JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 107, NO. D20, 8073, doi:10.1029/2001JD000374, 2002

Large area mapping of land-cover change in Rondônia using multitemporal spectral mixture analysis and decision tree classifiers

D. A. Roberts,[1] I. Numata,[1] K. Holmes,[1] G. Batista,[2] T. Krug,[2] A. Monteiro,[3] B. Powell,[1]
and O. A. Chadwick[1]

Received 16 January 2001; revised 24 July 2001; accepted 10 September 2001; published 6 September 2002.

[1] We describe spatiotemporal variation in land cover over 80,000 km^2 in central Rondônia. We use a multistage process to map primary forest, pasture, second growth, urban, rock/savanna, and water using 33 Landsat scenes acquired over three contiguous areas between 1975 and 1999. Accuracy of the 1999 classified maps was assessed as exceeding 85% based on digital airborne videography. Rondônia is highly fragmented, in which forests outside of restricted areas consist of numerous, small irregular patches. Pastures in Rondônia persist over many years and are not typically abandoned to second growth, which when present rarely remains unchanged longer than 8 years. Within the state, annual deforestation rates, pasture area, and ratio of second growth to cleared area varied spatially. Highest initial deforestation rates occurred in the southeast (Luiza), at over 2%, increasing to 3% by the late 1990s. In this area, the percentage of cleared land in second growth averaged 18% and few pastures were abandoned. In central Rondônia (Ji-Paraná), deforestation rates rose from 1.2% between 1978 and 1986 to a high of 4.2% in 1999. In the northwest (Ariquemes), initial deforestation rates were lowest at 0.5% but rose substantially in the late 1990s, peaking at 3% in 1998. The ratio of second growth to cleared area was more than double the ratio in Luiza and few pastures remained unchanged beyond 8 years. Land clearing was most intense close to the major highway, BR364, except in Ariquemes. Intense forest clearing extended at least 50 km along the margins of BR364 in Ji-Paraná and Luiza. Spatial differences in land use are hypothesized to result from a combination of economic factors and soil fertility. *INDEX TERMS:* 1640 Global Change: Remote sensing; 1615 Global Change: Biogeochemical processes (4805); 1610 Global Change: Atmosphere (0315, 0325); 9360 Information Related to Geographic Region: South America; *KEYWORDS:* spectral mixture analysis, Rondonia, land-cover change, deforestation, multitemporal, Amazonia

Citation: Roberts D. A., I. Numata, K. Holmes, G. Batista, T. Krug, A. Monteiro, B. Powell, and O. A. Chadwick, Large area mapping of land-cover change in Rondônia using multitemporal spectral mixture analysis and decision tree classifiers, *J. Geophys. Res.*, *107*(D20), 8073, doi:10.1029/2001JD000374, 2002.

1. Introduction

[2] Land-cover change is a major contributor to changes in carbon stocks, trace gas fluxes and soil fertility in Amazônia and has impacts on global climate [*Lean and Warilow*, 1989; *Shukla et al.*, 1990], river chemistry [*Williams and Melack*, 1997], and atmospheric and terrestrial biogeochemistry [*Detwiler and Hall*, 1988; *Lugo and Brown*, 1992; *Fearnside et al.*, 1993]. In the tropics, records of historic land cover are typically poor or nonexistent. Furthermore, the rapid pace of change, and large areal extent require tools that provide repeated, large-scale coverage. In these regions, historic satellite data offer, in many instances, the only practical means for determining what changes have occurred, their timing and their spatial distribution [*Detwiler and Hall*, 1988].

[3] In Amazônia, several classes of land-cover change are of interest. The most important entails the conversion of primary forest to croplands, pasture or other nonforested land-cover types. In the 1980s and early 1990s research focused on estimating deforestation rates primarily using remote sensing [*Fearnside and Salati*, 1985; *Stone and Woodwell*, 1988; *Malingreau and Tucker*, 1988; *Skole and Tucker*, 1993]. More recent research has focused on more detailed analysis of land-cover change, primarily concentrating on pasture and second growth [*Lucas et al.*, 1993; *Moran et al.*, 1994; *Adams et al.*, 1995; *Alves et al.*, 1999; *Lucas et al.*, 2000] because regenerating forest sequesters carbon [e.g., *Lugo and Brown*, 1992; *Moran et al.*, 1994] with sequestration rates varying with land use, age and soil fertility [*Uhl et al.*, 1988; *Foody et al.*, 1996; *Alves et al.*,

---

[1] Department of Geography, University of California at Santa Barbara, Santa Barbara, California, USA.

[2] Instituto Nacional de Pesquisas Espaciais, São Jose Dos Campos, São Paulo, Brazil.

[3] Instituto do Homem e Meio Ambiente da Amazônia (IMAZON), Belém, Pará, Brazil.

0148-0227/02/2001JD000374

1997; *Moran et al.*, 2000]. Differences in land-use practices and age since conversion also modifies below ground carbon stocks, soil nutrients and trace gas fluxes [*Keller et al.*, 1993; *Neill et al.*, 1995; *Feigl et al.*, 1995a, 1995b; *de Moraes et al.*, 1996; *Steudler et al.*, 1996]. Under these conditions, requirements expand to include the need for mapping the age of second growth, croplands and pasture, and the dynamics of each of these classes.

[4] Rondônia has been the focus of some of the most detailed remote sensing analysis in the Amazon basin using historical MSS [*Fearnside and Salati*, 1985], Advanced Very High Resolution Radiometer (AVHRR) [*Malingreau and Tucker*, 1988], Landsat Thematic Mapper (TM) [*Skole and Tucker*, 1993; *de Moraes et al.*, 1998; *Alves et al.*, 1999; *INPE*, 2000], SPOT HRV [*Alves and Skole*, 1996] and radar [*Rignot et al.*, 1997; *Saatchi et al.*, 1997]. These studies range from statewide estimates of deforestation rates [*Fearnside and Salati*, 1985; *Malingreau and Tucker*, 1988; *Skole and Tucker*, 1993; *INPE*, 2000], to finer scale, detailed land-cover mapping of pasture, second growth and crops [e.g., *Saatchi et al.*, 1997] and spatial analysis of the pattern of land clearing and abandonment in relationship to roads and municipalities [*Alves et al.*, 1999]. *Alves et al.* [1999] provide some of the most comprehensive analysis in the area, using seven Landsat scenes acquired between 1985 and 1995 to map cleared area for a scene centered between Ji-Paraná and Ariquemes (Figure 1). They report an increase in deforested area from 565,000 to 1.2 million ha, equal to 35.5% of the area of the scene with 81% of the clearing localized within 12.5 km of areas colonized by 1977. In a large number of municipalities, percent area cleared exceeded 50%, in violation of Brazilian law. Selective logging, which has been shown to be a major disturbance factor in other parts of Amazônia [*Nepstad et al.*, 1999], has not been documented to be extensive in Rondônia using remote sensing.

[5] Here we present a detailed study of land-cover transitions in Rondônia. Our analysis is similar in geographic scope to the analysis of *Alves et al.* [1999] yet covers a greater area and longer period of time. We describe the spatiotemporal aspects of land-cover change over a 80,000 km^2 area in central Rondônia, represented by thirty one Landsat Thematic Mapper (TM) scenes acquired in three contiguous locations between 1984 and 1999 and a pair of Landsat Multispectral Scanner (MSS) scenes from the 1975 and 1978 (Figure 1 and Table 1). We describe a multistage process in which standardized protocols are applied to large volumes of satellite data to map land cover using a single set of well-defined rules that are readily extensible to adjacent scenes and can be applied to new data sets as they become available. We apply our methodology to map the age of cleared lands and document temporal dynamics within nonforested cover types in Rondônia providing the depth of detail necessary to determine the role of land use and soil fertility on biogeochemical responses to forest clearing. Temporal and spatial patterns of land-cover change are compared among the three regions and discussed.

[6] *Land-use history in Rondônia:* Major changes in land cover are relatively recent in Rondônia, primarily occurring during the period when routine spaceborne observations are available. In 1960 Rondônia had the second lowest population density in Brazil, with a total population of 69,792 distributed over an area of approximately 240,000 km^2 [*FIBGE*, 1989]. Large tracts of forested land became accessible via the Porto Velho-Cuiaba highway, completed in the 1960s, but remained largely untouched because of a lack of fiscal incentives and paved surfaces.

[7] Dramatic population increases and rising deforestation rates throughout the 70s and 80s followed the development of improved road networks and the initiation of a variety of government sponsored colonization programs in the early 1970s [*Goza*, 1994]. Some of the earliest colonies were started in central Rondônia, with the establishment of Ouro Preto in 1970 and several more such as Ji-Paraná in 1973 [*Millikan*, 1992]. These colonies consisted of a planned regular grid along straight access roads spaced at 4 km intervals leading to the classic fishbone pattern of land conversion in Rondônia. During the 1970s land conversion was concentrated primarily along BR364 and within government sponsored colonies. By 1980 the population of Rondônia had more than quadrupled to 491,069 [*FIBGE*, 1989].

[8] The most dramatic changes in land cover and population have occurred over the past 20 years, following the establishment of the POLONOROESTE program in 1981 and the final paving of BR364 in 1984 [*Millikan*, 1992]. Between 1977 and 1988 the number of migrants to Rondônia increased from slightly more than 50,000 annually in 1980 to a peak of 165,000 in 1986 [*Goza*, 1994]. The length of paved roads increased from 1434 km in 1979 to 25,324 km in 1988 [*Dale et al.*, 1994]. Progressive degradation of the Brazilian economy in the late 1980s led to a decrease in annual migration to 50,000 by 1988 [*Goza*, 1994]. During the period of increasing migration statewide deforestation increased from 2.6% in 1978 to 9.8% in 1988 [*Skole and Tucker*,1993]. High rates of deforestation have persisted through the mid 1990s [*Alves et al.*, 1999].

[9] The predominant land use in Rondônia is pasture [*Browder*, 1994]. Although the initial intent of the POLONOROESTE program was to focus on perennial crops (Cacão, coffee, rubber, banana), by 1985 less than 4% of Rondônia consisted of perennial crops, with 5% in annual crop and 25.6% in pasture [*Browder*, 1994]. A typical land conversion scenario described by *Millikan* [1992] entails forest clearing, followed by either pasture establishment or the planting of annual crops. Annual crops typically fail after 1–2 years due to decreased yields and are followed by pasture establishment. Pastures are typically abandoned in 6–8 years [*Dale et al.*, 1994], although pastures up to 80 years old are found in Rondônia [*Neill et al.*, 1995]. In addition to farming and pasture, other common land uses in Rondônia include mining and logging [*Pedlowski et al.*, 1997].

2. Methods

2.1. Site Description

[10] This study was conducted over an area of approximately 80,000 km^2 located in central Rondônia consisting of three Landsat scenes (Figure 1). These three scenes provide a gradient in deforestation rates and pasture ages from low rates and young pastures in Ariquemes to higher

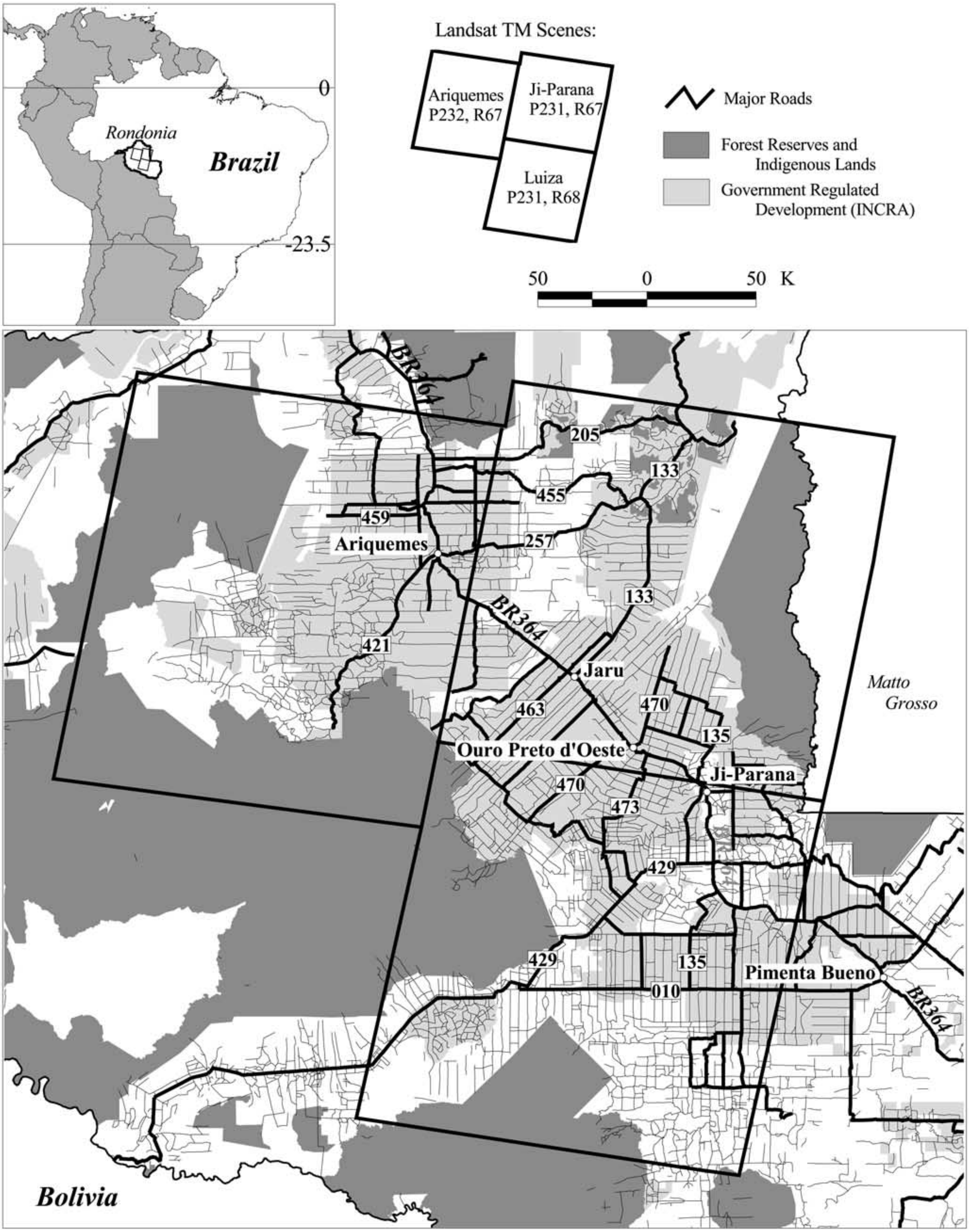


Figure 1. Index map showing the study site, location of the three scenes, land ownership, and roads. Roads, forest reserves, INCRA and indigenous boundaries were derived from *SEDAM* [1999].

Table 1. List of Landsat Multispectral Scanner (MSS) and Thematic Mapper (TM) Scenes Used in the Study

	Scene			
Date	Ariquemes	Ji-Paraná	Luiza	Type
1975	19 June			MSS[a]
1978		August		MSS[b]
1984	24 June			TM
1986		13 October	13 October	TM
1988	21 July	30 July	30 July	TM
1989	24 July	2 August	2 August	TM
1990	12 August	5 August	5 August	TM
1991	12 June			TM
1992	22 June		25 July	TM
1993	7 October	28 July		TM
1994	4 June			TM
1995	25 July		3 August	TM
1996	11 July	22 September	20 July	TM
1997	28 June	21 June	23 July	TM
1998	17 July	8 June		TM
1999	16 October	6 August	6 August	ETM

[a] WRS-1, P249, R67.
[b] WRS-1, P248, R67.

initial deforestation rates and older pastures in Ji-Paraná and Luiza. Elevations in the area range from 100 to 1000 m. Annual rainfall averages 1930 to 2690 mm/year (data are available from the Agencia Nacional de Energia Electrica web site at http://www.aneel.gov.br) falling primarily between October and April [*Gash et al.*, 1996] and varying spatially from highs in the northwest to lows in the southeast (data are available from the Agencia Nacional de Energia Electrica web site at http://www.aneel.gov.br). Average daily temperatures are relatively uniform ranging between 22 and 26° C at Jaru between 1991 and 1993 [*Culf et al.*, 1996]. Natural vegetation is dominated by dense tropical forests with locally abundant savanna, transitional forest and infrequent patches of more open, shorter forests [*RADAMBRASIL*, 1978]. Anthropogenic land-cover includes pastures, second-growth forest (Capoeira), annual crops (maize, beans, upland rice), perennial crops (cacao, coffee, banana), bare soil and urbanized areas [*Browder*, 1994]. Government regulated development by the Instituto Nacional de Colonização e Reforma Agrária (INCRA) and Forest Reserves and Indigenous lands constitute the largest proportion of land within the three scenes (Figure 1).

2.2. Remotely Sensed Data

[11] Thirty one Landsat TM scenes and 2 Landsat MSS scenes were assembled into a comprehensive time series for three contiguous areas: Ariquemes (P232, R67), Ji-Paraná (P231, R67) and Luiza (P231, R68) (Table 1). Because of a paucity of digital Landsat MSS from the 1970s, only two early scenes could be included, a 1975 scene from Ariquemes and a 1978 scene from Ji-Paraná. The best temporal coverage was obtained for Ariquemes, which, in addition to a 1975 scene, included thirteen TM scenes, one from 1984, and annual coverage from 1988 to 1999. Ten scenes were acquired for Ji-Paraná, ranging from 1986 to 1999 with data gaps as large as three years in the early 1990s. Nine scenes were acquired for Luiza (P231, R68), starting in 1986 and ending in 1999. All Landsat data were coregistered to 1998 or 1999 georectified digital PRODES data supplied by the Instituto Nacional de Pesquisas Espaciais [*INPE*, 2000]. The Digital PRODES data were considered by INPE collaborators to have the highest quality spatial accuracy and thus were chosen for a base map. Landsat data were georectified using between 30 and 40 tie points and rubber sheet stretching. All images were resampled using nearest neighbor resampling.

2.3. Land-Cover Classes

[12] Images were classified into 7 categories:

1. Primary upland forest, representing the dominant natural vegetation in the area, categorized as dense tropical forest [*RADAMBRASIL*, 1978].
2. Pasture and green pasture, dominated by several pasture grass species (*Brachiaria brizantha and Panicum maximum*) and ranging in quality from highly degraded to well-managed green pastures. Green pasture is included to account for well managed pastures that tend to remain productive throughout much of the dry season and pastures that are not senesced in early dry season images acquired in June. Recent burn scars are classified as pasture.
3. Second growth, dominated by small trees and shrubs with low species diversity and biomass relative to primary forest. Second growth may follow pasture after abandonment, or primary forest after anthropogenic or natural disturbance.
4. Soil/urban.
5. Rock/savanna. Rock is most abundant in areas of high topographic relief while Savanna is commonly located in close proximity to wetlands.
6. Water.
7. Cloud obscured, including smoke from burning, clouds and cloud shadows.

[13] Several important land-cover classes could not be mapped accurately using Landsat TM [*Roberts et al.*, 1998; *Alves et al.*, 1999]. These include (1) annual crops, which are likely to be mapped as pasture or green pasture, (2) Perennial crops, which are likely to be mapped as second-growth forest and, and (3) Mines, which are likely to be mapped as bare soil or pasture.

2.4. Image Analysis

[14] Land-cover change was mapped using a multistage process described by *Roberts et al.* [1998] and summarized in Figure 2. The eight stages can be summarized as:

2.4.1. Image End-Member Selection

[15] Using spectral mixture analysis, a spectrum consisting of radiance reflected off of multiple materials within the field of view is decomposed into fractions of several unmixed spectra, called end-members [*Adams et al.*, 1993]. Initial candidates for green vegetation (GV), Non-photosynthetic vegetation (NPV, stems, branches and litter), soil and shade are selected from the image then evaluated based on the fit (measured by a Root Means Squared Error (RMS)) and fraction images. If necessary, image end-members are revised to improve the fit and reduce fraction errors (physically unrealistic fractions) [*Adams et al.*, 1993]. The final product is five images, one for each end-member and a RMS image.

2.4.2. Reflectance Retrieval

[16] To identify surface materials and compare satellite observations to laboratory or field measured spectra it is often necessary to convert encoded radiance to apparent surface reflectance either through absolute calibration

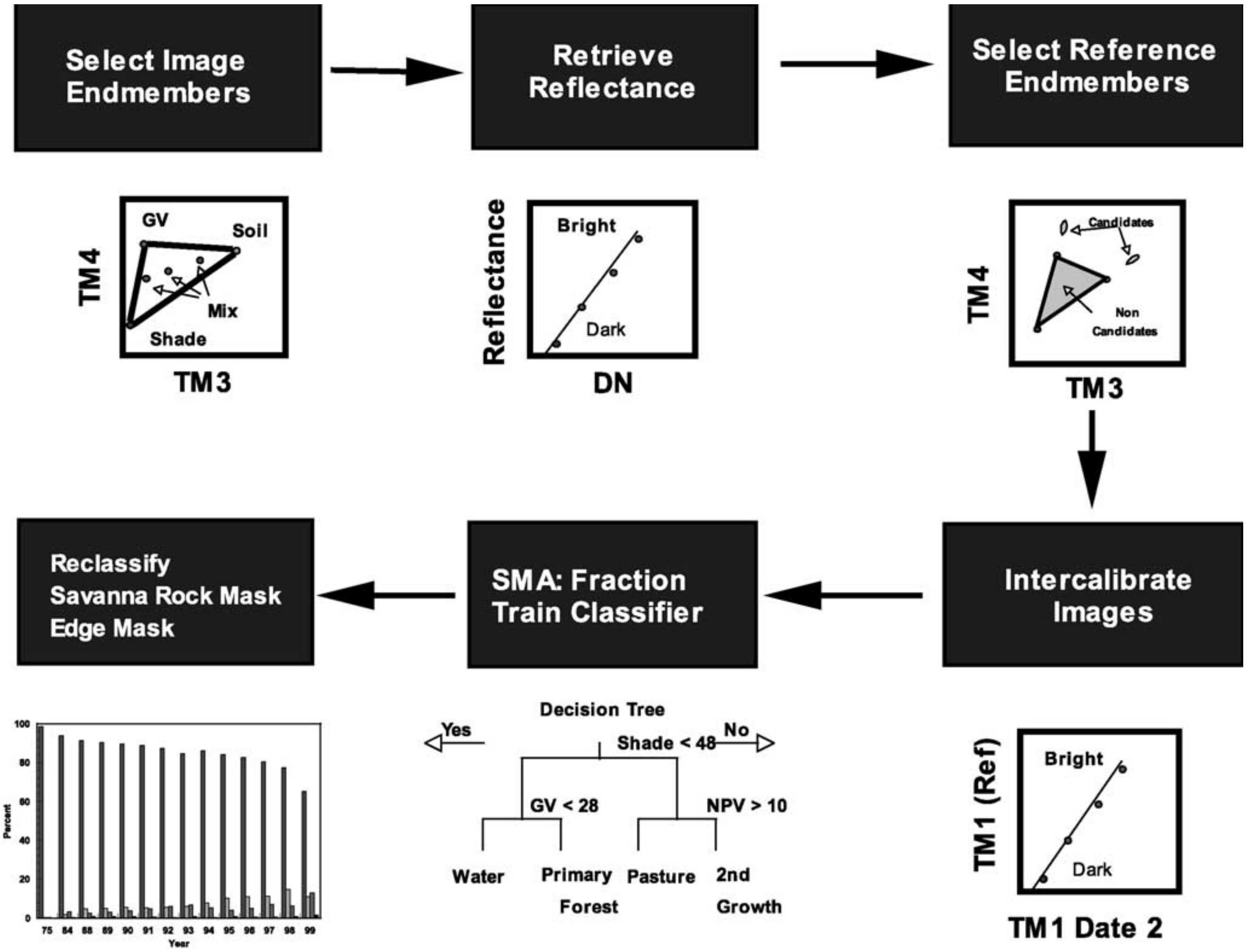


Figure 2. Flow chart summarizing remote sensing processing steps [*Roberts et al.*, 1998]. TM4 and TM3 refer to Thematic Mapper bands 4 (near infrared) and 3 (red). A digital number (DN) refers to quantized radiance measured by the sensor.

[*Kaufman*, 1989] or relative reflectance retrievals [*Elvidge and Portigal*, 1990]. Because of the diversity of data sources and lack of consistency in radiometric calibration, we used the modified empirical line approach described by *Smith et al.* [1990]. Using this technique, encoded radiance was regressed against laboratory and field measured reflectance from soils, water and NPV collected in Rondônia and Manaus between 1991 and 1992. Candidate models for converting encoded radiance to reflectance were assessed based on the shape of the intercept term (which should resemble a path radiance spectrum) and retrieved surface reflectance, which must be physically reasonable (i.e., non-negative) and match expected reflectance for known targets in the image, such as water. Spectra measured using the Airborne Visible Infrared Imaging Spectrometer of broadleaf deciduous and broadleaf evergreen forests in North America were used as spectral proxies for vegetation because no canopy level spectra were available for Brazilian forests covering the full spectral range of Landsat TM. The quality of retrieved surface reflectance for Rondônia was evaluated by comparison to surface reflectance measured over similar targets in Manaus, retrieved using multiple ground reflectance measured in the field during the summer the Manaus Landsat TM data were acquired.

2.4.3. Reference End-Member Selection

[17] Reference end-members are spectra of known materials [*Adams et al.*, 1993]. Ideally, an image end-member can be represented as a mixture of one or more spectrally pure, identifiable reference end-members. When selecting candidate reference end-members for each image end-member, the objective is to locate library spectra that are more extreme than the image end-members, provide a good fit (as measured by RMS) and fractions that match expected values based on field measurements or aerial photo interpretation [*Roberts et al.*, 1998]. Reference end-members were selected from the same spectral library used to retrieve surface reflectance.

2.4.4. Intercalibration

[18] Following step three, the remaining data sets are standardized to the reference scene using relative radiometric calibration techniques [*Schott et al.*, 1988; *Hall et al.*, 1991]. In this research 20–30 candidate invariant targets were manually located within each scene then used to convert encoded radiance, as measured on that date, to

the equivalent of encoded radiance measured in the reference scene. Candidate invariant targets, primarily water, forest, second growth and urban areas, were initially selected by comparing scenes acquired over the same location over several years. Encoded radiance was extracted for each target and regressed against encoded radiance measured within the reference scene. Candidates that are not temporally invariant are readily identified as outliers in the regression and removed from the analysis, typically resulting in the loss of only a few of the sites. Typical r^2 values range from lows of 0.85 to 0.9 for TM bands 1 and 2, to values exceeding 0.99 for TM bands 4, 5 and 7. A similar approach can be used for adjacent Landsat scenes using spatially invariant targets and overlap between scenes.

2.4.5. Spectral Mixture Analysis

[19] Once the entire time series has been intercalibrated and reference end-members selected, the same model can applied to the entire data set. This generates four fraction images for each scene (GV, NPV, soil and shade) and a RMS error image. Because each data set is standardized to a common reference and spectral library, spectral fractions can be compared directly between different scenes and across the entire time series.

2.4.6. Decision Tree Training and Classification

[20] Spectral fractions and the RMS error images are used to train a decision tree classifier (DTC) [*Hess et al.*, 1995; *Friedl and Brodley*, 1997; *Roberts et al.*, 1998]. The DTC was trained by extracting at least 100 samples for 6 of the 7 classes mapped (Rock/savanna were excluded from the initial training). To capture the within class variability and temporal variability in training sets, spectral fractions and RMS values were extracted from several scenes in Ariquemes, Ji-Paraná and Luiza that spanned the range of conditions present across the scenes. Decision rules were determined using Splus [*Clark and Pregibon*, 1992]. The final set of rules was derived after several iterations, including initial classification, followed by several additional stages of training and classification designed to reduce classification error at each stage.

[21] The Landsat MSS was also classified using a DTC, but was not subjected to spectral mixture analysis because (1) The spectral mixture model applied to TM could not be ported to Landsat MSS with its more limited spectral range and (2) more complex intercalibration seemed unwarranted given that only two scenes were available for analysis. For MSS each scene was trained individually to produce two separate sets of rules.

Table 2. Confusion Matrix and Kappa Coefficient for the Seven Classes[a]

Full classification								
	Reference data							
	R/Sav	Pforest	Pasture	Second	Water	U/Soil	Total	Users
R/Sav		1					1	0
Pforest		105	0	2			107	98.1
Image Pasture	1	1	72	7		3	84	85.7
Second		10	7	11			28	39.3
Water					2		2	100
U/Soil			1			3	4	75
Total	1	117	80	20	2	6	226	
Producers	0	89.74	90	55	100	50		85.4

Kappa = 0.761.

[a] Rock/savanna, primary forest, second growth, and urban/soil are listed as R/Sav, Pforest, Second, and U/Soil, respectively. Accuracy is reported as a percentage of 100%.

Table 3. Confusion Matrix and Kappa Coefficient for Three Classes[a]

Forest/Nonforest					
	Reference Data				
	Pforest	Nforest	Water	Total	Users
Pforest	105	2		107	98.1
Image Nforest	12	105		117	89.7
Water			2	2	100
Total	117	107	2	226	
Producers	89.7	98.1	100		93.8

Kappa = 0.894.

[a] Second growth, pasture, soil/urban, and rock/savanna have been combined into a single nonforest (Nforest) class. Accuracy is reported as a percentage of 100%.

2.4.7. Reclassification and Spatial Filtering

[22] Disallowed transitions represent any transition that is not physically reasonable such as a transitions from second growth or pasture to primary forest over a span of a few years [*Roberts et al.*, 1998]. Disallowed transitions can be screened by identifying them through time series, then reassigning the class of one of the pixels. In this research, simple rules were used to remove disallowed transitions by comparing three temporally contiguous dates and reclassifying pixels using the temporal median. Disallowed transitions include:

1. Pasture, urban, or second growth to primary forest
2. Water to any other class but water.

[23] This approach is also effective for cloud screening, treating all transitions as disallowed. In the event that two transitions occur in combination with a disallowed transition, the pixel is not reclassified. A transition from pasture to primary forest then second growth is an example of this type of transition, leading to a disallowed transition (pasture to primary forest) remaining in the time series. To reduce the effect of pixel misregistration, a spatial filter is applied to classified images prior to time series analysis. In this research, a median filter was applied along a 3 × 3 moving window and all pixels classified as having one or less neighbors within the same class were reassigned to the median class within the window.

2.4.8. Savanna/Rock Mask, Edge Mask

[24] Areas covered by rock and savanna were mapped and all areas outside of the overlap zone between all dates within a scene were masked. A rock/savanna mask became necessary because these two land-cover types are difficult to separate from pasture with sufficient accuracy. To map rock/savanna, a mask was developed for each scene then applied to the full time series for each scene. For Ariquemes and Ji-Paraná, the mask was formed by merging all nonforest classes in the MSS data, then manually editing the pastures and second growth from the mask. Because of the relatively low amount of pasture and second growth in the 1970s and their concentration along BR364, manual editing could be accomplished quickly. The rock/savanna mask for Luiza was generated from the 1986 TM scene using a similar approach, but required considerably more editing due to the greater extent of pasture and second growth. Edges were

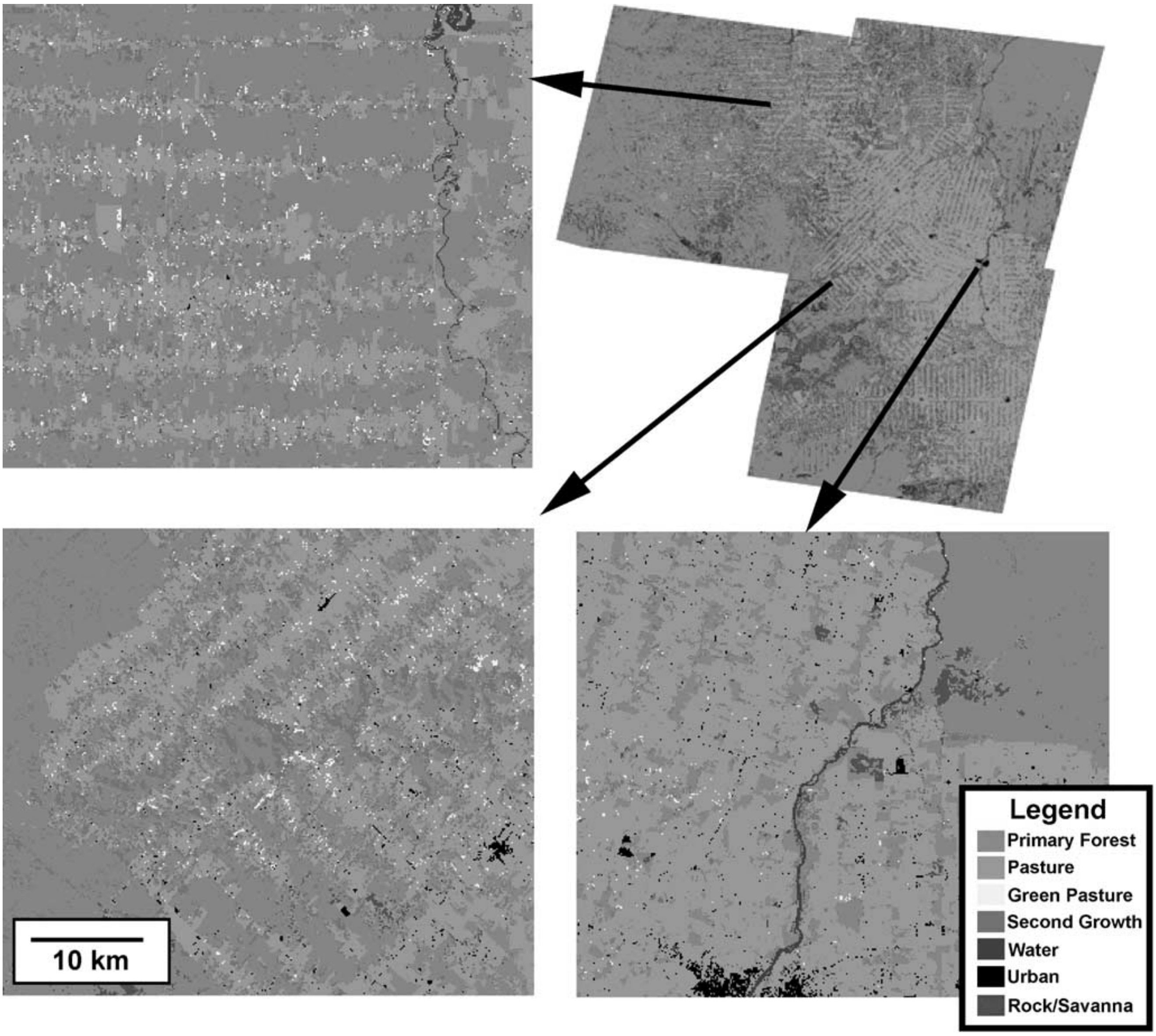


Figure 3. Map showing the seven categories mapped for Ariquemes (1998), Ji-Paraná (1999), and Luiza (1999). 1999 Ariquemes data were excluded from this mosaic due to extensive cloud contamination. A mosaic of the three scenes is shown in the upper right corner. Three regions are expanded, one located in southern Ji-Paraná (lower right), one in northwestern Luiza (lower left), and one in northeastern Ariquemes (upper left). The insets illustrate a region of old, dense land clearing (Ji-Paraná), new dense land clearing (Luiza), and old, low density land clearing (Ariquemes). See color version of this figure at back of this issue.

masked by determining the minimum area overlap for each scene within the time series and assigning all areas outside of the area of overlap to no-class.

2.5. Accuracy Assessment

[25] Accuracy of the classified map was assessed using digital airborne videography acquired over Rondônia in June 1999 using methods similar to those used by *Hess et al.* [2002]. Sample sites were chosen by randomly selecting image frames based on the time stamp along several flight lines that crossed Ariquemes, Ji-Paraná and Luiza. Several seconds of video frames were accessed for each sample to construct a mosaic. Flight-logs, recording aircraft location and altitude, were used to overlay a 3 × 3 30 m grid on each mosaic and locate the mosaics on the Landsat data. Land cover, within the central box corresponding to a Landsat pixel, was described as percentages of herbaceous cover, short shrubs, tall shrubs, medium forest, tall forest, human construction (roads/buildings), water, soil and rock then translated into their corresponding image classes. Classified values for each sample site were extracted from 1999 images for direct comparison to the videography. A total

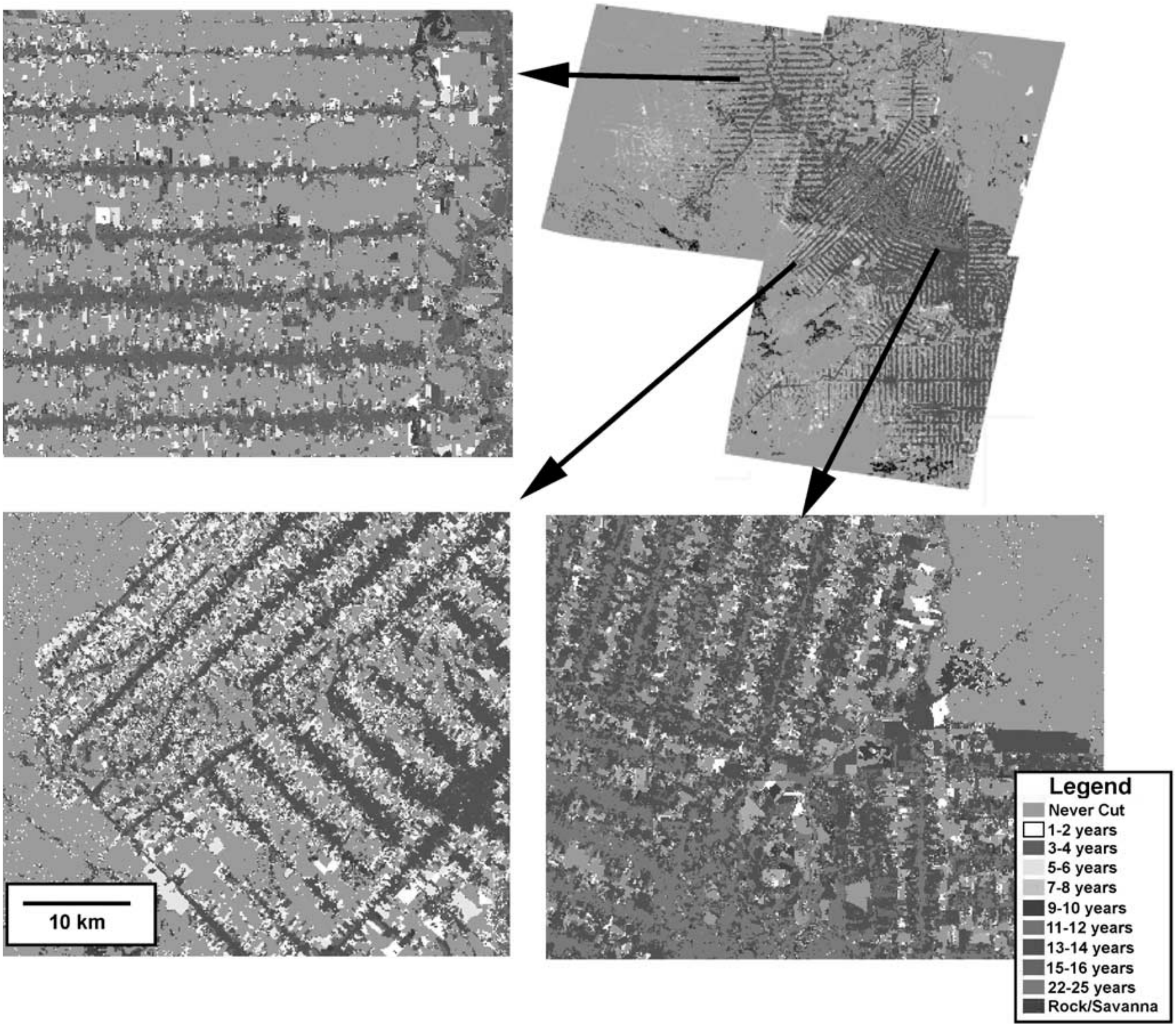


Figure 4. Map showing age since initial cut for the three scenes. The same mosaic and insets are shown for the age map as is shown in Figure 3. Several age classes have been combined to improve the clarity of the figure. See color version of this figure at back of this issue.

of 226 samples were acquired and used to develop a confusion matrix [*Richards*, 1999] and calculate a kappa coefficient [*Congalton and Mead*, 1983].

3. Results

[26] In this paper, we report on final classified maps and statistics derived from the maps. Detailed analysis of fraction maps for NPV, GV and soil, although of value in themselves [*Roberts et al.*, 1998; *Cochrane and Souza*, 1998] are excluded from this paper due to space constraints. We start with an evaluation of map accuracy.

3.1. Accuracy Assessment

[27] Overall accuracy for the seven classes was calculated as 85.4% with a kappa of 0.761 (Table 2). Rock, savanna, water, soil and urban were rarely encountered in the videography and thus have insufficient samples to assess accuracy of these classes. Second growth slightly exceeded a minimum standard of 19 samples [*Richards*, 1999], while pasture and primary forest were well represented. Producers accuracy, defined as the proportion of reference points mapped correctly by the classifier ranged from highs of 90% for pasture and 89.7% for primary forest to a low of 55% in Second growth. Users accuracy, defined as a measure of the proportion of pixels that are correctly classified to the total number mapped by the classifier, was 98.1%, 85.7% and 39.3% for primary forest, pasture and second growth.

[28] Confusion was greatest between second growth and primary forest. Detailed analysis of these samples showed that confusion occurred primarily in areas of rugged topography on Sun facing slopes where decreased shade resulted in the DTC interpreting these areas as second

Table 4. Percentage of Cleared Forest Within 5 Age Classes in the Three Scenes[a]

Age	Ariquemes, %	Ji-Paraná, %	Luiza, %
0	72.05	55.98	51.04
<4 years	4.27 (9.28)	5.94	7
4–9	8.47	12.89	13.73
10–24 (21,14)	8.96	18.32	26.49
oldest (25,22,14)	0.31	5.52	14.66
Savanna/Rock	0.93	1.32	1.74

[a] Age is reported as a percentage of the total area of each scene (2.8 million ha in Ariquemes, 2.645 million in Ji-Paraná, and 3.0 million in Luiza). Age classes were binned to match age classes of ecological interest and to match available age classes between the scenes (i.e., all scenes had data for 1997 and 1999, corresponding to the <4 year age class). An age of 0 corresponds to primary forest. The percentage in the <4 year class for Ariquemes is reported without 1999 and with 1999 (in parentheses).

growth. The second most significant source of error was in discriminating second growth from pasture, accounting for the largest error in mapping second-growth reference sites. Overall, second growth was overmapped relative to the other classes, primarily due to errors on sunlit slopes. One area classified as pasture, but mapped as primary forest in the videography, was located adjacent to a recent burn. High NPV fractions throughout the edge of the forest, suggest that the sample was a recently burned forest [*Cochrane and Souza*, 1998].

[29] After combining all of the nonforested classes (except water), overall accuracy increased to 93.8% with a kappa of 0.894 (Table 3). Users and Producers accuracies for nonforest classes increased to 89.7% and 98.1%, respectively.

3.2. Classified Images

[30] Images showing the seven land-cover classes were produced for each date. A mosaic, showing the classified maps for Ariquemes (1998) and Ji-Paraná and Luiza (1999) is shown in the upper right with three subsets expanded for better spatial definition (Figure 3). Comparison to the index map (Figure 1), reveals the extent to which roads, governmental colonies and forest reserves have controlled the location of forest clearing in Rondônia. The densest development is concentrated along BR364, in the vicinity of the oldest settlements in Ouro Preto, Jaru and Ji-Paraná (Figure 1). Large tracts of contiguous, relatively undisturbed forest remain but are restricted almost entirely to forest reserves and indigenous lands. Outside of these reserves, a majority of the forest is highly fragmented, ranging from small irregular blocks less than 5 km across in the oldest developed regions of Ji-Paraná (lower right, Figure 3), to thin (<4 km wide) strips of contiguous forest in Ariquemes (upper left, Figure 3) and northern Ji-Paraná. Although the fishbone pattern of cutting dominates the landscape, several new spatial patterns are in evidence, including radial cuts in central Ariquemes and large, rectangular cuts in northwestern Ji-Paraná in a region outside of governmental regulated development (Figure 1, mosaic in Figure 3).

[31] The dominance of pasture is evident as large areas displayed as orange (Figure 3). Second-growth forest, displayed as magenta, varies regionally in abundance, ranging from very low areal extent in the oldest developed regions in Ji-Paraná near BR364 (lower right, Figure 3), to moderately low abundance in the oldest developed regions in Ariquemes (upper left, Figure 3) to its highest abundance in newly developed areas outside of the core area of pasture along BR364 in northern Ji-Paraná, Ariquemes and western Luiza (lower left, Figure 3). The urban/bare soil class, mapped as black, is restricted to large urban centers such as Ariquemes, Jaru, Ouro Preto and the city of Ji-Paraná.

3.3. Age and Deforestation Rates

[32] The classified data were used to develop maps showing the age distribution of cleared lands by tracking the timing when primary forest underwent a transition to a nonforest class (Figure 4). Analysis of the spatial patterns of age classes reveals that the age classes are not equally distributed across the three scenes (Figure 4). Old cuts (>14 years) are located in all three scenes, primarily in close proximity to BR364. However, the areal extent of the oldest age class varies regionally. For example, in Ji-Paraná and Luiza, a majority of the cuts in close proximity to BR364 are 14 years or older (lower right, Figure 4). In contrast, in Ariquemes the area of old cuts is far lower, even though many of them were initially established by 1984 (upper left, Figure 4).

[33] All three scenes have a complete suite of age classes. New developments, established in central Ariquemes and southwestern Luiza after 1994 account for a large proportion of young age classes in both scenes (Figure 4, mosaic). However, a wide range of age classes occur even in the oldest developed regions in Ji-Paraná and Luiza within 50 km of BR364 (Figure 4, lower right). In this area, new cuts concentrate in the interstices between parallel roads gradually filling in the space between older pastures. Beyond a 50–100 km buffer centered on BR364, the extent to which younger cuts fill in the spaces between older developed areas varies spatially. Directly north of Jaru, along RO133, parallel cuts are present, but the density of young cuts (<6 years old) remains below 50% even though the initial cuts are at least 14 years old (Figure 1). Similar patterns were observed in northern Ariquemes, in areas

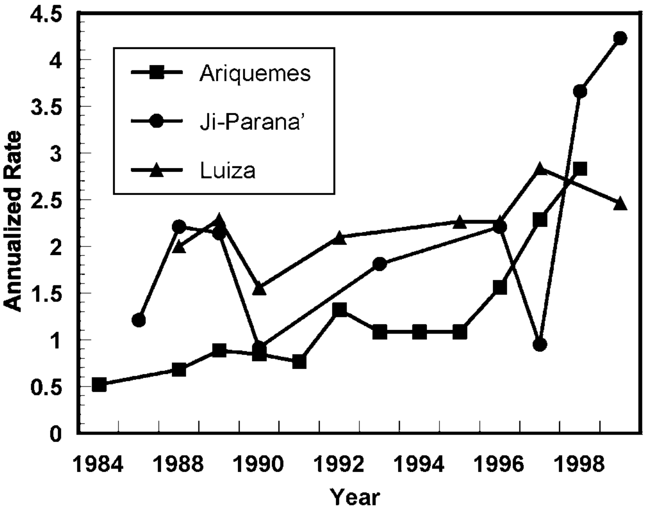


Figure 5. Deforestation rates for the three scenes. Annualized rates were estimated as the percentage of primary forest mapped in one date minus the percentage mapped in an earlier date divided by the number of years separating the dates.

Table 5. Table Summarizing Transition Statistics for Primary Forest (Pforest), Pasture, and Second Growth (Second)[a]

			Ariquemes				Balance	
Year	Pforest	Pasture	Second	Rate	PtoS	StoP	(PS − SP)	S/(P + S)
1975	98.508	0.225	0.078					
1984	93.836	1.915	3.249	0.52	0.042	0.007	0.035	0.629
1988	91.121	5.274	2.514	0.68	0.138	1.155	−1.017	0.323
1989	90.236	5.358	2.963	0.885	0.685	0.328	0.357	0.356
1990	89.39	5.655	3.513	0.845	0.557	0.617	−0.06	0.383
1991	88.625	5.333	4.745	0.76	1.164	0.66	0.504	0.471
1992	87.304	5.717	5.84	1.32	0.812	0.678	0.134	0.505
1993	84.477	6.588	6.631	1.083	0.979	0.976	0.003	0.502
1994	85.959	6.791	4.904	1.083	0.864	1.2	−0.336	0.419
1995	84.055	10.756	3.972	1.083	0.579	1.408	−0.829	0.27
1996	82.495	11.061	4.96	1.56	1.087	0.537	0.55	0.31
1997	80.21	11.492	6.833	2.285	1.506	0.74	0.766	0.373
1998	77.382	14.9	6.107	2.83	0.639	2.062	−1.423	0.291
Average								0.403
			Ji-Paraná				Balance	
Year	Pforest	Pasture	Second	Rate	PtoS	StoP	(PS − SP)	S/(P + S)
1978	91.665	2.466	1.253					
1986	81.972	12.426	2.336	1.21	0.169	0.848	−0.679	0.158
1988	77.55	15.129	4.897	2.21	1.76	0.771	0.989	0.245
1989	75.405	17.357	5.327	2.145	1.392	1.522	−0.13	0.235
1990	74.493	17.824	5.51	0.91	1.479	1.354	0.125	0.236
1993	69.057	23.302	5.563	1.81	1.155	2.153	−0.998	0.193
1996	62.431	30.852	2.85	2.21	0.339	3.14	−2.801	0.085
1997	61.478	21.046	12.904	0.95	8.521	0.056	8.465	0.38
1998	58.38	24.473	15.383	3.10	3.8	3.808	−0.008	0.386
1999	54.157	35.992	7.627	4.22	0.636	9.045	−8.409	0.175
Average								0.233
			Luiza				Balance	
Year	Pforest	Pasture	Second	Rate	PtoS	StoP	(PS − SP)	S/(P + S)
1986	79.271	10.224	6.776					
1988	75.275	17.201	3.77	2.0	0.863	3.924	−3.061	0.18
1989	72.987	19.581	4.749	2.29	1.313	1.004	0.309	0.195
1990	71.43	21.145	4.97	1.56	1.238	1.386	−0.148	0.19
1992	67.231	23.835	6.354	2.1	1.619	1.457	0.162	0.21
1995	60.434	31.563	5.681	2.265	1.026	2.82	−1.794	0.153
1996	58.171	32.157	6.716	2.26	1.902	1.517	0.385	0.173
1997	55.334	34.509	7.751	2.84	1.931	1.794	0.137	0.183
1999	50.402	38.685	7.626	2.47	1.225	2.917	−1.692	0.165
Average								0.181

[a] Transitions from pasture to second growth (**PtoS**) and second growth to pasture (**StoP**) are used to calculate the balance between these two classes (**PS − SP**). The proportion of second growth to cleared areas is calculated as the ratio of second growth to combined pasture and second growth (**S/(P + S)**). Transitions for a specific year are calculated as a difference from the prior date. Deforestation rates are annualized. Figures for 1999 are excluded due to extensive cloud cover in that year.

located close to BR364 (Figure 4, upper left). A very different pattern emerges in northwestern Luiza where numerous young cuts occur and expand outward from a much older preexisting road network (Figure 4, lower left).

[34] The age maps also reveal a temporal change in the spatial patterns of development within the area. Whereas all of the oldest developed regions follow the "herringbone" pattern characteristic of Rondônia, newer developments include the radial pattern in central Ariquemes and large (up to 30 km long), rectangular tracts in northwestern Ji-Paraná.

[35] The age distribution of cut areas can be compared between the scenes by placing various age classes in bins and summing their area over each scene (Table 4). Spatial differences in the timing and extent of deforestation are apparent. In Ariquemes, by 1975 only 0.31% of the area of the scene was deforested. In contrast, by 1978 in Ji-Paraná, 5.5% of the scene had undergone conversion. If we combine all areas 10 years or older into a single age class, we observe an age gradient from east to west, with the largest proportion of old cuts in Luiza at 26.5%, followed by Ji-Paraná at 18.3% and Ariquemes at 8.96%. This spatial pattern remains for the 4–9 year old class, but becomes less pronounced. By 1999, 51% of the primary forest remained in Luiza, 56% in Ji-Paraná and 72% in Ariquemes (77% if we exclude 1999).

[36] By comparing the spatial extent of primary forest between dates, it is possible to estimate annual rates of deforestation (Figure 5 and Table 5). In Luiza, deforestation rates remained stable and high, with a low of 1.56% between 1989 and 1990 and a range of 2 to 2.26% between 1988 and 1996. The highest deforestation rates occurred between 1996 and 1997, peaking at 2.84%. Deforestation rates were considerably more variable in Ji-Paraná. Initial deforestation rates were modest, averaging 1.2% annually between 1979 and 1986. These rates increased throughout the late 1980s, peaking at 2.15% between 1988 and 1989. As in Luiza, dramatic decreases were observed between

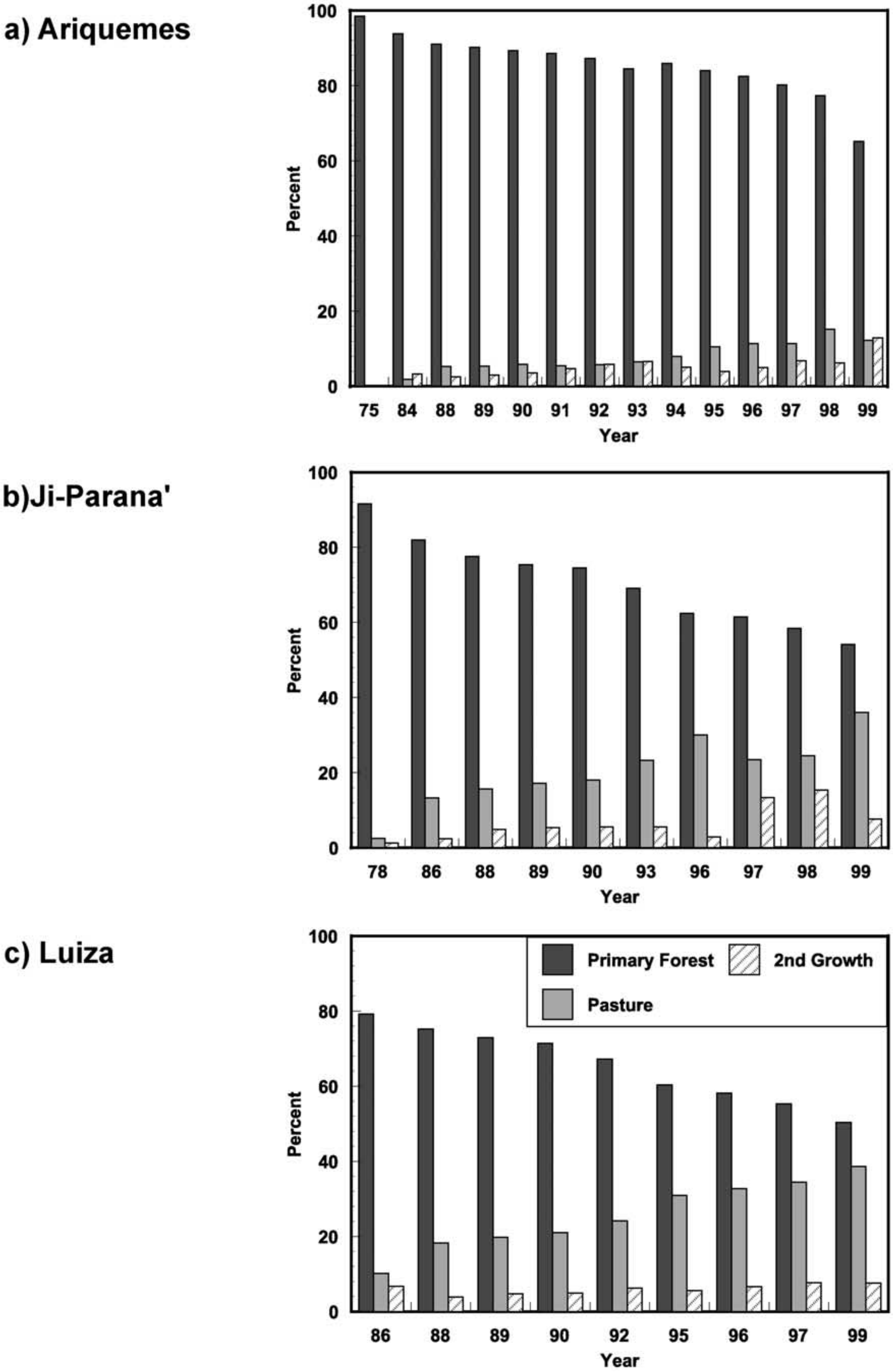
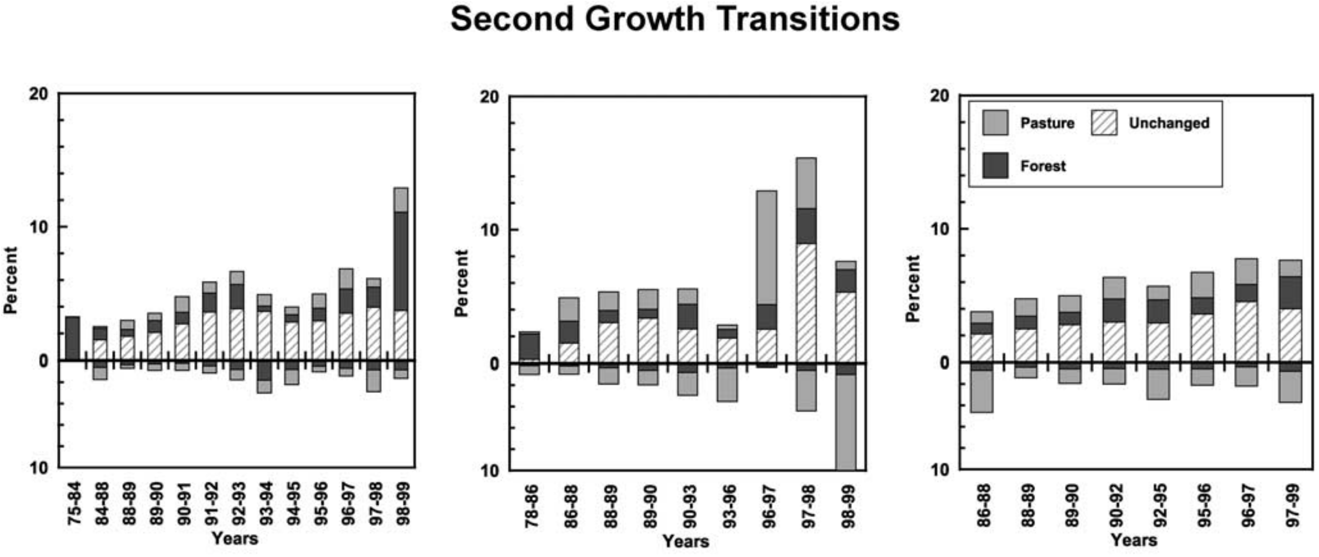


Figure 6. Areal percentage of the three major land-cover classes as they varied between the three scenes. Green Pasture and Pasture are combined in this figure. Urban, clouds, and water are excluded.



a) Ariquemes b) Ji-Parana' c) Luiza

Figure 7. A graphical representation of no change, gain, or loss of pasture for the three scenes. Numbers are reported as areal percentages of each scene. Gains or no change are plotted above the 0 line, losses below the line. Different patterns display which classes contributed to the gain or loss of pasture. Disallowed transitions appear as pasture loss to primary forest below the 0 line.

1989 and 1990 with an annual rate of 0.91%. Following 1990, deforestation rates in Ji-Paraná steadily increased, peaking at 4.22% in 1999. The one exception was between 1996 and 1997, which showed a decrease to 0.95%. While such a decrease is possible, no similar pattern was observed in Ariquemes or Luiza, suggesting that the estimate is erroneous. Most likely such an error would arise from the compounding effects of a slight underestimate of forested area in 1996 and a slight overestimate in 1997.

[37] The lowest initial deforestation rates were estimated for Ariquemes (Figure 5 and Table 5). Between 1975 and 1984, the annual deforestation rate in Ariquemes was approximately 0.5%. This rate increased modestly throughout the 1980s peaking at 0.89% between 1988 and 1989, followed by a slight decline to 0.76% between 1990 and 1991. Throughout the 1990s deforestation rates in Ariquemes were higher than any rate in 1980s, increasing dramatically from 1995 to 1999 and peaking at 2.83% in 1998.

3.4. Temporal Analysis of Land-Cover Change

[38] The percentage of primary forest, pasture and second growth was calculated by dividing the area mapped in each class by the total area of the scene for each year (Figure 6 and Table 5). Significant differences are apparent between the three scenes. Luiza can be characterized as having the lowest percentage of remaining primary forest, highest area of pasture and lowest ratio of second growth to nonforest (pasture + second growth: Figure 6c). Temporally uniform deforestation rates result in a steady decline in primary forest and a steady increase in pasture and second growth. The proportion of second growth to cleared area remained relatively stable, averaging 18% (Table 5).

[39] Ji-Paraná showed a similar temporal pattern as Luiza. However, increasing rates of deforestation in the late 1990s resulted in a greater decrease in the area mapped as primary forest and greater increase in pasture and second growth. The ratio of second growth to cleared area was only slightly higher than in Luiza, but showed considerably more variation, with area mapped as second growth increasing dramatically in 1997 and 1998, primarily at the expense of pasture, which showed a decrease.

[40] The Ariquemes scene had the highest proportion of primary forest, lowest pasture area, but surprisingly similar areal extent of second growth (Figure 6a and Table 5). Primary forest declines steadily throughout most of the time series, showing the most rapid declines in the late 1990s. Pasture area remained over a factor of two lower in Ariquemes than it was in Luiza and Ji-Paraná. In contrast, the area mapped as second growth was only slightly lower in Ariquemes than it was in the other two scenes. When calculated as the ratio of second-growth forest to nonforest, this ratio is nearly a factor of two higher in Ariquemes, than it is in Ji-Paraná or Luiza.

[41] Dramatic fluctuations in pasture and second growth, most evident in the 1997 and 1998 Ji-Paraná data, illustrate limitations of the technique in separating primary forest, pasture and second growth. The technique assumes that the spectral properties of the various land-cover types do not change from one dry season image to the next. However, interannual variation in precipitation and the timing of image acquisition have the potential of invalidating this assumption. In general, we would expect pastures in early dry season images to be considerably greener than the same pastures imaged later in the dry season. This is likely to result in increased confusion between green pastures and second growth. If we inspect the timing of image acquisition for Ji-Paraná, it can be observed that only the 1997 and 1998 data sets were acquired early in the dry season, the same dates which show the highest areal extent of second growth.

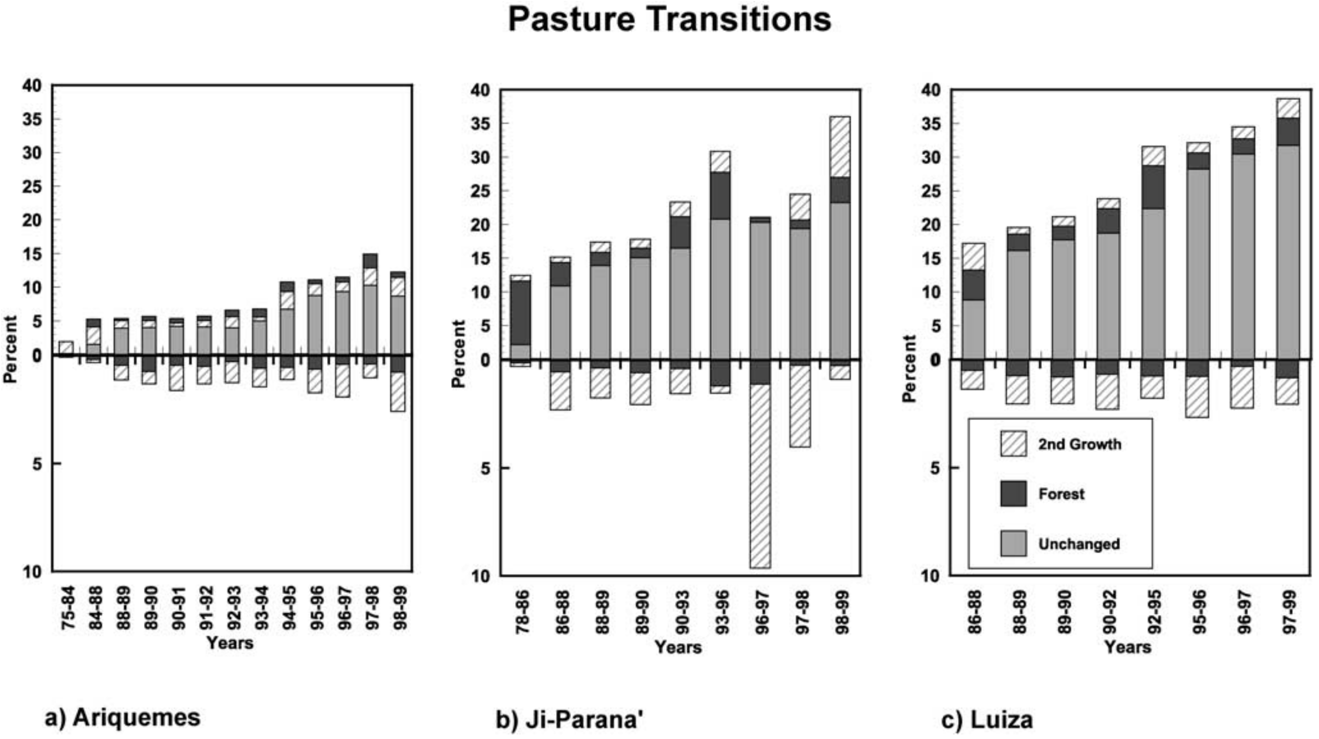


Figure 8. A graphical representation of no change, gain, or loss of second growth for the three scenes. Numbers are reported as areal percentages of each scene. Gains or no change are plotted above the 0 line, losses below the line. Different patterns display which classes contributed to the gain or loss of second growth. Disallowed transitions appear as second growth loss to primary forest below the 0 line.

Similar problems were not observed in Luiza where no early dry season images were used. We suspect that problems similar to what occurred in Ji-Paraná also occurred in the Ariquemes time series in which 5 of 14 dates were acquired in the early dry season. However, because pasture area remained low until relatively recently, large fluctuations in pasture and second growth were not observed.

[42] To test the hypothesis that phenology caused errors in mapping second growth, we performed a two-sample t-test comparing early dry season images (early June) to late dry season images (July). We pooled data into these two categories, comparing the ratio of second growth to cleared forest because this ratio normalizes out differences in the amount of cleared area between regions and is highly sensitive to a phenological error of this type. The resulting t value was 3.677 ($\alpha = 0.005$) suggesting that the proportion of area mapped as second growth is significantly higher in early dry season images than it is in the late dry season. A similar comparison across regions for images acquired in July resulted in a t value of 3.32 ($\alpha = 0.01$) when comparing Ariquemes to Ji-Paraná and a 5.47 ($\alpha = 0.005$) when comparing Ariquemes to Luiza. No significant differences were observed between Ji-Paraná and Luiza. From this analysis we can conclude that regional differences are significant, but phenological differences cannot be ignored.

3.5. Pasture and Second-Growth Dynamics

[43] The balance between pasture growth, maintenance and abandonment can be displayed graphically as a balance sheet for pasture and second growth (Figures 7 and 8 and Table 5). Several common features can be observed when comparing pasture transitions between the three scenes (Figure 7). First, in all scenes the most common source of pasture in a given year is pasture from the previous year. The only exception is very early in the time series for Ariquemes and Ji-Paraná, in which the dominant source of pasture is forest. Second, the dominant source of new pasture is from cleared primary forest. Cleared second-growth forest constitutes up to 5% of new pasture, but is typically lower than primary forest. Notable exceptions are shown for Ji-Paraná in the late 1990s, which shows very large shifts in pasture and second growth that we suspect is an error.

[44] Pasture was lost primarily to second growth. However, losses remained relatively low and stable over time. For example, in Ariquemes, the transition of pasture to second growth remained between 0.5 and 1.3% throughout a majority of the time series. Pasture transitions to second growth remained relatively stable and low in Ji-Paraná and Luiza as well. In Ji-Paraná, if we exclude the period between 1996 and 1998, losses ranged between 0.6 and 1.6% of total area. In Luiza, losses were highest, ranging between 1.0% and 2.9%. Disallowed transitions from pasture to primary forest, resulting from three transitions in sequence occurred, but represented less than 0.2% for most of the time series.

[45] Second-growth transitions showed some similarities to pasture in that the most common source of second growth was second growth from the previous year (Figure 8). The primary source of new second growth was pasture, although

Table 6. Temporal Stability of Land-Cover Classes Expressed as Number of Transitions (Ntrans)[a]

Ariquemes	Pasture Ntrans			Second growth Ntrans		
Age	0	1	2+	0	1	2+
<4 years	2.08	0.27	0	1.61	0.24	0
4–8	1.99	0.65	2.22	0.6	0.58	0.69
9–13	0.95	0.34	3.04	0.29	0.11	0.94
14–24	0.57	0.48	1.83	0.3	0.02	0.73
25+	0.07	0.06	0.07	0.01	0.02	0.03
	5.66	1.8	7.16	2.81	0.97	2.39
Ji-Paraná	Pasture Ntrans			Second growth Ntrans		
Age	0	1	2+	0	1	2+
<4 years	2.82	0.81	0.26	2.44	0.17	0.04
4–8	4.17	0.96	5.23	0.48	0.93	0.5
9–13	2.43	0.67	3.89	0.34	0.21	0.89
14–21	4.12	0.49	5.37	0.22	0.19	0.87
22+	1.17	1.84	1.32	0.03	0.1	0.21
	14.71	4.77	16.07	3.51	1.6	2.51
Luiza	Pasture Ntrans			Second growth Ntrans		
Age	0	1	2+	0	1	2+
<4 years	3.89	0.26	0	2.22	0.19	0
4–8	7.31	1.58	2	1.12	0.74	0.43
9–13	3.84	0.64	2.91	0.47	0.29	0.68
14+	6.66	4.37	2.56	0.38	0.3	0.49
	21.7	6.85	7.47	4.19	1.52	1.6

[a] A zero transition means that the land-cover class remained within that class after initial clearing. One transition means that the area did not start within its final class, undergoing one transition over the time series. Two or more transitions translate to a lack of temporal stability. For example, if an area were cleared to pasture (0), reverted to second growth (1), then was converted back to pasture (2), this would translate as two transitions.

primary forest was the major source for several years. A majority of the losses were mapped as transitions from second growth to pasture, although the percentage typically fell below 1%. On average transitions between pasture and second growth tended to balance. As a result, pasture and second growth tended to increase proportionally as primary forest decreased.

[46] Detailed time series offers the potential of asking the question: what is the temporal stability of a land-cover class and how does that vary spatially? Temporal stability was addressed by calculating the number of transitions following initial clearing for pasture and second growth within several age classes (Table 6). In this analysis, the final land-cover class mapped in 1999 for Ji-Paraná and Luiza, and 1998 for Ariquemes was used to define the land-cover class.

[47] The youngest age class (<4 years) was temporally stable for pastures and second growth independent of spatial location (Table 6). After 4 years, the land-cover classes began to show greater instability and more spatial variation. For pasture, all three areas showed a bimodal distribution, with pasture either undergoing no transition, or at least 2 transitions for the 4–8 year old class (Table 6). However, the ratio of stable to unstable pasture varied spatially. In Ji-Paraná and Ariquemes, temporally unstable pastures were slightly more common than stable pastures. In Luiza, a majority of the pastures were stable undergoing no transitions. We suspect that Ji-Paraná would have behaved more like Luiza in the absence of classification errors in 1997 and 1998. For the second oldest age class (9–13 years), differences in spatial patterns were even more pronounced. In Ariquemes, a majority of the older pastures were unstable, undergoing two or more transitions. In Ji-Paraná, the proportion of stable pastures increases, but was still outweighed by pastures undergoing two or more transitions. Luiza also showed a bimodal distribution, but favored temporally stable pastures. For the oldest class in each scene, all the three stability classes tended to be equally weighted.

[48] Second growth, unlike pasture, tended more toward temporal instability and showed less spatial variation (Table 6). This is particularly true for classes older than 8 years, in which a majority of the second growth was mapped as undergoing 2 or more transitions for all three areas. Mixed responses were observed for the 4–8 year class, in which 0, 1 or 2 transitions were nearly equal in Ariquemes, 1 transition was favored in Ji-Paraná and the largest area was mapped as stable in Luiza.

4. Discussion

4.1. Accuracy and Errors

[49] Overall accuracy reported here is comparable to similar studies in Amazônia [e.g., *Alves et al.*, 1999]. Confusion between second growth and pasture suggests that caution must be used when interpreting transitions between these two classes. Airborne videography from 1999, suggests that second growth was overmapped by the DTC. Because errors between pasture and second growth tended to balance, overmapping occurred primarily at the expense of primary forest. Analysis of the origin of error is encouraging. Sunlit slopes, which were erroneously mapped as second growth, should represent a systematic bias across all dates because topography and illumination will not change significantly during the time series. This bias will cancel when deforestation rates are estimated as the difference in primary forest between two dates. Furthermore, estimates of the magnitude of error derived from airborne videography are probably high for the whole region. If 10% of the primary forest is being mapped as second growth due to topography as the videography suggests, second growth mapped in

Ariquemes and Ji-Paraná in the 1970s would have been considerably higher than the 0.078 and 1.25% observed (Table 5). Finally, the error is potentially correctable, either through the use of a digital elevation model or a digital mask showing temporally invariant areas of second growth localized over rugged terrain.

[50] Phenology is another significant source of error. Ratios of second growth to cleared area showed that this ratio was significantly higher for early dry season images than it was for late dry season images independent of location. While the extent to which phenology might impact other studies will depend upon methodology, our results suggest that interpretations of second growth should take into account the timing of acquisition in addition to the year. Phenology, while important, does not account for spatial differences in second growth observed between Ariquemes and the other two sites.

[51] Deforestation rates reported here are consistent with other estimates, but difficult to compare directly due to differences in methodology, temporal coverage and spatial extent. *Skole and Tucker* [1993] report an annual deforestation rate for Rondônia of 0.7% between 1978 and 1988, which is higher than the rate we observed in Ariquemes, but lower than Ji-Paraná. PRODES estimates of deforestation for the whole state, initially calculated using hard copy maps and most recently digital processing, range between 0.62% and 2.75% between 1977 and 1998 with an average rate slightly exceeding 1% [*INPE*, 2000]. The closest comparison can be made to *Alves et al.* [1999], who report a percentage of area cleared for 1977, 1985 and 1995 for the scene centered over Ji-Paraná, equal to 6%, 17% and 35%, respectively. We find 5.5% in 1978, 15.9% by 1986 and 36.7% by 1996.

[52] Our deforestation rates must be viewed with some caution. We calculate deforestation rates as the percentage of change in primary forest divided by the number of years between images. Over a long time series, such a calculation should be accurate because classification errors between years will balance over the long term while the magnitude of change in forest grows larger. However, when calculated from image pairs acquired in contiguous years, an error in the first year opposite in sign to the second year will compound the error in both years. Likely examples in our time series include the rate estimated for Ji-Paraná between 1996 and 1997 and Ariquemes between 1993 and 1994, in which the area mapped as primary forest in Ariquemes actually increased (Table 5).

4.2. Land-Cover Change and Land Use

[53] Land-cover change in Amazônia is a complex product of infrastructure, economics, government policy, biology, culture and soils [*Browder*, 1994; *Moran et al.*, 1994]. Infrastructure and government policy can be considered the primary factors controlling the spatial distribution and timing of land clearing in Rondônia. Forest clearing in Rondônia is concentrated in close proximity to major roads and urban centers [*Dale et al.*, 1993; *Frohn et al.*, 1996; *Alves et al.*, 1999]. The most extensive tracts of forest in 1999 remain in Forest Reserves or Indigenous lands. The oldest land clearing concentrates in the vicinity of planned government settlements. New settlements in Ariquemes, while largely outside of government colonies, are clustered around seven INCRA settlements in central Ariquemes. The classic fishbone pattern observed in Rondônia occurs along planned parallel access roads spaced at 4 km. Other spatial patterns are only observed outside of planned settlements in northern Ji-Paraná and new settlements in central Ariquemes.

[54] The combination of government planned settlement patterns, intensive forest clearing within 50 km of BR364 and increasing density of cleared land has created an extensive patchwork of forest fragments. Forest edges experience increased mortality, loss of diversity, increased leaf turnover, higher wind throw and drier, warmer conditions over a buffer extending as much as 300 m from edge [*Laurance et al.*, 1998a]. Forest edges are also likely to act as a significant carbon source as older, high biomass trees die and are replaced by secondary species along the margin [*Laurance et al.*, 1998b]. Conservative estimates of edge impacts, assuming a 100 m buffer [*Laurance et al.*, 1998a] and square or rectangular patches places a minimum width requirement of 200 m for all patches and suggests a majority of a patch would be impacted even if it were 0.5 km by 1.2 km in size. Although we do not calculate measures of fragmentation in this paper, it is clear that many of the forest fragments in close proximity to BR364 are small and irregular enough to be highly impacted (lower right, Figure 3). Even in Ariquemes, which has lower density of clearings near roads, the spatial pattern is conducive to increasing the amount of edge relative to area of a patch (upper left, Figure 3). Estimates of carbon emissions based on our estimates of deforestation rates, are likely to be underestimates due to edge effects because they would not take into account carbon loss along margins of fragmented forest. Extensive, unfragmented forests persist in the Forest Reserves and Indigenous lands.

[55] In Rondônia, patterns of pasture use and abandonment differ from many other parts of Amazônia. A typical pattern of land use described in much of the Amazonian literature, involves initial forest clearing followed by either pasture establishment or annual crops, pasture establishment following crops and eventual abandonment and forest regeneration [*Uhl et al.*, 1988; *Dale et al.*, 1994; *Steininger*, 2000]. This pattern has been described for Manaus [*Steininger*, 1996], Altamira [*Moran et al.*, 1994] and much of the basin [*Lucas et al.*, 2000]. Abandonment after cutting or short duration cropping (light use), 6–10 years of pasture (moderate) or extended use (heavy), is followed by rapid growth of secondary species and accumulation of biomass which depends on the intensity of use [*Uhl et al.*, 1990; *Steininger*, 2000] and soil fertility [*Moran et al.*, 2000].

[56] Much of the pasture we map in Rondônia would be categorized as either moderate or heavy use [*Uhl et al.*, 1990]. A relatively modest proportion of the deforested landscape is second growth, averaging less than 24% in the Ji-Paraná and Luiza scenes. Furthermore, when second growth was mapped, it did not tend to persist beyond 8 years, consistent with findings by *Alves and Skole* [1996] and by *Pedlowski et al.* [1997]. However, there are portions of Rondônia that may better approximate the model described elsewhere. Higher estimates of second growth were observed in Ariquemes, where precipitation is higher and soils tend to be poorer [*EMBRAPA*, 1983(data are available from the Agencia Nacional de Energia Electrica

at http://www.aneel.gov.br)]. When averaged over the state, low estimates of the proportion of second growth to cleared land in Ji-Paraná and Luiza may balance with higher estimates to the northwest, more closely approximating the 30% estimated by *Skole et al.* [1994].

[57] We observe significant spatial and temporal differences in land use between Ariquemes and the two scenes toward the southwest. Although BR364 passes through all three regions, development in Ariquemes has been considerably delayed and has only recently begun to approximate clearing rates in the other two scenes. Similar patterns were observed in northern Ji-Paraná, which like Ariquemes, has numerous old settlements, yet has not experienced the density of clearing that is typical of areas within 50 km of BR364 in Luiza and Ji-Paraná. In both Ariquemes and northern Ji-Paraná, recent accelerated rates of clearing can be attributed primarily to new settlements, not intensified use in old settlements. Many of these differences may be due to economics. The highest density of clearing occurs in closest proximity to BR364 and to some of the oldest cities in the state. Improved infrastructure in these areas and close proximity to markets provides the means to transport farm products and a market to sell them in.

[58] However, other factors may also account for regional differences in land use. Biological constraints may be a contributing factor to the slow development of Ariquemes. Rondônia has some of the highest occurrences of malaria in South America [*Browder*, 1994]. Soil fertility is also likely to be a factor. BR364 and older settlements were placed over some of the most nutrient rich soils in the state [*EMBRAPA*, 1983]. The highest density of land clearing near BR364 is in the areas with fertile soils near cities such as Ouro Preto and Ji-Paraná. Areas outside of regions mapped with high soil fertility such as northeastern Ariquemes, and north central Ji-Paraná coincide with the lower density land clearings even when they were deforested early (14+ years). Synergism between proximity to markets, soil fertility and land availability may account for some of these patterns. In Ji-Paraná a majority of the uncut forest was difficult to access throughout the 1990s. If a farmer were interested in expanding operations, he would have the choice of purchasing land a considerable distance from the original property near BR364, with the knowledge that the soil fertility is likely to be poor, or clearing some of the remaining forest on existing plots known to have more fertile soils. Given lax enforcement of the 50% (80% by 1998) law, the choice is obvious.

[59] In Ariquemes and northern Ji-Paraná, a different choice may have been made. In these areas, large tracts of uncut forest remain outside of Reserves and Indigenous lands. Given low soil fertility in an existing plot, and the potential of finding better soils elsewhere, a farmer may be more likely to move to a new area. Given additional benefits of selling the timber from the cleared land, a farmer can adhere to forest preservation laws and still benefit economically from the higher soil fertility of newly cleared lands and other benefits such as timber.

[60] Differing spatial patterns in the stability of pasture and the ratio of second growth to cleared land are consistent with the idea that soil fertility could be an important driver of land use. Of the three scenes, Ariquemes has the least stable pastures and the highest proportion of second growth relative to cleared land. In this area, a majority of the pastures older than 8 years have undergone at least two transitions.

5. Conclusions

[61] We describe a protocol designed to enable large areal mapping over long time series. We apply the methodology to three scenes in Rondônia, and use the land-cover maps to estimate deforestation rates, map the age structure of cleared land and document the spatiotemporal dynamics of pasture and second growth. Rondônia can be characterized as a highly fragmented landscape in which areas outside of Forest Reserves and Indigenous lands are dominated by numerous irregular small patches. Unlike some other parts of the basin, we find that pastures persist over many years in Rondônia and are not typically abandoned to long term second growth. We observe temporal and spatial differences in deforestation rates, pasture development and loss of pasture to second growth between the three scenes. Although the placement and timing of land clearing are predictable based on infrastructure and government policy, the temporal stability of pasture and second growth are not. A good example is provided by land clearing in northeastern Ariquemes, which was established early, but follows a very different path than clearing in Ji-Paraná and Luiza that are also close to BR364.

[62] Several new research directions are obvious. Environmental data sets [*ITERON*, 1998] and road network databases [*SEDAM*, 1999] offer the potential of testing how soil fertility and access to markets influence land use. The impact of habitat fragmentation could be evaluated quantitatively through a variety of spatial metrics and buffers around forest edges. Spectral fractions, which were only used as inputs to a classifier here, could be used to quantify forest degradation [*Cochrane and Souza*, 1998] and pasture biogeochemistry [*Asner et al.*, 1999] through analysis of the NPV and GV fractions. This analysis can be readily extended to the northwest to include Porto Velho, and southeast to Cacoal, with georeferencing and the development of a Rock/Savanna mask as the only time-limiting steps. Newly available ETM scenes can be easily incorporated. The spatiotemporal patterns in land-cover change observed in Rondônia illustrate the importance of regional variation in land use within the Amazon basin, the causes of which will be the focus of future research.

[63] **Acknowledgments.** This research was funded primarily by NASA grant NCC5-282 as part of LBA Ecology. Landsat TM and MSS images used in the project were acquired from several sources including the Landsat Pathfinder program, the Tropical Rain Forest Information Center (TRFIC) and through direct purchase by INPE. Digital PRODES used as a base map was kindly supplied by INPE. A portion of this research was also conducted at INPE in São Jose Dos Campos, while the senior author was on sabbatical. We wish to acknowledge Trent Biggs, Charles Kiedman, and Andy Ballantine for help in image georectification and data management. Finally, we wish to thank Carlos de Souza and Laura Hess for invaluable help in accuracy assessment and analysis of digital videography.

References

Adams, J. B., M. O. Smith, and A. R. Gillespie, Imaging spectroscopy: Interpretation based on spectral mixture analysis, in *Remote Geochemical Analysis: Elemental and Mineralogical Composition*, edited by C. M. Pieters and P. Englert, pp. 145–166, Cambridge Univ. Press., New York, 1993.

Adams, J. B., D. Sabol, V. Kapos, R. Almeida Filho, D. A. Roberts, M. O.

Smith, and A. R. Gillespie, Classification of multispectral images based on fractions of endmembers: Application to land-cover change in the Brazilian Amazon, *Remote Sens. Environ.*, *52*, 137–154, 1995.

Alves, D. S., and D. L. Skole, Characterizing land cover dynamics using multi-temporal imagery, *Int. J. Remote Sens.*, *17*, 835–839, 1996.

Alves, D. S., J. V. Soares, S. Amaral, E. M. K. Mello, S. A. S. Almeida, O. F. da Silva, and A. M. Silveira, Biomass of primary and secondary vegetation in Rondônia, western Brazilian Amazon, *Global Change Biol.*, *3*, 451–461, 1997.

Alves, D. S., J. L. G. Pereira, C. L. De Sousa, J. V. Soares, and F. Yamaguchi, Characterizing landscape changes in central Rondonia using Landsat TM imagery, *Int. J. Remote Sens.*, *20*, 2877–2882, 1999.

Asner, G. P., A. R. Townsend, and M. C. Bustamante, Spectrometry of pasture condition and biogeochemistry in the central Amazon, *Geophys. Res. Lett.*, *26*(17), 2769–2772, 1999.

Browder, J. O., Surviving in Rondônia: The dynamics of colonist farming strategies in Brazil's northwest frontier, *Stud. Comp. Int. Dev.*, *29*(3), 45–69, 1994.

Clark, L. A., and D. Pregibon, Tree-based models, in *Statistical Models in S*, edited by J. M. Chambers and T. J. Hastie, pp. 377–420, Wadsworth, Belmont, Calif., 1992.

Cochrane, M. A., and C. M. Souza, Linear mixture model classification of burned forests in the eastern Amazon, *Int. J. Remote Sens.*, *19*, 3433–3440, 1998.

Congalton, R. G., and R. A. Mead, A quantitative method to test for consistency and correctness in photointerpretation, *Photogramm. Eng. Remote Sens.*, *49*(1), 69–74, 1983.

Culf, A. D., J. L. Esteves, A. O. Marques Filho, and H. R. da Rocha, Radiation, temperature and humidity over forest and pasture in Amazonia, in *Amazonian Deforestation and Climate*, edited by J. H. C. Gash et al., pp. 175–191, John Wiley, New York, 1996.

Dale, V. H., R. V. O'Neill, M. Pedlowski, and F. Southworth, Causes and effects of land-use change in central Rondônia, Brazil, *Photogramm. Eng. Remote Sens.*, *59*(6), 997–1005, 1993.

Dale, V. H., R. V. O'Neill, F. Southworth, and M. Pedlowski, Modeling the effects of land management in the Brazilian Amazonian settlement of Rondônia, *Conserv. Biol.*, 196–206, 1994.

de Moraes, J. F. L., B. Volkoff, C. C. Cerri, and M. Bernoux, Soil properties under Amazon forest and changes due to pasture installation in Rondonia, Brazil, *Geoderma*, *70*, 63–81, 1996.

de Moraes, J. F. L., F. Seyler, C. Cerri, and B. Volkoff, Land cover mapping and carbon pools estimates in Rondonia, Brazil, *Int. J. Remote Sens.*, *19*, 921–934, 1998.

Detwiler, R. P., and C. A. S. Hall, Tropical forests and the global carbon cycle, *Science*, *239*, 42–47, 1988.

Elvidge, C. D., and F. P. Portigal, Change detection in vegetation using 1989 AVIRIS data, in *Proc. SPIE Imaging Spectroscopy of the Terrestrial Environment, Orlando, Fla., 16–17 April*, edited by G. Vane, pp. 178–189, Int. Soc. for Opt. Eng., Bellingham, Wash., 1990.

EMBRAPA, *Mapa de levantamento de reconhecimento de meia intensidade dos solos do estado de Rondônia*, 1:500,000, Com. Estadual de Planejamento Agrícola, Porto Velho, 1983.

Fearnside, P. M., and E. Salati, Explosive deforestation in Rondonia, Brazil, *Environ. Conserv.*, *12*(4), 355–356, 1985.

Fearnside, P. M., N. Leal, and F. M. Fernandes, Rainforest burning and the global carbon budget: Biomass, combustion efficiency, and charcoal formation in the Brazilian Amazon, *J. Geophys. Res.*, *98*(D9), 16,733–16,743, 1993.

Fiegl, B. J., J. Mellilo, and C. C. Cerri, Changes in the origin and quality of soil organic matter after pasture introduction in Rondônia (Brazil), *Plant Soil*, *175*, 21–29, 1995a.

Fiegl, B. J., P. A. Steudler, and C. C. Cerri, Effects of pasture introduction on soil CO_2 emissions during the dry season in the state of Rondônia, Brazil, *Biogeochemistry*, *31*, 1–14, 1995b.

Foody, G. M., G. Palubinskas, R. M. Lucas, P. J. Curran, and M. Honzak, Identifying terrestrial carbon sinks: Classification of successional stages in regenerating tropical forest from Landsat TM data, *Remote Sens. Environ.*, *55*, 205–216, 1996.

Friedl, M. A., and C. E. Brodley, Decision tree classification of land cover from remotely sensed data, *Remote Sens. Environ.*, *61*, 399–409, 1997.

Frohn, R. C., K. C. McGwire, V. H. Dale, and J. Estes, Using satellite remote sensing analysis to evaluate a socio-economic and ecological model of deforestation in Rondonia, Brazil, *Int. J. Remote Sens.*, *17*, 3233–3255, 1996.

Fundação Instituto Brasileiro de Geografia a Estatística (FIBGE), *Anuário estatístico do Brasil*, Fundação Inst. Bras. de Geogr. a Estatística (FIBGE), Rio de Janeiro, 1989.

Gash, J. H. C., C. A. Nobre, J. M. Roberts, and R. L. Victoria, An overview of ABRACOS, in *Amazonian Deforestation and Climate*, edited by J. H. C. Gash et al., pp. 1–14, John Wiley, New York, 1996.

Goza, F., Brazilian frontier settlement: The case of Rondônia, *Popul. Environ.*, *16*(1), 37–60, 1994.

Hall, F. G., D. E. Strebel, J. E. Nickeson, and S. J. Goetz, Radiometric rectification, toward a common radiometric response among multidate, multisensor images, *Remote Sens. Environ.*, *35*, 11–27, 1991.

Hess, L. L., J. M. Melack, S. Filoso, and Y. Wang, Delineation of inundated area and vegetation along the Amazon floodplain with the SIR-C synthetic aperture radar, *IEEE Trans. Geosci. Remote Sens.*, *33*(4), 896–904, 1995.

Hess, L. L., et al., Geocoded digital videography for validation of land cover mapping in the Amazon Basin, *Int. J. Remote Sens.*, *23*(7), 1527–1555, 2001.

INPE, *Monitoramento da floresta Amazônica Brasileira por satélite 1998–1999*, 22 pp., Inst. Nac. de Pesqui. Espaciais, Sao Jose Dos Campos SP, Brazil, 2000.

ITERON, *SIGTERON: Sistema de informação geográfica para os terrenos e solos do estado de Rondônia, Brasil*, completed by the consultancy consortium TECNOSOLO-DHV, Porto Velho, Rondônia, 1998.

Kaufman, Y. J., The atmospheric effect on remote sensing and its correction, in *Theory and Applications of Optical Remote Sensing*, edited by G. Asrar, pp. 336–428, John Wiley, New York, 1989.

Keller, M., E. Veldkamp, A. M. Weitz, and W. A. Reiners, Effect of pasture age on soil trace-gas emissions from a deforested area of Costa Rica, *Nature*, *365*, 244–246, 1993.

Laurance, W. F., L. V. Ferreira, J. M. Rankin-deMerona, and S. G. Laurance, Rain forest fragmentation and the dynamics of Amazonian tree communities, *Ecology*, *79*(6), 2032–2040, 1998a.

Laurance, W. F., S. G. Laurance, and P. Delmonica, Tropical forest fragmentation and greenhouse emissions, *For. Ecol. Manage.*, *110*, 173–180, 1998b.

Lean, J., and D. Warilow, Simulation of the regional climate impact of Amazon deforestation, *Nature*, *342*, 411–412, 1989.

Lucas, R. M., M. Honzak, G. M. Foody, P. J. Curran, and C. Corves, Characterising tropical secondary forests using multi-temporal Landsat sensor imagery, *Int. J. Remote Sens.*, *14*, 3061–3067, 1993.

Lucas, R. M., M. Honzak, P. J. Curran, G. M. Foody, R. Milne, T. Brown, and S. Amaral, Mapping the regional extent of tropical forest regeneration stages in the Brazilian Legal Amazon using NOAA AVHRR data, *Int. J. Remote Sens.*, *21*, 2855–2881, 2000.

Lugo, A. E., and S. Brown, Tropical forests as sinks of atmospheric carbon, *For. Ecol. Manage.*, *54*, 239–255, 1992.

Malingreau, J. P., and C. J. Tucker, Large-scale deforestation in the southeastern Amazon Basin of Brazil, *Ambio*, *17*(1), 49–55, 1988.

Millikan, B. H., Tropical deforestation, land degradation, and society, lessons from Rondônia, Brazil, *Lat. Am. Perspect., Issue 72*, *19*(1), 45–72, 1992.

Moran, E. F., E. Brondizio, P. Mausel, and Y. Wu, Integrating Amazonian vegetation, land-use and satellite data, *BioScience*, *44*, 329–338, 1994.

Moran, E. F., E. S. Brondizio, J. M. Tucker, M. C. da Silva-Forsberg, S. McCracken, and I. Falesi, Effects of soil fertility and land-use on forest succession in Amazonia, *For. Ecol. Manage.*, *139*, 93–108, 2000.

Neill, C., M. C. Piccolo, P. A. Steudler, J. M. Melillo, and B. J. Feigl, Nitrogen dynamics in soils of forests and active pastures in the western Brazilian Amazon Basin, *Soil Biol. Biochem.*, *27*(9), 1167–1175, 1995.

Nepstad, D. C., et al., Large-scale impoverishment of Amazonian forests by logging and fire, *Nature*, *398*, 505–508, 1999.

Pedlowski, M. A., V. H. Dale, E. A. T. Matricardi, and E. P. de Silva Filho, Patterns and impacts of deforestation in Rondônia, Brazil, *Landsc. Urban Plan.*, *38*, 149–157, 1997.

RADAMBRASIL, *Mapa exploratório de solos, Projeto Radambrasil: Programa de Integração Nacional*, 1:1,000,000, Minist. das Minas e Energ., Dep. Nac. de Prod., Rio de Janeiro, 1978.

Richards, J. A., *Remote Sensing Digital Image Analysis: An Introduction*, Springer-Verlag, New York, 1999.

Rignot, E., W. A. Salas, and D. L. Skole, Mapping deforestation and secondary growth in Rondônia, Brazil, using imaging radar and Thematic Mapper data, *Remote Sens. Environ.*, *59*, 167–179, 1997.

Roberts, D. A., G. Batista, J. Pereira, E. Waller, and B. Nelson, Change identification using multitemporal spectral mixture analysis: Applications in eastern Amazonia, in *Remote Sensing Change Detection: Environmental Monitoring Applications and Methods*, edited by C. Elvidge and R. Lunetta, pp. 137–161, Ann Arbor Press, Chelsea, Mich., 1998.

Saatchi, S. S., J. V. Soares, and D. S. Alves, Mapping deforestation and land use in Amazon rainforest by using SIR-C imagery, *Remote. Sens. Environ.*, *59*, 191–202, 1997.

Schott, J., C. Salvaggio, and W. Volchok, Radiometric scene normalization using pseudoinvariant features, *Remote Sens. Environ.*, *26*, 1–16, 1988.

SEDAM, *GIS Coverages* (*Roads, Forest Reserves, INCRA and Indigenous Land Boundaries*), Secr. de Estado do Desenvolvimento Abiental, Porto-Velho, RO, Brazil, 1999.

Skole, D., and C. Tucker, Tropical deforestation and habitat fragmentation in the Amazon: Satellite data from 1978 to 1988, *Science*, *260*, 1905–1910, 1993.

Skole, D. L., W. H. Chomentowski, W. A. Sala, and A. D. Nobre, Physical and human dimensions of deforestation in Amazonia, *BioScience*, *44*, 314–322, 1994.

Shukla, J., C. Nobre, and P. Sellers, Amazon deforestation and climate change, *Science*, *247*, 1322–1325, 1990.

Smith, M. O., S. L. Ustin, J. B. Adams, and A. R. Gillespie, Vegetation in deserts, I, A regional measure of abundance from multispectral images, *Remote Sens. Environ.*, *31*, 1–26, 1990.

Steudler, P. A., J. M. Melillo, B. F. Feigl, C. Neill, M. C. Piccolo, and C. C. Cerri, Consequences of forest-to-pasture conversion on CH_4 fluxes in the Brazilian Amazon Basin, *J. Geophys. Res.*, *101*(D13), 18,547–18,554, 1996.

Steininger, M. K., Tropical secondary forest regrowth: Age, area and change estimation with Thematic Mapper data, *Int. J. Remote Sens.*, *17*, 9–27, 1996.

Steininger, M. K., Secondary forest structure and biomass following short and extended land-use in central and southern Amazonia, *J. Trop. Ecol.*, *16*, 689–708, 2000.

Stone, T. A., and G. M. Woodwell, Shuttle imaging radar analysis of land use in Amazonia, *Int. J. Remote Sens.*, *10*, 1663–1672, 1988.

Uhl, C., R. Buschbacher, and E. A. S. Serrao, Abandoned pastures in eastern Amazonia, I, Patterns of plant succession, *J. Ecol.*, *76*, 663–681, 1988.

Uhl, C., D. Nepstad, R. Buschbacher, K. Clark, B. Kauffman, and S. Subler, Studies of ecosystem response to natural and anthropogenic disturbances provide guidelines for designing sustainable land-use systems in Amazonia, in *Alternatives to Deforestation, Steps Toward Sustainable Use of the Amazon Rain Forest*, edited by A. B. Anderson, pp. 24–42, Columbia Univ. Press, New York, 1990.

Williams, M. R., and J. M. Melack, Solute export from forested and partially deforested catchments in the central Amazon, *Biogeochemistry*, *38*, 67–102, 1997.

O. A. Chadwick, K. Holmes, I. Numata, B. Powell, and D. A. Roberts, Department of Geography, EH3601, University of California at Santa Barbara, Santa Barbara, CA 93106, USA. (dar@geog.ucsb.edu)

G. Batista and T. Krug, Instituto Nacional de Pesquisas Espaciais, São Jose Dos Campos, São Paulo, Brazil.

A. Monteiro, Instituto do Homem e Meio Ambiente da Amazônia (IMAZON), Caixa Postal 1015, Belém, Pará, CEP 66017-000, Brazil.

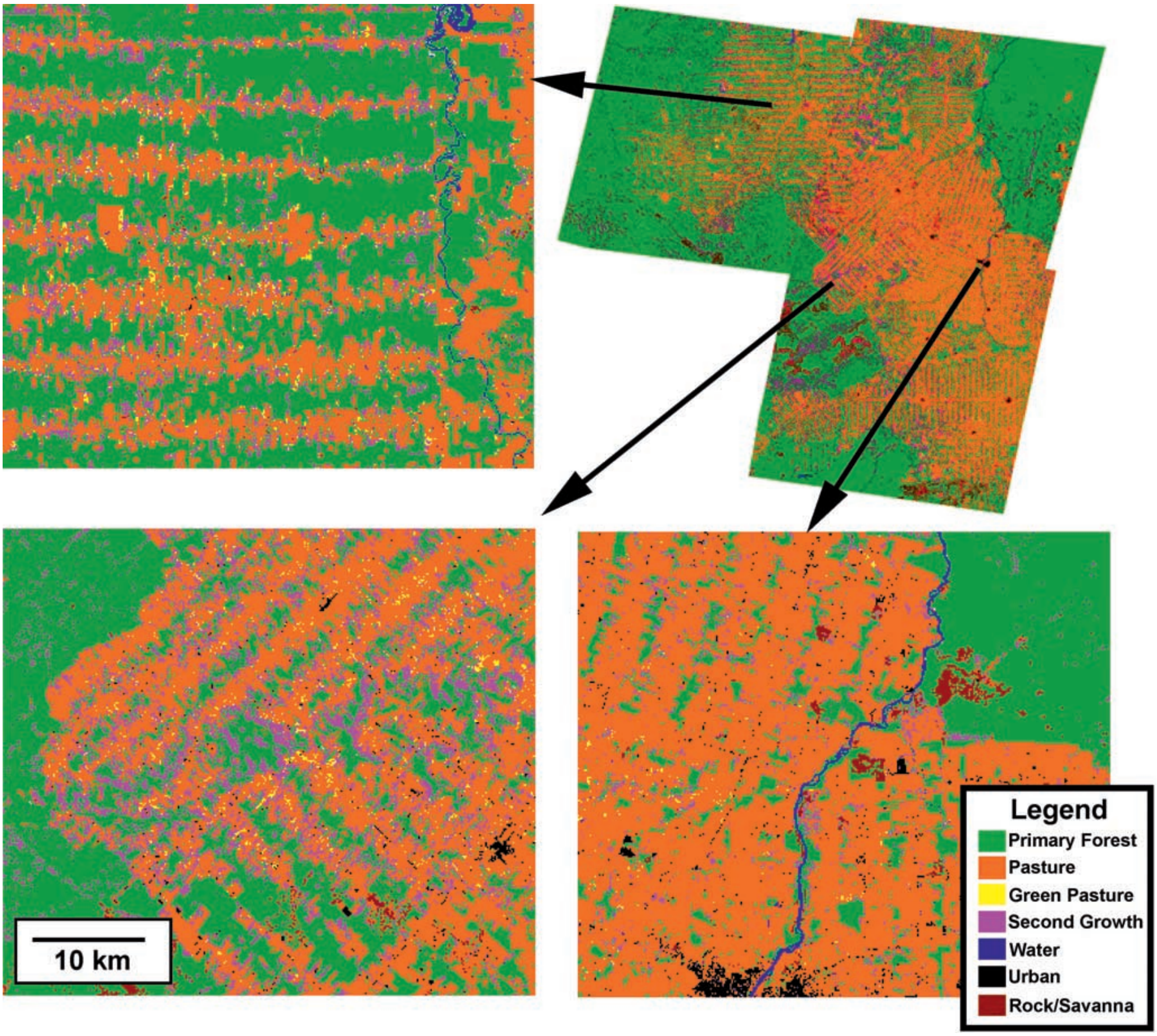


Figure 3. Map showing the seven categories mapped for Ariquemes (1998), Ji-Paraná (1999), and Luiza (1999). 1999 Ariquemes data were excluded from this mosaic due to extensive cloud contamination. A mosaic of the three scenes is shown in the upper right corner. Three regions are expanded, one located in southern Ji-Paraná (lower right), one in northwestern Luiza (lower left), and one in northeastern Ariquemes (upper left). The insets illustrate a region of old, dense land clearing (Ji-Paraná), new dense land clearing (Luiza), and old, low density land clearing (Ariquemes).

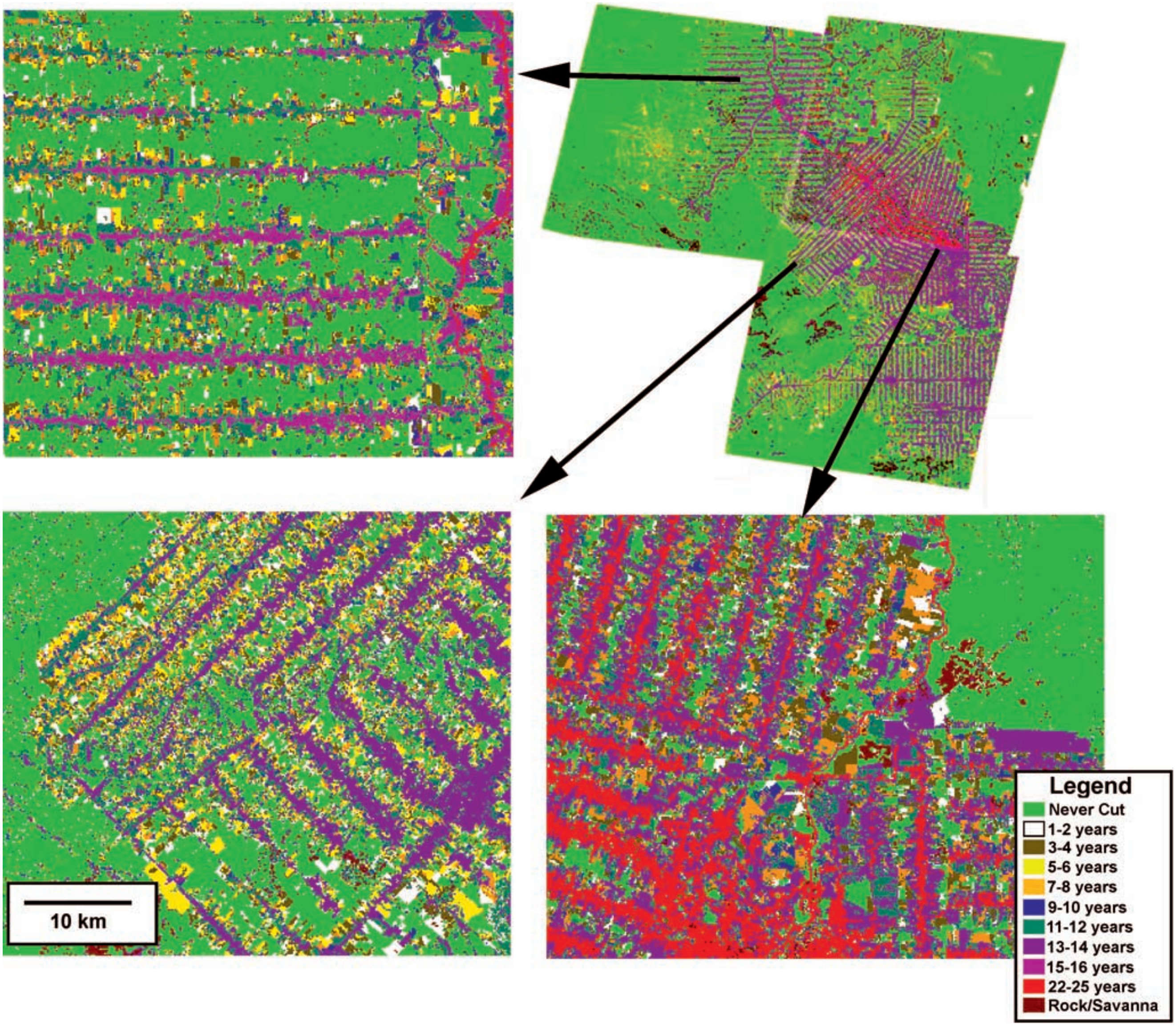


Figure 4. Map showing age since initial cut for the three scenes. The same mosaic and insets are shown for the age map as is shown in Figure 3. Several age classes have been combined to improve the clarity of the figure.