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Land cover mapping and carbon pools estimates in the Southwestern Brazilian Amazon basin.

Cartographie de l'occupation du sol et estimation des flux de carbone dans la région du sud ouest du bassin amazonien brésilien.

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In order to estimate changes in carbon pools and fluxes to the atmosphere, we used LANDSAT/TM data to calculate the extent of areas converted to pasture to different lengths of time in a 100 x 92 km area of the southwestern Brazilian Amazon. Image processing and the supervised classification allowed the production of an accurate land cover map including forest and pastures of different ages. The results showed that almost 30% of the natural forest were deforested and occupied with pasture. From the 2800 km2 of pasture almost 60% consits of pasture with less than three years of establishment. The accuracy of digital image classification is closely related to factors such as the date of image acquisition, the definition of those channels which provide the best discrimination between different land covers and the size of the training samples areas. During dry season differences in electromagnetic reflectance were more intense between pastures with differents ages. Estimates of carbon pools and fluxes to the atmosphere were carried out using the results of LANDSAT image analysis and published data about carbon stocks in vegetation and soils. The results showed that the highest release of CO2 to the atmosphere (12x10^3 g.C.m^2) occurred in the first three years after burning. Forest biomass burning (7.3 x 10^3 g.C.m2) and subsequent decay of the unburnt biomass (4.7 x 10^3 g.C.m2) are the main contributors to the total amount of CO2 released during this period. After the initial burning, more than fifty percent of the total carbon of the forest biomass remained as unburnt biomass. The decay of this unburnt biomass occurs over a period of ten to twenty years as a result of natural decomposition or due to subsequent reburnings of the pasture. The total amount of carbon released after twenty years was 16 x 10^3 g.C.m2. From the initial burning and after fifth year under pasture, the system functioned as a source of CO2 to the atmosphere. After this period the balance of cabon is slightly negative and the amount of CO2 released in lower than the amount released in the initial period.

Keywords : Land-use, Remote Sensing, Carbon Pools, Amazon Basin.
Mots clés : utilisation des terres, télédétection, flux de carbone, bassin amazonien

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1. Introduction

Land exploration in Rondônia state increased by the construction, in 1968, of the Cuiabá-Porto Velho road, which happened to be cut through some of the better soils available in the region (Moran 1993). Tropical forests are exploited for a variety of purposes, including timber extraction, shifting cultivation, permanent agriculture and pasture (Detwiler and Hall 1988, Andreux and Cerri 1989, Buschbacher *et al.* 1988). Estimates of the area of pasture in the Brazilian Amazon range from 70,000 km^2 (Serrão and Toledo 1990), 100,000 km^2 (Hecht 1985) and 120,000 km^2 (Koehelhepp 1984).

The large scale conversion of forest to pasture leads to changes in carbon storage in forest biomass and soil (Fearnside *et al.* 1993,, Kauffman et al. submitted, Moraes *et al.* 1996), and therefore, the global carbon budget. Moist forests of the tropics cover only about 11% of the Earth´s land surface but are estimated to contain 41% of the global terrestrial biomass (Moran 1993). About 80% of the carbon flux from the biota is due to conversion of tropical forest to agriculture and ranching systems (Buschbacher 1986).

In order to calculate changes in carbon pools and fluxes in forest-converted-to pastures areas we must (i) obtain precise estimates of pastures areas; (ii) quantify the carbon pools in different compartments and (iii) the respectives rates of soil organic matter decomposition on different time scales.

To quantify the carbon pools in different compartments, we dispose of (i) some improved estimates of total aboveground biomass (Klinge and Rodrigues 1974, Brown and Lugo 1992, Fearnside *et al.* 1993, Kauffman *et al.* submited), (ii) the soil carbon stocks in Amazonian forest and (iii) its changes due to land exploitation (Volkoff and Cerri 1987, Martins *et al.* 1991, Choné *et al.* 1991, Cerri *et al.* 1991, Moraes *et al.* 1995 and Moraes *et al.* 1996). The present study had two basic objectives. First, to map the land cover using TM/Landsat images in an twenty thousand hectare area in

Southwestern Rondonia, Brazil, and second, to quantify the gain and loss of carbon in the same area, using the estimates of deforested area converted to pasture and the published data about carbon stocks in soil and vegetation.

2. Material and methods

2.1 Study area

The study area was located in the southwestern Brazilian Amazon basin, in Rondonia State. The experimental site was located at Nova Vida Ranch (10^0 10’05” S; 62^0 49’27” W), between the cities of Ariquemes and Jaru. In the area of the ranch, (22,000ha), changes in soil carbon stocks due to deforestation and pasture establishment, were studied in chronosequences by Moraes *et al.* (1996). Pastures are dominated by Brachiaria brizantha sewed in the years 1989, 1987, 1972 and 1911 and Panicum maximum sewed in the years 1983, 1972 and 1979.

2.2 Remote sensing and digital image processing

One quadrant of digital Landsat thematic mapper (TM) image (Path: 231, Row 67) was acquired on 7 July 1991, at the peak of the dry season. The techniques of image enhancement used consisted of linear contrast modifications, image filtering operations and band ratio. A principal component analysis was performed on the three visible and three infrared bands from the TM data. A normalized vegetation index, was calculated using the following band ratio:

$$\mathbf{IVN = 128.[1+(TM4 - TM3)/(TM4 + TM3)]}$$

Using a color composition (TM bands 5(R), 4(G) and 3(B)), training areas were sampled for the image classification. These areas include forest, pastures of different ages, rural residential (urban areas and non-vegetated surfaces) and water. The supervised classification method applied was based on the Euclidean minimum distance between a pixel and the mean of the training cluster.

2.3. Estimates of Carbon Pools

A review of the literature provided the values for the different variables (above and below-ground biomass, burning coeficient, decay of unburnt biomass, pasture growth and soil carbon stocks) used to calculate the carbon balance in forest converted to pasture area.

Above-ground biomass: Studies available for other Amazonian regions suggest an above-ground biomass of 262,5 t ha^{-1} (Fearnsinde, in preparation) in Pará and 290,2 t ha^{-1} to 361,2 t ha^{-1} (Kauffman et al., submitted) in Rondonia. In the study of biomass estimation at Nova Vida ranch, Graça (personal communication) found an above-ground biomass of 298.7 t ha^{-1}. We used a mean value of 316.7 t ha^{-1} for the above ground biomass in Rondonia obtained from the estimates of (Kauffman et al., submitted) and Graça (personal communication) For the corresponding carbon content of biomass, we utilized the value of 0.50 used in calculations by Brown and Lugo (1984) and Fearnside (1992) which resulted in a carbon content of 158 t C ha^{-1}.

Burning Coeficient (CE): Kauffman et al. (submitted), estimated a burning coeficient of 42% and 57% in Rondonia. Graça(personal communication) reported a combustion efficiency (CE) of 39.5%. A mean value of 46% for the burning coeficient was used.

Below-ground biomass: Fearnside *et al*. (1993) estimated that below-ground biomass represented 15.1% of the total biomass. Considering an mean above-ground biomass of 316.7 t ha^{-1} we estimated a below-ground biomass of 56.3 t ha^{-1} which represents approximately 28 t C ha^{-1}.

Decay of unburnt biomass: The biomass remained after the initial burn is consisted of trunks with a CE of 20.9% (Fearnside *et al.*, 1993). We assumed this value to determined the decay of the remained biomass during subsequent burns.

Pasture growth: For pasture biomass we assumed a mean value of 6.4 t ha^{-1} yr^{-1}, considering the estimates of Teixeira (1987) and Barbosa (1994).

Soil Carbon: A total of 3.70±0.11 kg C m^{-2} was found in the top 30 cm of forest soil (Moraes *et al.,* 1996). The loss of carbon derived from forest was estimated on 0.50 kg C m^{-2} , 0.30 kg C m^{-2} and 0.70 kg C m^{-2} respectively between zero to three, three to five and five to twenty years.

3. Results and discussion

3.1. Visual and Spectral Analysis

The interpretation of the image based on ground information permitted the discrimination of eight different land-cover classes listed in Table 1. The TM bands 4, 5 and the calculated images VI (Vegetation Index) and PC1 (First Principal Component) showed better discrimination between the different land cover classes (Figure 1). Pastures of different ages presented distinct electromagnetic reflectance (EMR) in the near and middle-infrared and in Vegetation Index and First Principal Component images. Comparing the EMR of the three classes of pasture, we observed a decrease from younger to older pastures in the near infrared and an increase in the middle-infrared. In older pasture, a reduction of vigor and water content in the dry season which characterizes a pattern of senescence, resulted in a lower reflectance in near infrared.

3.2. Image Classification Results

The area occupied by the less than three years old pasture is twice the extent of the more than five years old pasture.Our observations are consistent with the peak deforestation which occurred in 1987 (Fearnside *et al.* 1993, Moran 1993). Patterns that control forest regrowth, mainly in areas recently burned, are related to some parameters including regeneration sources, microhabitats and nutrient availability (Uhl 1987). In the study area, even after few years, large areas which have been burned for pasture establishment showed a rapid rebounding of forest, mostly due to light grazing.The ground data, collected one year after the satellite acquisition, showed that in the area that surrounded the Nova Vida ranch, areas of secondary regrowth following pasture abandonedment were not frequently found. Therefore, the uncertainty often reported in the literature, related to the similar image response of new pastures and abandoned ones were not a major problem during this study.

Table 1. Land-cover classes observed in the Landsat TM image of 100x92 km.

Land-cover classes	**Área (km$^{2)}$**
Forest	6370
Pasture with more than 5 year old	752
Pasture between 3 to 5 year old	410
Pasture with less than 3 year old	1613
Rural residential	16
Water	2
Roads	6
Not classified	50
Total	**9219**

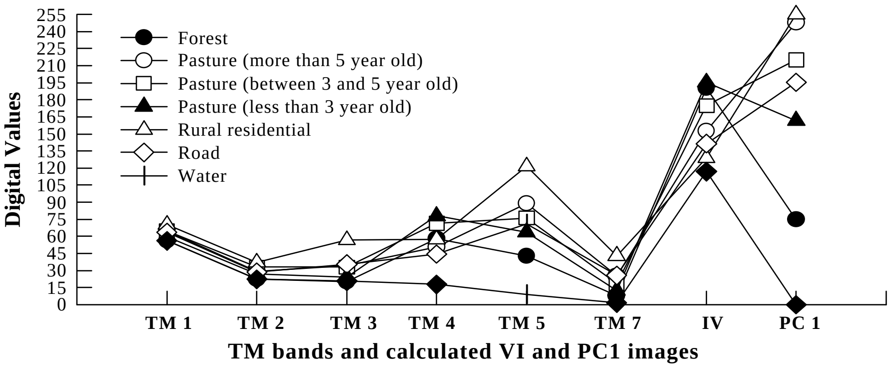

Figure 1. Spectral signature of land cover classes based on Landsat/TM

The final land cover map with the limits of the Nova Vida ranch superimposed is presented in Figure 2. Areas dominated by pastures with less than three years appear rather fragmented, like a mosaic consisting of the juxtaposition of yellow, blue and brown. The three to five year old pasture is frequently associated with older pastures and therefore this class is inter-mixed with all the other classes. Inside each land cover class some differences were observed in the spectral response related to topographical positions, because the image was not corrected according to elevation and the illumination angle of the scene. Pasture older than 5 years, for example, presented spectral differences between those areas located on the flat top of the hills or on the lower part of the slope. When training areas were choosen within two distinct topographic situations, two distinct classses were formed. To avoid the high intra-class distance which could cause mis-classification, these two classes that represents the same pasture were grouped to produce the final land-cover map.

3.3. The Carbon Balance: (gain and loss)

In the present paper we assumed that all deforested land was converted to pasture and remained as pasture for at least twenty years. The definition of this period was based on the presence in the study area of many pastures with twenty or more years

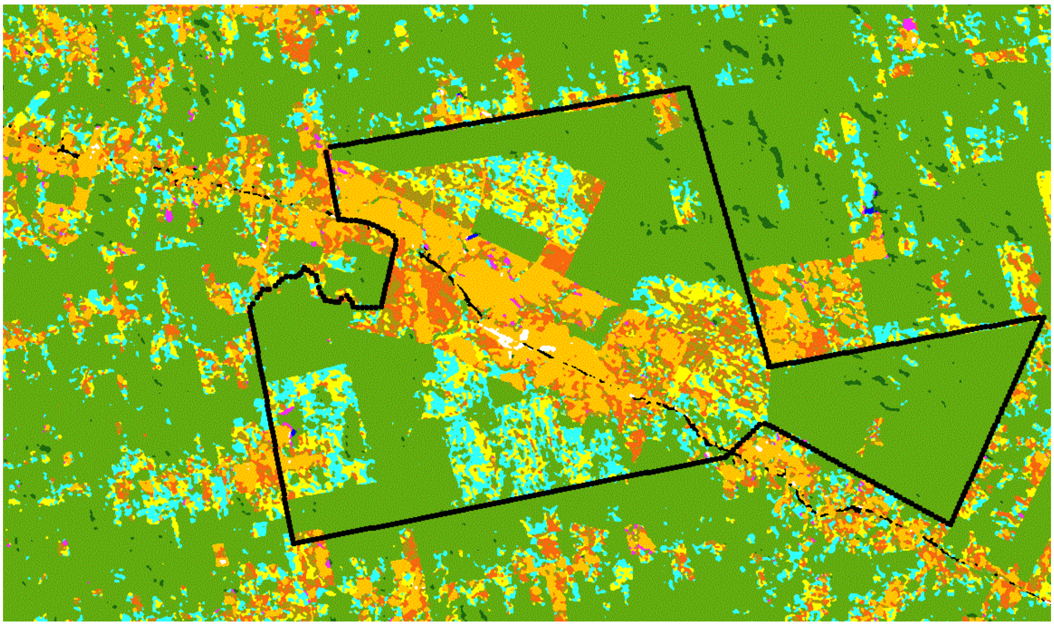

Figure 2. Classified image derived from supervised classification of Landsat/TM. (green) forest areas; (organge) pastures with more than five-years-old; (red) pastures between three-and-five-years-old; (mosaic=light blue, yellow and brown) pasture with less than three years old mixtured with palm, trees, wood debris and shrubs; (whte) rural residential; (blue) water.

old. In Table 2 we show the initial carbon pool (in forest) and its fluxes to the atmosphere after burning and pasture establishment.

The highest release of CO_2 to the atmosphere (12 x 10^3 g C m^{-2}) occurred in the first three years after burning. Forest biomass burning (7.3 x 10^3 g C m^{-2}) and subsequent decay of the unburnt biomass (4.7 x 10^3 g C m^{-2}) are the main contributors to the total amount of CO_2 released during this period. After the initial burning, more than fifty percent of the total carbon of the forest biomass remained as unburnt biomass.

In the first five years after forest burning, the system functions as a source of C-CO_2 to the atmosphere. Between five to twenty years the amount of carbon released to the atmosphere is far lower and the system tends towards equilibrium. After about twenty years, the system which was functioning as a source of atmospheric CO_2 tends to function as a sink. In table 2 the soil carbon compartment showed that the loss of carbon derived from the forest is compensated by the accumulation of the carbon derived from pasture biomass over all periods considered. The balance at the end of twenty years showed a net accumulation of 0.9 x 10^3 g C m^{-2} in the soil.

Using (i) the net fluxes of carbon presented in table 2 and (ii) the areas of pasture of different age within the region (100 x 92 km, see table 1), we estimated the amount of carbon storage in the remaining forest and the loss of carbon for different periods of time. The amount of carbon stored in the 6400 km^2 of forest corresponds to 0.14Pg (1 Pg = 10^5 g). After twenty years the total amount of carbon released is 0.023 Pg. Of this total 0.02Pg was released during the first three years after forest burning. Making the assumption that twenty percent of the remaining forest was converted to pasture (the maximum authorized deforestation is 50% of the total area), the amount of carbon released to the atmosphere after twenty years would be 0.05 Pg of C. Estimates

Tabela 2. Carbon pools (gain and loss) associated to pasture establishment in Rondônia.

(minus represents the amount of carbon release to the atmosphere)

Compartments	Carbon pools	C - Transfer			
		$x\ 10^3$ g C m^{-2}			
		0-3years	**3-5years**	**5-20years**	**End of 20 years**
Forest Biomass					
Forest above-ground biomass	15.8				
Forest bellow-ground biomass	2.8	-1.4	-1.4		-2.8
Forest burning		-7.3			-7.3
Decay of unburnt biomass		-4.7	-2.4	-1.4	-8.5
Soil Carbon					
Total soil carbon	3.7				
Decay of carbon from forest		-0.5	-0.3	-0.7	-1.5
Carbon introduced by pasture		0.7	0.4	1.2	2.3
Pasture Biomass					
Above-ground-biomass		0.6			
Bellow-ground-biomass		1.0			
Total	22	-12	-4	-1	-16

of deforested area in the entire Brazilian Amazon basin is reported at almost 10.5% (426000 km^2) of total forest area (Fearnside *et al.* 1993). If fifty percent where used for pasture for at least twenty years, the amount of CO_2 released to the atmosphere would be $3.4x10^{15}$ g C which is far lower than the total of CO_2 release due to fossil fuel combustion ($5.6\ x\ 10^{15}$ g C yr^{-1}), Houghton (1990). In relation to the total amount of atmospheric carbon (353 ppmv CO_2, i. e. $748\ x\ 10^{15}$g C (Lal 1993)), the contribution from Amazon forest burning represents less than 0.46 % (1.6 ppmvCO^2).

4. Conclusions

The accuracy of digital image classification is closely related to factors such as the **date of image acquisition, the definition of those channels which provide the best discrimination between different land covers and the size of the training samples areas.** During the dry season, differences in electromagnetic reflectance were more intense between pastures with differents ages. In this period, the reflectance of older pastures in the near infrared channel is lower than the younger pastures, and near and middle infrared bands, vegetation index and first principal component images provided better discrimination of land cover classes.

The amount of CO_2 released to the atmosphere over the next twenty years due to forest cutting and pasture establishment is far lower than the amout released from fossil fuel combustion per year. When large areas of natural forest are converted to pasture the system functions as a net source of CO_2 to atmosphere during the first five years. Despite we did not consider in this study the contribution of forest regrowth to the carbon balance, our estimates of carbon released to the atmosphere therefore should be considered as a first approximation of the maximum liberation of CO_2.

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