensen 1997). The associated statistic determines whether variables are related to each other and indicates the relative importance of the explanatory variables in predicting a dependent variable (Cristensen 1997). Here, pasture classes derived from the MODIS NDVI time series were used as the categories of the dependent variable and all other variables (age, soil, average annual precipitation, and stocking rate) were used as independent variables in the generalized linear model. For the categorical variables including pasture greenness, land use age, and soil orders, their categories should follow a certain order. The pasture classes were ordered according to their greenness: from high to low greenness, whereas the soil orders were ordered according to soil fertility: from low to high. To verify relative importance of the explanatory variables, we calculated the difference between null deviance and residual deviance of a generalized linear model without including one of the variables. As null deviance indicates a function of the constant model for the input data while residual deviance indicates how well the variables used in the model perform to fit the data, the difference between them from a model without a variable indicates the relative impact of this excluded variable on the model with the rest of the variables. For example, to calculate relative impact of the variable "land use age," a generalized linear model without this variable was run, and the difference between null and residual deviances was calculated. A set of the independent variables characterized each location, or observation. Each observation corresponded to a 250 m × 250 m pixel. Input data for statistical analysis consisted of 10 000 observations (pixels), which were randomly selected and extracted from each map.

After the impacts of the controlling variables on pasture greenness change patterns were determined, areas subject to pasture degradation and other sites that tend to be more productive were defined. Degraded pastures were defined as the areas with low NDVI pasture classes at an early stage of pasture use, whereas productive pastures were defined as those counties that held high grass greenness even at the older stages. For degraded pastures, the percentage of low NDVI classes was calculated within the first 10 yr since deforestation. In the case of the productive pastures, the percentage of high NDVI classes was calculated in pastures more than 16 yr old for each county. The top five degraded and productive counties were selected and were compared in terms of their environmental and human-related characteristics.

3.5. Characterization of pasture degradation processes through time using SMA derived from Landsat times series

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 and 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):

$$\rho_\lambda = \sum_{i=1}^{N} f_i^* \rho_{i\lambda} + \varepsilon_\lambda, \tag{3}$$

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-square error (RMSE) is calculated for each pixel of the scene to assess model fit (Adams et al. 1993):

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{\lambda=1}^{M} (\varepsilon_\lambda)^2}{M}}, \tag{4}$$

where M is the number of bands. SMA typically assumes single interactions between photons and surfaces, producing a linear mixing of the surface fractions and their reflectance. In this study, a four-endmember model was used including nonphotosynthetic vegetation (NPV), green vegetation (GV), shade, and the combination of NPV + soil fractions. Furthermore, these fractions showed reasonable relationships with pasture physical properties (Asner et al. 2004; Numata et al. 2007). Here, we used SMA fractions derived from Landsat time series data to demonstrate pasture physical change through time for these counties. Trajectories of pasture change (pasture degradation) were determined for two contrasting counties, that is, degraded and productive, previously defined, over the period between 1988 and 2001. We delineated the 16-yr-old pasture area on each county based on the pasture class map, described previously in this section. The sets of Landsat Thematic Mapper (TM) and Landsat Enhanced Thematic Mapper (ETM+) images were selected for each county covering the time period between 1988 and 2001. To minimize phenological differences among the images over time, scenes were selected to correspond as closely as possible to the period from mid-July to early August.

Fractions used for the analysis were NPV, GV, and shade. The fractions were generated by the technique developed and used by Roberts et al. (Roberts et al. 1998; Roberts et al. 2002) for the land cover mapping of Rondônia. All of the images for each scene were intercalibrated to the reference images. Next, the endmembers for SMA were calculated and adjusted to the reference endmembers from the spectral library (Roberts et al. 1998). Based upon the conceptual model established in Numata et al. (Numata et al. 2007), our hypothesis is that degraded pastures will show an increase in NPV and a decrease in GV over time, while pastures in productive or sustainable regions will show smaller changes or show stable fractions over time. To test this hypothesis, the degraded and productive areas were determined for the fractional data over the time series. NPV and shade were used for the dynamics of degraded areas and GV was used for productive area. The thresholds were established for the fractions based upon the results from Numata (Numata 2006); NPV > 50% and shade 10% indicate pastures with very low biomass (around 1–2.5 thresholds per hectare), while GV > 20% represents pastures with high biomass (7–10 thresholds per hectare). The percentages of degraded and productive areas were calculated for two counties using these thresholds applied to each date of the time series.

4. Results

4.1. Pasture greenness change patterns from the MODIS NDVI time series

Figure 4a shows the resulting pasture greenness classes from ISODATA classification applied to the MODIS NDVI time series for 3 yr since 2001. The NDVI pasture dynamics in Rondônia illustrated the dominant role of precipitation in pasture greenness. At the start of the dry season in April and May, a drastic decrease in precipitation (Figure 4b) leads to a decrease in pasture greenness 1 month later, presumably because of a decline in soil moisture. The lowest NDVI values occur in July and August followed by rapid recovery as rainfall increases in September and October. Additionally, interannual variability is evident within the 3 yr. The amplitude NDVI time series in 2001 was much lower compared to 2002 and 2003. However, the monthly precipitation data (Figure 4b) do not show this variability. The actual causes for this variability are not known.

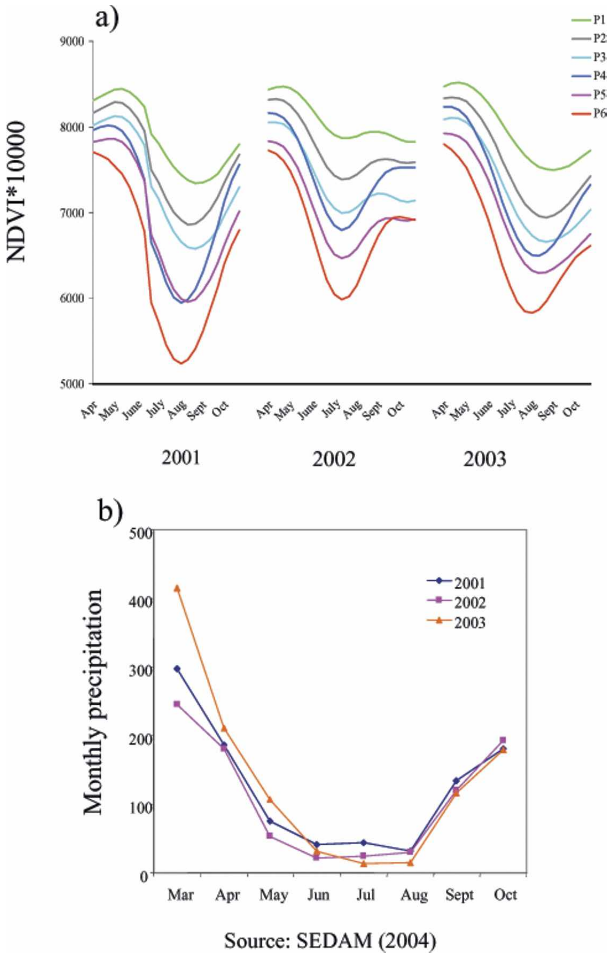

Figure 4. (a) Temporal patterns of six pasture classes derived from classified NDVI time series by ISODATA classification. (b) Monthly precipitation data from March to October, averaged from three counties in Rondônia.

Pasture greenness variation patterns for different pasture classes (P1–P6) vary each year (Figure 4b). The patterns of P1, P2, P5, and P6 are most consistent during the 2001 to 2003 time interval; that is, P1 and P2 are the greenest pastures and P5 and P6 had the lowest greenness. P4 shows a unique pattern within the pasture classes. It has a stronger depression in the dry season, while keeping its greenness level as high as P3 before and after this period. In 2001, P4 showed a depression in the dry season as deep as that of P5, but the greenness recovery occurred very rapidly and its level exceeded P3. P4 and P5 were very distinct in 2002 and 2003; P4 had a higher NDVI than P5 at this time.

4.2. Characterizing pasture greenness classes relative to controlling variables

Distributions of the pasture classes and of the controlling variables across the 32 counties are shown by histograms (Figure 5a). Most pastures fell in the interme-

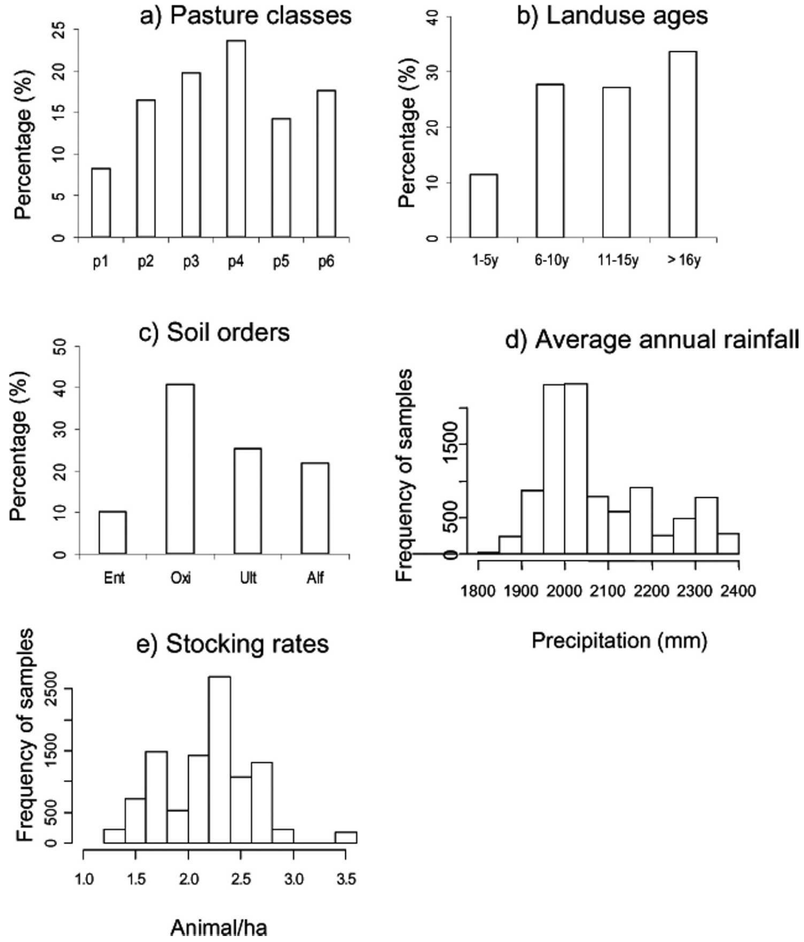

Figure 5. Histograms showing the distributions of each variable over 32 studied counties in Rondônia: (a) pasture classes, (b) land use age, (c) soil orders, (d) average annual rainfall, and (e) stocking rates

diate condition characterized by P3 and P4, although low greenness pastures, P5 and P6, make up 14% and 18%, respectively. By contrast, P1, the greenest pasture class, constitutes <10%.

Figure 5b shows that pastures more than 16 yr old occupy 34% of the area, whereas those <10 yr old constitute nearly 40%, illustrating the continued expansion of pasture area in Rondônia. In the case of soils, Oxisols are the most common soil order on which pastures in our study region are installed (41%), followed by Ultisols (25%), Alfisols (22%), and Entisols (10%; Figure 5c). The annual average precipitation in Rondônia (Figure 5d) ranges between 1800 and 2400 mm across pastures in Rondônia. Nearly 40% of samples fall between 1950 and 2050 mm, and lower amounts of samples are distributed in a wider range of higher precipitation (i.e., >2100 mm). The rainfall data show a gradient ranging from dry to wet occurring from the south to the north across Rondônia (Figure 3c).

Stocking rates varied from 1.25 to 3.50 head per hectare with a median of 2.22

head per hectare (Figure 5d). Most of the sampled areas had between 2.0 and 2.8 head per hectare (64%), and nearly 30% are below 2.0 head per hectare. High stocking rates are mostly found in the region with a high concentration of small-scale producers (Ouro Preto, Jurú, and Teixeiranópolis; Figure 3d), whereas pastures in the north and the south regions have lower stocking rates.

4.3. Effects of controlling variables on pasture greenness

Statistical results of a generalized linear model for pasture dynamic patterns as a function of the controlling variables are shown in Table 2a. The results reveal that most variables were statistically significant. The difference between null and residual deviances is the smallest for the model without the variable "age." This shows that the residual increases with all variables except age, indicating that land use age has the greatest effect on pasture patterns of Rondônia, followed by stocking rate, precipitation, and soil orders. For more detailed analyses, we found that all age classes have strong effects on pasture dynamics and z values increased according to the ordered land use ages with those >16 yr old as the most influential age class on pasture classes. Histograms of land use age for pasture classes (Figure 6) show the variation of age distributions across pasture classes. High greenness pastures, that is, P1, P2, and P3, were characterized with well-distributed age classes, while P4, P5, and P6, representing intermediate to low greenness pastures, were dominated by ages >16 yr old.

Soil type appears to have the smallest effect on determining pasture dynamic patterns in Rondônia. Entisols and Alfisols had significant effects, while Oxisols and Ultisols did not, according to the generalized linear regression analysis (Table 2a). However, the histograms suggest that the distribution of soil orders varied as a function of pasture classes (Figure 6). For example, although Oxisols are the predominant soil order in the region and consistently the most abundant in all

Table 2a. Statistical summary derived from the generalized linear model and relative impacts of variables (null deviance – residual deviance).

Variables	Estimate	Std error	*Z* value
(Intercept)	1.892*	0.1	19.47
Age	0.097*	0.0059	16.34
Soil	0.018**	0.006	−4.41
Precipitation	−0.0028*	0.00005	−8.05
Stocking rate	−0.19*	0.014	−13.02
Age classes			
6–10 yr	0.23*	0.025	9.29
11–15 yr	0.3*	0.024	12.35
>16 yr	0.38*	0.024	15.82
Soil orders			
Entisols	−0.13**	0.046	−2.98
Oxisols	−0.067	0.46	−1.48
Ultisols	−0.015	0.45	−0.32
Alfisols	0.14**	0.48	−2.88

* >0.001.
** >0.01.
>0.05.

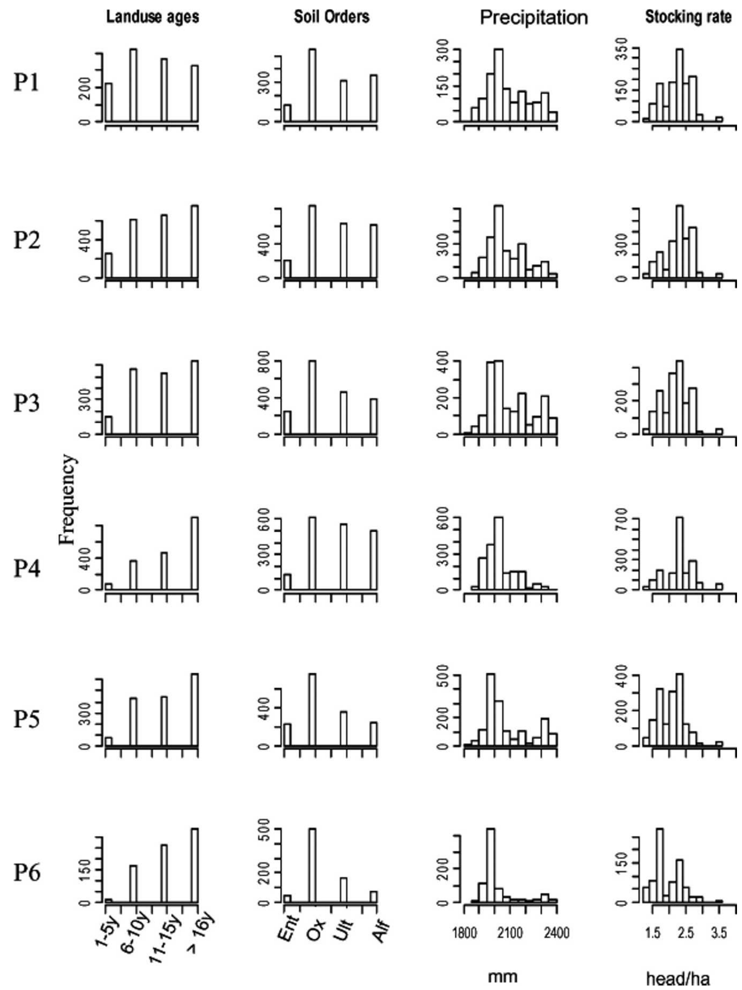

Figure 6. Histograms of showing distributions of the categories of each controlling factor for each pasture class.

pasture classes, the dominance of this soil type is more pronounced in P5 and P6, the low greenness pastures. The other soil orders are more uniformly distributed across the pasture classes. There are significant amounts of Ultisols and Alfisols for P2 and P4, whereas these soils are found less often in P1 and P3 and seldom found in P5 and P6.

Table 2b. Relative impacts of variables.

Excluded variable	Null–residual
Age	297.6
Soil	551.7
Precipitation	523.2
Stocking rate	394.9

Figure 6 shows that the effect of rainfall on pasture conditions is relatively straightforward. The negative effect of this variable on pasture classes indicates that the pasture greenness increases with the increase of average annual precipitation. It can be noted that lower greenness pastures, especially P6, are found in the drier conditions, mostly in the south, whereas greener pastures occur over a wide range of precipitation.

Stocking rate is the second most significant factor. However, its strong negative effect, revealed by the generalized linear model, suggests that low greenness pastures occur under low stocking rates and high greenness pastures under high stocking rate conditions, as is seen in Figure 6. This contradicts the results obtained in a previous study. Numata et al. (Numata et al. 2007) found a negative relationship between stocking rates and green vegetation fraction, suggesting that the larger the stocking rate, the lower the green leaf amount resulting in the low green vegetation fraction. A similar positive relationship between stocking rate and NDVI has been documented previously by Oesterheld et al. (Oesterheld et al. 1998). The result found in this study may have several explanations. One may be related to animal carrying capacity, the capacity of pastures that can support a certain animal stocking rate. In the Amazon region, the animal carrying capacity usually decreases along with degradation of soil and pasture productivity (Serrão and Toledo 1990; Faminow 1998). In our study, the areas with low stocking rates are characterized by poor soils (Oxisols and Entisols) and low precipitation, which may reduce the potential of pasture productivity and, as a result, animal carrying capacity. In contrast, the counties with high stocking rates, in general, are concentrated on more fertile soils such as Ultisols and Alfisols, and receive more precipitation (Figure 3), which supports higher grass productivity and consequently accommodates larger numbers of cattle in the area.

Another reason may be related to the different land use systems: the intensive and complex system of small-scale producers and the extensive and uniform system administrated by large cattle ranchers. The counties where ranches have high stocking rates are represented by a high concentration of small-scale farmers, particularly in the region around Ouro Preto and Jarú. The soils are more nutrient rich there, and the settlers have increased stocking rates and developed combined beef and dairy on their small properties. By contrast, large ranches that are used exclusively for beef production have more cows but distribute them over greater land area (Fujisaka and White 1998; Faminow 1998). Settlements pose particular difficulties for MODIS characterization because they have small, spatially complex land use structures that integrate different crops and pastures.

4.4. Degraded and productive areas

To understand change in potential pasture productivity over time, the proportion of each pasture class for each land use age period was calculated for each county. The averaged pasture dynamic patterns resulting from 32 counties are shown in Figure 7. The high greenness pastures dominate in the first 5 yr, followed by intermediate and low greenness pastures. The gradual shift of pasture greenness classes from high to intermediate and to low can be seen over the age classes. The levels of lower greenness pastures (P5 and P6) become very similar to those of the

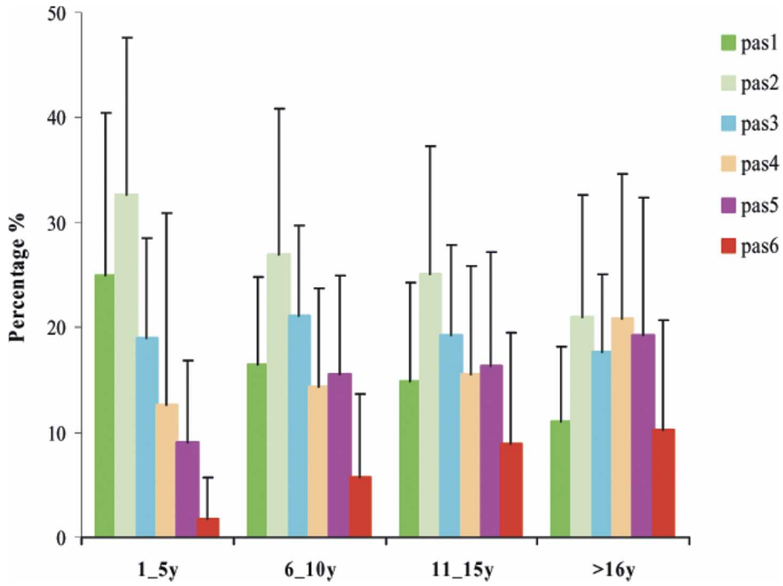

Figure 7. Change of the composition of pasture classes through time. Each bar represents averaged percentage of a pasture class from 32 counties.

high greenness pastures, that is, P1 (29.5%) and P2 (31%), at more than 16 yr old. The general patterns agree with the previous studies of the pasture degradation process, which suggest that pasture degradation progresses over time (Serrão and Toledo 1990). On the other hand, the large error bars indicate high variability of these patterns within the 32 counties of Rondônia.

By decomposing Figure 7 into different age classes, two extreme cases were found: areas of rapid pasture degradation and areas with long-term productivity. The former are areas where pastures have lower greenness in young pastures (<10 yr), whereas the latter are areas where pastures remain green even after 16 yr of land use. These areas represent two extreme cases: pastures that have degraded rapidly and those that are sustainable or resilient for longer periods. To address these cases, two different maps were prepared: a pasture degradation map (Figure 8a) and a productive pasture map (Figure 8b). The first map refers to the potential for pasture degradation, where pastures are classified as P5 or P6 within the first 10 yr of use for each county. The second map shows the proportion of P1 + P2 at >16 yr. Figure 9 shows histograms of soil orders and precipitation for both degraded and productive classes, whereas describes demographic and agricultural characteristics including rural population density, area per person, agricultural area (nonpasture), and stocking rates, for the top five counties derived from both maps. The counties from the high degradation case are Pimenteira (53% of pastures belong to P5 or P6 at 0–10 yr old), Corumbiara (52%), Chupinguaia (36%), Castanheira (42%), and Candeia do Jamari (42%). The first three counties are from the south, in the transition zone from tropical forest to savanna, where pastures are on nutrient-poor soils (Oxisols) and are more likely to be affected by longer

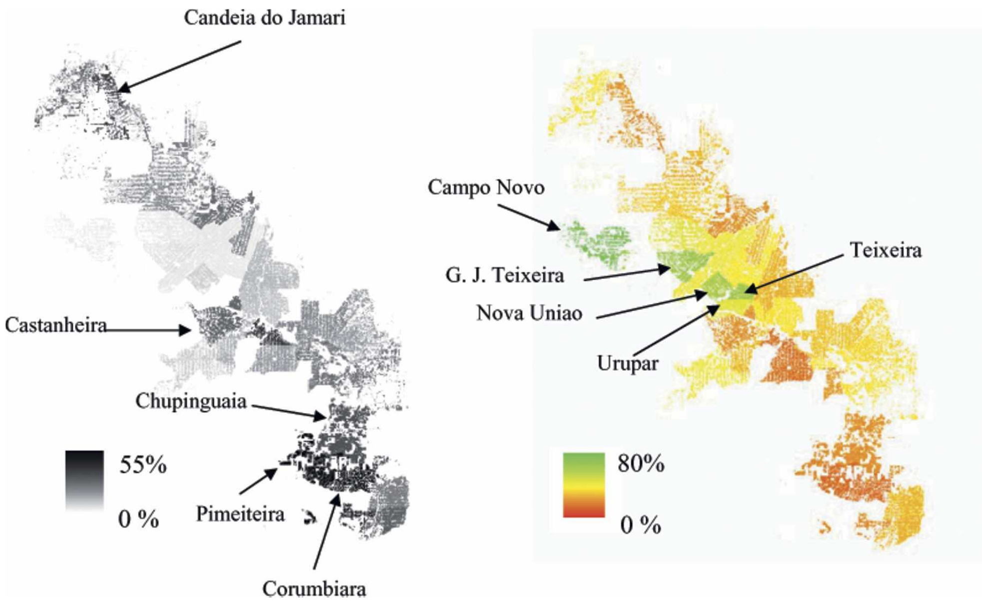

Figure 8. (left) Map of degraded pasture indicating the proportion of low greenness classes from the first 5 yr. (right) Map of productive pasture indicating the proportion of high greenness classes from pastures more than 16 yr old.

periods of drought (Figure 8). The fourth area, Castanheira, has similar precipitation to that in the south, while its small rural population density indicates an intermediate to extensive system (Table 3b). In the fifth area, Candeia do Jamari, the soil nutrient status is similar, but it receives high precipitation that appears to enhance the risk of degradation. Perhaps here flooding caused by intense rainfall during the rainy season is responsible for poor pasture quality (M. Maluf 2004, personal communication).

Conversely, the long-lasting, high greenness pastures mapped in Figure 8b are concentrated in the central region. The top five counties are Campo Novo (80% of pasture belongs to P1 or P2 at >16 yr old), Governador Jorge Teixeira (68%), Teixeira (65%), Nova Uniao (62%), and Urupa (44%). In general, pastures from these counties have soils consisting of Alfisols and Ultisols as much as Oxisols, and an intermediate precipitation rate ranging from 2000 to 2250 mm (Figure 9). In the case of soil distributions, for the counties such as Campo Novo, Governador Jorge Teixeira, and Nova Uniao, Alfisols seem to play an important role for maintaining pasture productivity. As discussed before, differentiated land use systems can be noted between two classes (Tables 3a and 3b). However, in the case of Campo Novo, despite its high percentage, the amount of the >16-yr-old pasture in the total land use area of this county is very small, and it is not representative of general characteristics of pastures in this county.

In general, high greenness pastures are planted under small land holder systems, high population density, small lot size, high stocking density, and diverse land use, which are the characteristics of intensive and complex land use systems (Table 3).

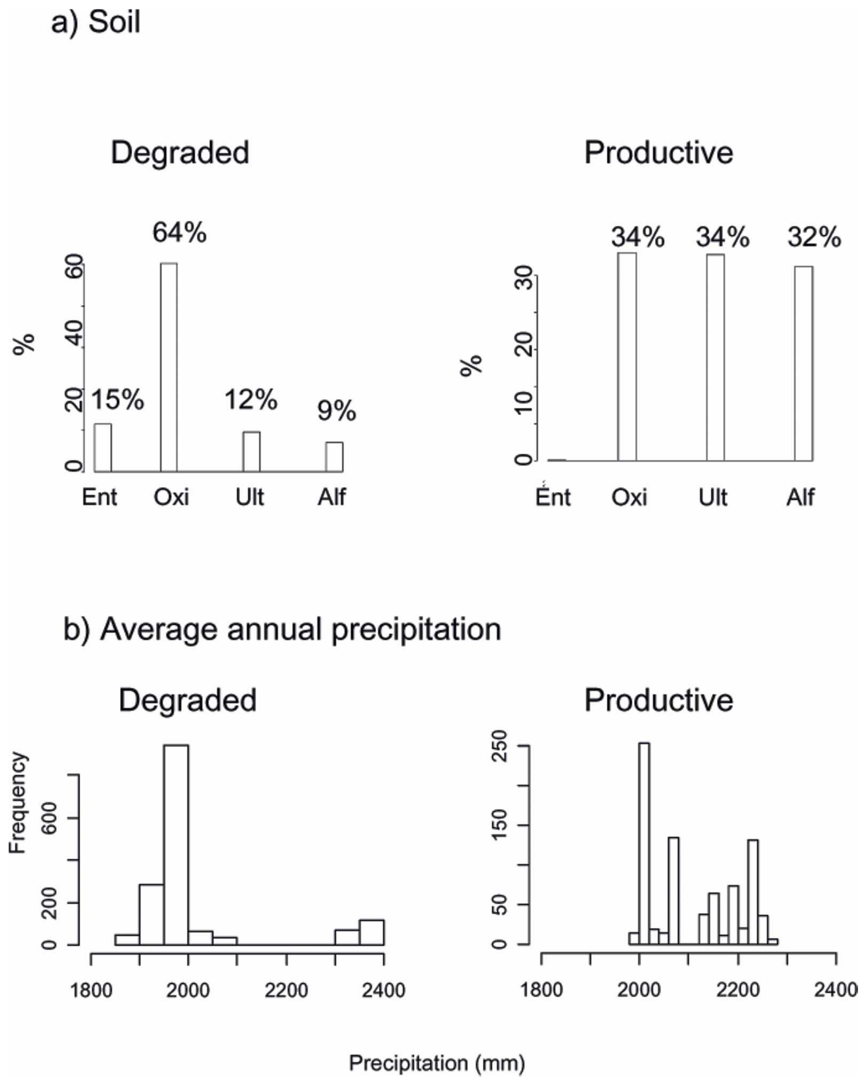

Figure 9. Environmental characteristics for degraded and productive pastures: (a) soil orders and (b) average annual precipitation.

Low greenness pastures or degraded pastures, in contrast, have lower rural population density, agriculture proportion, and lower stocking density, indicating extensive systems for those counties with high pasture degradation risk (Table 3a). This may account for the relationship between stocking rates and pasture greenness change patterns in Rondônia.

4.5. Characterization of pasture degradation processes using Landsat time series

Pimenteira and Governador Jorge Teixeira were selected to build general trajectories of pasture change through time in Rondônia. The two counties represent

Table 3. Description of top 5 (a) productive and (b) degraded counties. Source: adapted from IBGE (2005). RPD is the rural population density; Agri is the agricultural area, nonpasture; and STC is the stocking density.

County	RPD	Area per person	Agri (%)	STC
(a) Productive				
Campo Novo	0.12	8.4	12	2.13
GovJV	0.15	6.7	10	2.85
Teixeira	0.13	8.0	12	2.79
Nova Uniao	0.13	7.5	10	2.83
Urupa	0.19	5.3	14	2.96
Average	0.14	7.0	11.6	2.71
(b) Degraded				
Pimenteira	0.01	72.4	5	1.36
Corumbiara	0.05	19.7	4	1.85
Castanheira	0.07	15.2	9	2.63
C. do Jamari	0.05	18.9	3	1.93
Chupinguaia	0.02	54.9	3	1.67
Average	0.04	36	4.8	1.67

the pattern of pasture processes: degraded and productive. The Landsat times series data used for these two counties are shown in Table 4. The trajectories of fractional changes for two counties are shown in Figure 10. The first trajectory illustrates the model of pasture degradation. This is represented by Pimenteira, an extensive pasture type, from southern Rondônia. NPV and shade increase and GV decreases as pastures age. Moreover, high standard deviations also indicate fairly large variability in these fractions over time. In the case of a signal of low pasture biomass, represented by NPV (>50%), the percentage of critical areas increased over time, indicating a reduction of grass biomass in Pimenteira (Figure 10). For GV, an indicator of high grass biomass, an increase in areas with GV above the threshold is shown between 1988 and 1990, equal to 12% to 23.6%, respectively. However, the general trend is of GV reduction with areas with low GV decreasing to 7.72% by 2001, indicating possible loss of the potential of pasture production. Areas with low shade fractions, an indication of reduced grass volume or stature, increased over time, starting from 1.4%, in 1988, and increasing to 7.7% by 1995, although the trend of increase is not consistent after 1999. Similar trends, suggesting decreased grass volume and cover, were found in other counties such as Corumbiara, Chupinguaia, and Cabixi (data not shown).

The second trajectory illustrates the model of productive, but small holder

Table 4. Landsat time series data for Pimenteira and Governador Jorge Teixeira.

Year	Pimenteira (path 230, row 69)	Governador Jorge Teixeira (path 231, row 67)
1988	8 Aug 1988	30 Jul 1988
1990	16 Jul 1991	5 Aug 1990
1993	21 Jul 1993	23 Jul 1993
1996	11 Jul 1995	20 Jul 1996
1999	30 Jul 1999	6 Aug 1999
2001	4 Aug 2001	11 Aug 2001

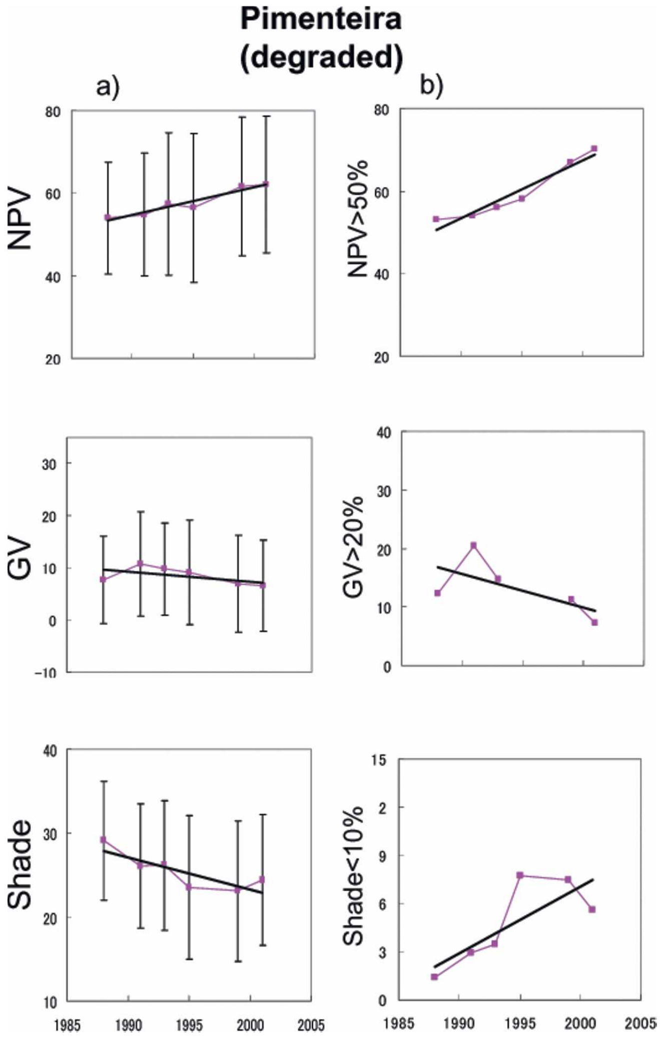

Figure 10. Fractional changes in Pimenteira between 1988 and 2001: (a) averaged fractions and (b) percentage of critical area determined by threshold.

pastures represented by Governador Jorge Teixeira. The trajectory is more irregular compared to Pimenteira (Figure 11). The variability in NPV and shade for Governador Jorge Teixeira is larger than Pimenteira. In terms of a signal of low pasture biomass, NPV began with a low percentage and showed an increase up to 2001, but from 1999 to 2001, the degraded area decreased from 44% to 30%. Overall, the amount of degraded areas was much lower compared to Pimenteira. GV showed an irregular trend over time, but its percentage was higher compared to Pimenteira. This result indicates that Governador Jorge Teixeira pastures remain consistently greener compared to Pimenteira, which matches the NDVI classification of pastures using MODIS. In the case of shade, trends were similar to Pimenteira, but with higher shade fractions. The increase of low shade fraction

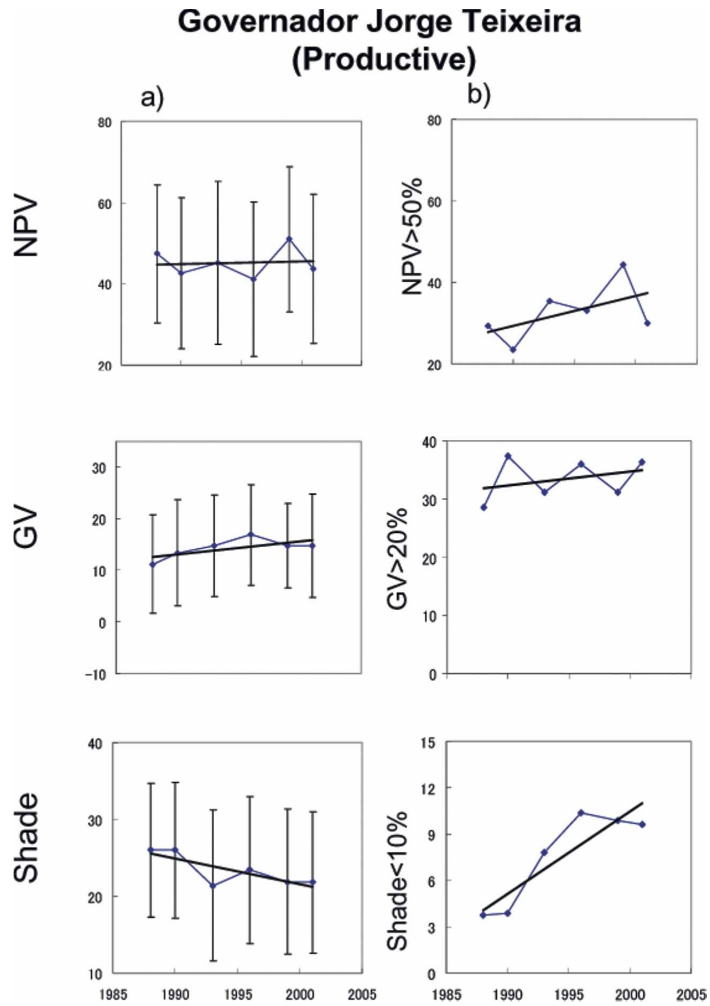

Figure 11. Fractional changes in Governador Jorge Teixeira between 1988 and 2001: (a) averaged fractions and (b) percentage of critical areas determined by threshold.

percentage continued up to 1995 and then stabilized. Other counties such as Teixeira, Urupa, and Nova Uniao had similar results to Governador Jorge Teixeira.

5. Discussion

Whereas remote sensing and census data have been used to characterize changes in agricultural land use (Cardille and Foley 2003), pasture degradation has not been addressed using these tools. Our results show that the spatiotemporal approach using NDVI time series can detect changes in pasture greenness at the regional scale. These changes were further evaluated using ancillary data on soil, rainfall, and management to provide information on patterns of pasture sustainability.

5.1. Regional analysis of potential pasture degradation and controlling variables in Rondônia

As interpreted from the seasonal NDVI patterns, pasture productivity decreased over time, a trend observed elsewhere in the Amazon (Serrão and Toledo 1990; Dias Filho et al. 2000). The spatial patterns of pasture change varied according to the relative importance of individual variables or their combinations. For example, low precipitation and low soil fertility seem to affect pasture productivity in the southern region (Figure 9), producing high concentrations of low greenness pastures around the counties of Chupinguaia and Pimenteira. On the other hand, excess precipitation in combination with low soil fertility, as seen in Candêia do Jamarí, in the north, appears to produce undesirable conditions for pasture growth as well. In central Rondônia, with fertile soils (Ultisols and Alfisols) and moderate precipitation (2000–2250 mm), pastures remain green even at an advanced age (Figure 8).

The hypothesis that high stocking rates reduce grass NDVI relative to grass production was not supported by this study. Based on the NDVI time series, the counties with extensive beef pastures are more degraded than those with a high proportion of intensively managed pasture systems. These two systems, extensive and intensive, differ in a number of ways (Table 3b). Intensive agriculture is characterized by small holdings; diversified crops; and small, dual-purpose pastures of irregular shape (Pedlowski et al. 1997; Browder et al. 2004; Caviglia-Harris 2004). Although abandoned pastures and second growth can increase greenness in coarse-resolution remote sensing data, they are not common in Rondônia (Alves et al. 2003; Caviglia-Harris 2004). Therefore, the higher greenness exhibited in the 250-m MODIS NDVI images is likely due to intensive system pastures.

Most studies of temporal patterns of pasture change in Rondônia have been near Ariquemes, Ji-Paraná, and Ouro Preto, with little work done in southern Rondônia. Despite claims by local farmers and researches about pasture degradation and the need for the system improvements in this southern region (F. Leonidas 2006, personal communication), more documentation is required.

5.2. Longitudinal analysis of pasture degradation using MODIS and Landsat TM

The SMA fractions captured different patterns of change depending on pasture condition. Fractional changes through time characterize the possible progress of pasture degradation in Pimenteira; an increase of the low biomass signal characterized by high NPV, an increase in areas of low shade, and a decrease in GV between 1988 and 2001.

Using 250-m MODIS data to develop an accurate analysis of pastures for these spatially complex properties is difficult. The 250-m MODIS pixel is too large for complex structural landscapes in the Governador Jorge Teixeira region. To overcome this problem, synergetic use of both coarse and high spatial resolution data such as MODIS with Landsat, Aster, etc., is recommended (Doraiswamy et al. 2004). In this study, the results from Landsat data confirmed the patterns of possible pasture change from the MODIS NDVI analysis, coarser spatial resolution. Landsat data minimize possible overestimation of GV due to inclusion of adjacent primary or second growth forest. However, the question of how differences in land use complexity (heterogeneity) and the effect of large and small holders on the remotely sensed signal remain unclear. Furthermore, in using Landsat data for pasture temporal analysis, annual differences in pasture phenology create interpretive complications. The impacts of land use spatial structures, that is, small and large producers, as well as satellite spatial resolutions on pasture characterization need further evaluation.

6. Conclusions

We analyzed pasture degradation across 32 counties in Rondônia. Spatiotemporal NDVI data helped to characterize pasture growth conditions as constrained by environmental (soil and precipitation) and land management (stocking rate). We found a general decrease in greenness in pasture areas across Rondônia as pastures aged, which suggests a decrease in productivity in this state. However, the magnitude varied across the state according to environmental constraints and land use systems. Pasture degradation processes tend to be more severe and advanced in the southern region, due to poor soil types and low precipitation rates, while pastures are likely to be productive for longer periods in the central regions associated with better soil fertility and intermediate precipitation. These patterns are also reflected by stocking rates in the regions, where the stocking rate is lower in the degraded regions that have a lower animal carrying capacity, and are higher in more productive regions that have a higher animal carrying capacity. The trajectories of pasture changes over 13 yr with time series SMA fractions gave us insights about consequences of pasture degradation processes according to the combinations of these factors. Our results suggest that regional-scale monitoring of pasture properties is important for determining areas of rapid degradation and that these efforts can be focused on areas with particular management styles and environmental conditions.

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