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Spatial and temporal evolution of family-farming land use in the Tapajós region of the Brazilian Amazon

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ABSTRACT

Pressures on the Brazilian Amazon forest have been accentuated by agricultural activities practiced by families encouraged to settle in this region in the 1970s by the colonization program of the government. The aims of this study were to analyze the temporal and spatial evolution of land cover and land use (LCLU) in the lower Tapajós region, in the state of Pará. We contrast 11 watersheds that are generally representative of the colonization dynamics in the region. For this purpose, Landsat satellite images from three different years, 1986, 2001, and 2009, were analyzed with Geographic Information Systems. Individual images were subject to an unsupervised classification using the Maximum Likelihood Classification algorithm available on GRASS. The classes retained for the representation of LCLU in this study were: (1) slightly altered old-growth forest, (2) succession forest, (3) crop land and pasture, and (4) bare soil. The analysis and observation of general trends in eleven watersheds shows that LCLU is changing very rapidly. The average deforestation of old-growth forest in all the watersheds was estimated at more than 30% for the period of 1986 to 2009. The local-scale analysis of watersheds reveals the complexity of LCLU, notably in relation to large changes in the temporal and spatial evolution of watersheds. Proximity to the sprawling city of Itaituba is related to the highest rate of deforestation in two watersheds. The opening of roads such as the Transamazonian highway is associated to the second highest rate of deforestation in three watersheds.

KEYWORDS: Deforestation, Watershed scale, Landsat Satellite Images, Cities, Roads.

Evolução espacial e temporal do uso da terra para agricultura familiar na região do Tapajós, Amazônia Brasileira

RESUMO

As pressões sobre a Floresta Amazônica Brasileira têm sido acentuadas por atividades agrícolas de muitas famílias que foram estimuladas a se estabelecer nessa região durante o Programa de Colonização do Governo Federal, na década de 1970. Os objetivos deste presente estudo foram de analisar a evolução espacial e temporal em termos de mudanças de cobertura da terra e uso da terra (CTUT) na região do baixo Tapajós, no Estado do Pará. Contrastam-se 11 bacias que são geralmente representativas do processo de colonização regional por agricultores familiares, e para tanto imagens de satélite Landsat de três diferentes anos (1986, 2001, e 2009) foram analisadas utilizando-se um Sistema de Informação Geográfica. Imagens individuais não-supervisionadas foram classificadas usando-se GRASS, e o algoritmo de classificação de Probabilidade Máxima, para todos os comprimentos de onda do espectro visível e infravermelho (1 a 5 e 7). As classes retidas para a representação do CTUT nesse estudo foram: (1) floresta primária levemente alterada; (2) floresta de sucessão; (3) terra agricultável e pastagem; e (4) solo nu. A análise e observação de tendências gerais em 11 bacias mostram que o CTUT tem mudado rapidamente. O desmatamento médio de floresta primária em todas as bacias foi estimado em mais de 30% no período de 1986 a 2009. A análise em escala local de bacias revela a complexidade do CTUT, notavelmente em relação a grandes mudanças na evolução espacial e temporal das bacias. A proximidade com a cidade de Itaituba, que se encontra em plena expansão, está relacionada com a maior taxa de desmatamento em duas bacias hidrográficas, ao passo que a abertura de estradas, como a Rodovia Transamazônica, está associada à segunda maior taxa de desmatamento em três bacias hidrográficas

PALAVRAS CHAVE: Desmatamento, Nível de bacia, Imagens de Satélite Landsat, Cidades, Estradas

INTRODUCTION

Since the 1970s, a series of incentives have been put in place by the Brazilian state to encourage the establishment of more than a million of farming families in the Amazon (Moran 1993; Browder *et al.* 2004; Margulis 2004). The extent of deforestation due to family farming in the Amazon is estimated to be of the same order of magnitude as the combined deforestation from logging, large-scale cattle farming and more recently soybean cultivation (Fearnside 2001; Walker *et al.* 2002; Le Tourneau and Bursztyn 2010). Family farmers typically practice short term agriculture after slash and burn, then leave fallow regrowth before burning it again after a few years and ultimately converting their land to pasture (Watrin *et al.* 1998; Caviglia-Harris 2004). A mosaic of old-growth forest, pastures, cultivated lands, and succession forests now extends in patches around road networks (Nepstad *et al.* 1991; Farella 2005). Several researchers have studied the spatial and temporal changes in land cover and land use (LCLU) in the Amazon based on satellite images (Moran *et al.* 1994; Foody 2002; Soares-Filho *et al.* 2006). INPE (2010a; 2010b) documented the annual progression of deforestation since 1988. While satellite image analysis allows for the monitoring of LCLU, it cannot elucidate their complex causes of change (Pfaff 1999). Indeed, such transformations are the result of economic, environmental, topographical or socio-cultural factors (Scatena *et al.* 1996; Walker *et al.* 2002; Oestreicher *et al.* 2014). Additionally, the proximity of populations and roads is increasingly recognized as a catalyst of LCLU change in areas of colonization of the Amazon (Fearnside 1990; Moran *et al.* 1994; Gutman *et al.* 2004). While many researchers have analyzed the evolution of LCLU at a regional scale, Fujisaka and White (1998) and Parkes *et al.* (2010) argue that analyses at the local watershed scale allow for a refined understanding of temporal and spatial changes. This study aims at contrasting the evolution of LCLU of 11 distinct watersheds, each adjacent to the Tapajós River in the state of Pará, from 1986 to 2009 and to relate it to socio-ecological dynamics.

MATERIALS AND METHODS

The study region is located in the state of Pará, along the Tapajós River, spanning broadly between the cities of Aveiro and Itaituba (Figure 1). All the watersheds studied are located within 03°50' to 04°5' S and from 55°0' to 56°5' W. This region is within the sphere of influence of two major roads, the BR-230 and the BR-163, both built with investments and initiatives originating from the Brazilian colonization plan (Figure 1).

Many small communities in the region, close to the river or inland, are not included in the analysis as no reliable quantifiable data is available. The city of Itaituba, founded in 1812, is by far the most populous in the region (Table 1). The region around Itaituba was identified as an area of settlement for the first large wave of immigration, under the colonization program of the 1970s (IBGE 2000). As such, more than 2,700 families had established themselves in this

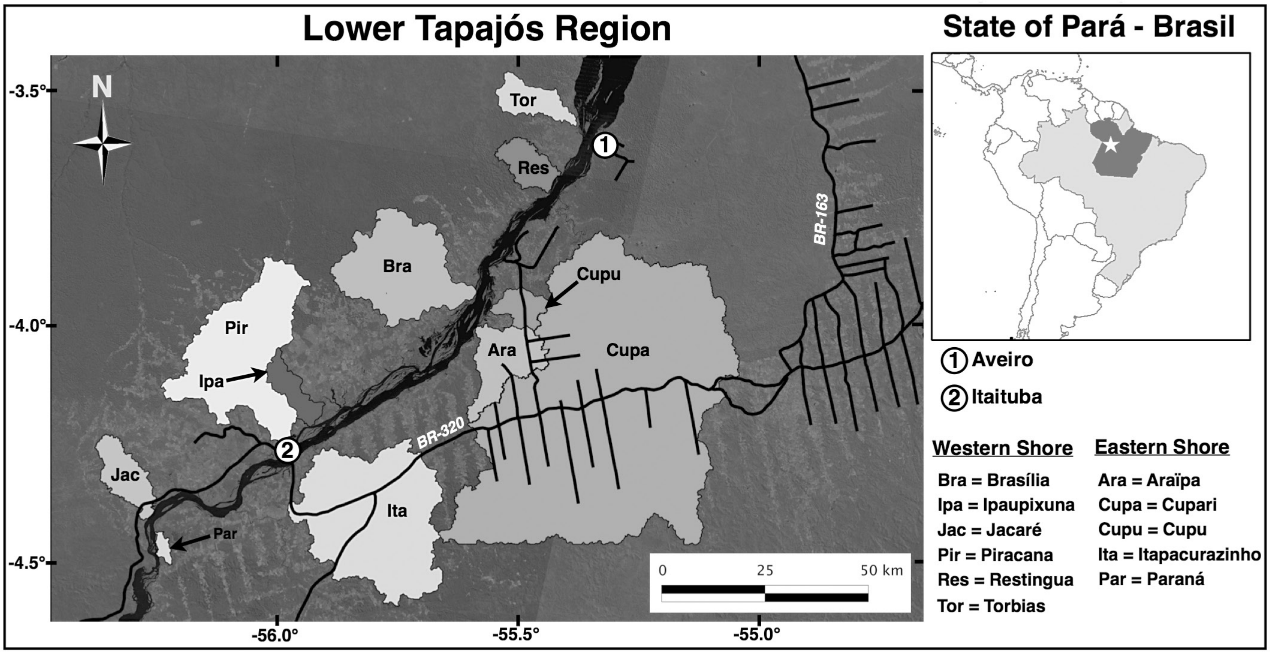

Figure 1. The region studied, showing the 11 watersheds under study.

Table 1. Populations of the largest municipalities and cities in the region of study (IBGE 2000, 2010).

Municipalities	Total population 2000	Total population 2010	Increase 2000-2010 (%)	Density 2010 (pers.km^{-2})	Main city 2010	Main city population 2010 (% total population)
Aveiro	15,518	15,767	+ 1.6%	0.93	Aveiro	2 179 (13%)
Itaituba	94,750	97,343	+ 2.7%	1.57	Itaituba	70 682 (72%)
Rurópolis	24,660	40,068	+ 62.2%	5.71	Ruropolis	13 035 (32%)

area by 1972 (Moran 1981). In the 1980s, Itaituba then became the center of activities linked to the gold boom of the lower Tapajós region, yielding drastic population increases. The city of Aveiro, founded in 1781, has undergone so far relatively limited development, as it is isolated from the road network (Table 1). Finally, Ruropolis was concomitantly founded with the opening of the Transamazonian highway in the early 1970s (Table 1).

Mapping methodology

A temporal series of ten land cover categories over three different years (1986, 2001, 2009) was created based on Landsat satellite images at 30 m resolution, acquired through the U.S. Geological Survey (USGS) and the National Institute for Spatial Research (INPE). Three satellite images were necessary to cover the region studied, namely those numbered 227/063, 228/062, and 228/063 (Table 2). Image selection was based on the quality of images available, determined by a low percent cloud-cover. Intervals of more than five years were preferred, in order to observe significant changes between the years studied. Finally, somewhat similar time spans between images were preferred, in order to facilitate the comparison of changes observed.

In order to complete the mapping aspect of this project, ground-truth data was collected using Global Positioning System (GPS) in February and March of 2010 in order to validate LCLU classes. According to Lu *et al.* (2007), between 15 and 20 GPS control points are necessary to validate each LCLU class studied. Based on the objective of validating eight classes and a general knowledge of LCLU types in the region, more than 200 control points were collected. For each of these control points, photographs were taken and a variety of information was documented, such as soil drainage, vegetation types and height and the slope.

Because satellite images can be distorted in significant ways, the images were georeferenced using a GeoCover 2000 series of orthorectified satellite images, produced by the National Aeronautics and Space Administration (NASA). To do so, a minimum of eight points, easily identifiable and stable over time (such as airports or roads) were identified on the GeoCover 2000 images and on the images used in the study. The corrections were based on the Nearest Neighbor Resampling algorithm, with a second order polynomial adjustment using the Geographic Information System (GIS) Geographic Resources Analysis Support System (GRASS), version 6.4.1, an open-source GIS platform.

The unsupervised classification of individual images was achieved using the Maximum Likelihood Classification (MLC) algorithm, as modified by Neteler and Mitasova (2008) on all wavelengths of the visible and infrared spectrum. The MLC algorithm is available on GRASS and was performed at a 99% confidence interval, and a maximum of nine iterations. Firstly, each image was divided into 50 classes, with the aim of regrouping these into smaller, similar subclasses as is typically done in unsupervised classification procedures. However, validation with control points demonstrated that accurate regrouping was not possible as there was a significant noise within the data. An alternative methodology was adopted, whereby each image was reclassified into three integrated classes each with a distinct spectral signature, making the unsupervised classification more reliable: 1) water, 2) forest, and 3) anthropogenic zones. Following this, a secondary classification into 25 standard classes was applied only to the forest and anthropogenic zones, which were selected from the original satellite imagery using a mask. Water was not subject to secondary classification, since the distinction between different elements in this class was not a research objective. With this methodology, the noise present in the data from the original image was reduced.

Based on the spatial and spectral characteristics of the images and using ground-truth data, thematic LCLU maps of eight classes were produced for the three years. The validation of classes was only possible for the 2009 images, as control points from 1986 and 2001 were not available. The reliability of the LCLU classification was, however, ensured by extending the spatial and spectral elements of each class.

Table 2. Landsat images acquisition dates

227/063	228/062	228/063
1986-08-14	1986-08-05	1986-08-05
2001-07-30	2001-08-06	2001-08-06
2009-07-28	2009-08-20	2009-08-20

Watersheds were delimitated with a 90 m spatial resolution Shutter Radar Topographic Mission Program (SRTMP)-based Digital Elevation Model (DEM). In each watershed, it was then possible to calculate the area, of LCLU classes over the three years. The temporal evolution of LCLU in watersheds were analyzed using the G test, which compares proportions or percentages (Scherrer 1984). For the spatial analysis of LCLU in the watersheds, in each year studied, a correspondence analysis was used to determine which watersheds had similar LCLU. A G test was applied to this data to identify significant differences in the spatial configurations of LCLU in watersheds. In this case, a significant probability ($p < 0.05$) indicates that there is a difference in LCLU between groups of watersheds. All statistical analyses were performed with JMP 7.1 software.

RESULTS

LCLU typology

A total of eight classes were defined to represent LCLU in the region: (1) water – all bodies, (2) areas with poor drainage – zones with macrophytes or wetland vegetation, with hydromorphic soils, (3) slightly altered old-growth forest – dense and humid tropical forest that has been subject to minor anthropogenic disturbance, (4) late succession forest – ligneous vegetation more than ten years old, with a closed canopy, (5) early succession forest – ligneous vegetation less than ten years old, with an open canopy, typical of agricultural lands left in fallow, (6) crop land and pasture – herbaceous vegetation, typical of family farms and pastures, (7) bare soil – most zones without vegetation and/or showing areas of exposed soil, and (8) urban / built zones – areas that are highly reflective, typical of urban areas, areas with buildings and roads. Some of these classes were grouped together, in order to simplify the analysis of the 11 watersheds, and to determine which LCLU elements are undergoing important changes in this region of the Amazon under the influence of family farming. As such, the final classification used in the study was as follows: (1) slightly altered old-growth forest, (2) succession forest (the combination of both types previously mentioned), (3) crop land and pasture, and (4) bare soil, including urban and built environments.

Analysis of the LCLU evolution at the regional scale

Observation of the 11 selected watersheds revealed general trends in LCLU, at the regional scale. In 1986, close to 80% of the surface areas of most watersheds were still covered by slightly altered old-growth forest. These proportions were, however, greatly reduced in 2001 and 2009, corresponding to an increase in anthropogenic classes (Figure 2). Despite these major changes, however, slightly altered old-growth forest cover remained the most common class in almost all watersheds, representing on average close to 53% of the surface area of watersheds in 2009 (Figure 2). Succession forest was the second most abundant class in 1986, covering an average of 13% of the watershed area increasing to an average of 24% of the total area by 2009 (Figure 3). Though by a smaller factor, the average area of crop land and pasture also increased: from close to 4% of the area in 1986 to 13% in 2009 (Figure 4). Finally, the bare soil class remained the smallest, having gone from 3% to 8% between 1986 and 2009 (Figure 5).

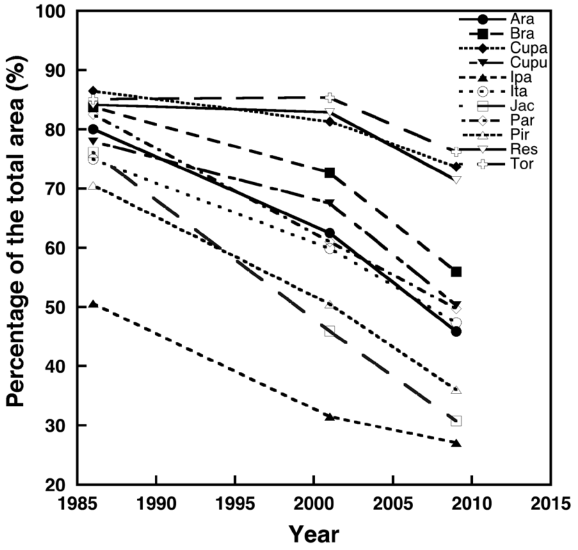

Figure 2. Evolution of the slightly altered old-growth forest class for all watersheds, for the three years studied, 1986, 2001 and 2009 (percentages of the total area). Acronyms as in Figure 1.

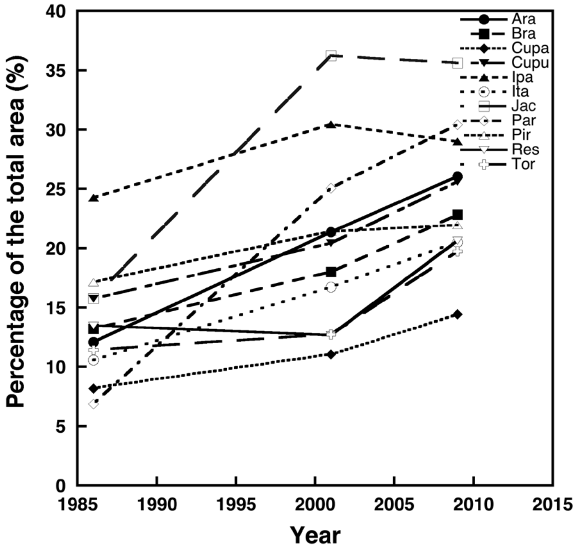

Figure 3. Evolution of the succession forest class for all watersheds, for the three years studied, 1986, 2001 and 2009 (percentages of the total area). Acronyms as in Figure 1.

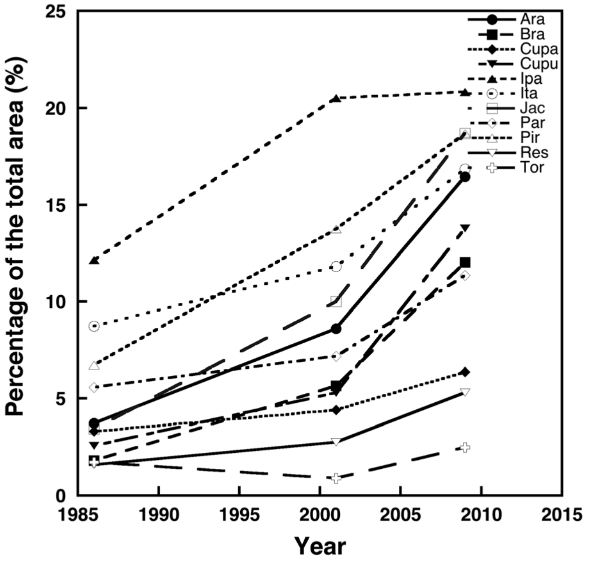

Figure 4. Evolution of the crop land and pasture class for all watersheds, for the three years studied, 1986, 2001 and 2009 (percentages of the total area). Acronyms as in Figure 1.

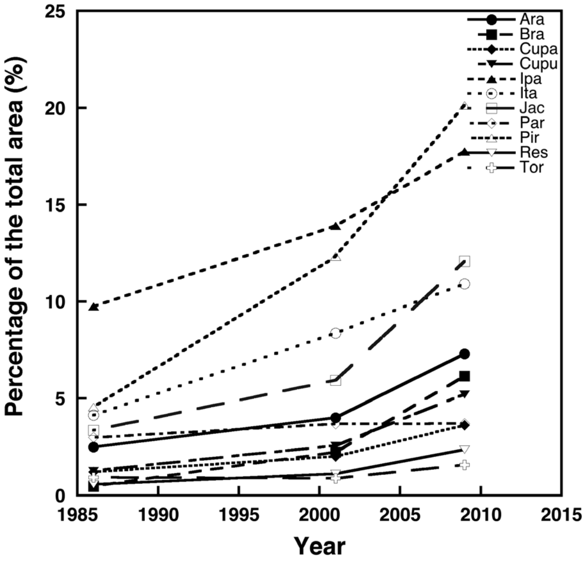

Figure 5. Evolution of the bare soil class over all watersheds, for the three years studied, 1986, 2001 and 2009 (percentages of the total area). Acronyms as in Figure 1.

Analysis of the LCLU evolution at the watershed scale

Results of G tests indicated that significant changes in the temporal evolution of LCLU at the scale of individual watersheds occurred in most watersheds with **Cupa**, **Ipa**, **Res**, and **Tor** watersheds being the exceptions (Table 3). While none of the watersheds considered in this study underwent significant changes between 2001 and 2009, four watersheds did show significant changes in LCLU in the larger time span of 1986 to 2001, namely **Ara**, **Jac**, **Par**, and **Pir**.

With regards to the spatial evolution of LCLU for each of the years studied, the results of correspondence analysis and G tests identified on the basis of similarities in LCLU three significantly different groups of watersheds. The composition of these groups of watersheds changed over time. In 1986, the group 1986-A included the **Ara, Bra, Cupa, Cupu, Par, Res** and **Tor** watersheds. They were clearly distinguished from other watersheds, having approximately 78% to 86% of their total areas covered by the slightly altered old-growth forest class (Table 4). The group 1986-B included the **Ita**, **Jac**, and **Pic** watersheds, which had less area covered by slightly altered old-growth forest than the 1986-A group (71% to 76%) and a larger presence of anthropogenic classes. The third group, 1986-C, was limited to the **Ipa** watershed and was found to be quite different from the 1986-B group ($p < 0.0006$ between 1986-B and 1986-C) because it had larger area in anthropogenic classes corresponding to less area (48%) in slightly altered old-growth forest cover. The difference between watersheds of the groups 1986-A and 1986-B was much smaller ($p < 0.0121$) than that between groups 1986-B and 1986-C ($p < 0.0006$), indicating that the **Ipa** watershed had considerably different LCLU than other watersheds in 1986.

In 2001, the group 2001-A, made up of the **Cupa, Res** and **Tor** watersheds, is significantly different from the group

Table 3. Presence of significant differences in watersheds' land cover and land use for each of the years studied (p values). Acronyms as in Figure 1.

Years	Ara	Bra	Cupa	Cupu	Ipa	Ita	Jac	Par	Pir	Res	Tor
1986-2001	0.0317	0.0784	0.7750	0.3466	0.0948	0.2427	0.0004	0.0024	0.0001	0.6182	0.4892
2001-2009	0.1362	0.0899	0.5984	0.0784	0.0788	0.4917	0.0597	0.5922	0.2432	0.2145	0.2229
1986-2009	0.0001	0.0001	0.0862	0.0001	0.0584	0.0019	0.0001	0.0001	0.0175	0.0646	0.1001

$p<0.05$ = presence of a significant difference

2001-B, made up of the **Ara, Bra, Cupu, Ita, Jac, Par** and **Pir** watersheds ($p < 0.0064$ between the two groups) (Table 4). While in 1986 the watersheds **Ara, Bra, Cupu** and **Par** were part of the same group as **Cupa, Res** and **Tor**, in 2001 there were significant differences between them. There was considerable loss of slightly altered old-growth forest cover (between 10% and 15%) in the **Ara, Bra, Cupu** and **Par**, watersheds, with a rise in anthropogenic classes, and especially succession forest. In consequence, LCLU in these watersheds resembled that of **Ita, Jac** and **Pir** in 2001. The **Ipa** watershed remained distinct from other watersheds, forming the group 2001-C ($p < 0.0057$ between the groups 2001-B and 2001-C). This difference could be attributed to comparatively large area in crop land and pasture (20%), as well as bare soil (14%), and by a comparatively low proportion of slightly altered old-growth forest (33%) in the **Ipa** watershed. Finally, difference between the groups 2001-B and 2001-C ($p < 0.0057$) was smaller than that observed between groups 1986-B and 1986-C ($p < 0.0006$), indicating a reduction over time in the differences in LCLU which separated **Ipa** from other watersheds.

Further changes were observed between 2001 and 2009 in watersheds that had previously been grouped by similar LCLU patterns (Table 4). The only group that did not change from 2001 is 2009-A, which included the **Cupa, Res** and **Tor** watersheds in the 2001-A group as well. While reductions in slightly altered old-growth forest cover have occurred recently, the 2009-A group still has between 71% and 76% of land area in forest. As such, these watersheds are very different from other watersheds ($p < 0.0001$ between the groups 2009-A and 2009-B). The group 2009-B, composed of the **Ara, Bra, Cupu, Ita** and **Par** watersheds, also lost slightly altered old-growth forest cover. While forest was still the dominant LCLU class in 2009 in these watersheds, they underwent a high degree of forest loss compared to other groups, which explains the large difference observed between 2009-B and 2009-A. The 2009-C group was composed of the **Ipa, Jac** and **Pir** watersheds. Because of their similar LCLU patterns in 2001, the **Jac** and **Pir** watersheds were grouped together in 2001-B. However, in 2009, LCLU shifted in these watersheds, and the patterns more closely resembled the **Ipa** watershed. While the **Jac** and **Pir** watersheds showed higher levels of disturbance over time when compared to other watersheds, in 2009 there was no longer a significant difference between them and the **Ipa** watershed. The 2009-C group did show a strong differentiation ($p < 0.0001$) with the 2009-B group.

It was therefore possible to group watersheds with similar spatial and temporal patterns of LCLU (Figure 6). Group A, composed of the **Cupa**, **Res**, and **Tor** watersheds, displayed the lowest levels of anthropogenic disturbances throughout

Table 4. Groups of watersheds that show similarities in their land cover and land use for each of the years studied: 1986, 2001 and 2009 (percentages of total area by class). Acronyms as in Figure 1.

						1986					
Groups	A	A	A	A	A	A	A	B	B	B	C
Watersheds	Ara	Bra	Cupa	Cupu	Par	Res	Tor	Ita	Jac	Pir	Ipa
Slightly altered-old-growth forest	80.6	84.1	87.1	78.4	83.6	84.5	86.1	76,4	77.3	71.4	52.7
Succession forest	12.1	13.3	8.2	15.7	6.8	13.4	11.3	10,6	15.7	17.1	24.2
Crop land, pasture	3.7	1.8	3.3	2.6	5.6	1.5	1.7	8,8	3.4	6.8	12.1
Bare soil	2.5	0.5	1.2	1.3	3.0	0.5	0.9	4,2	3.3	4.6	9.8
						2001					
Groups	A	A	A	B	B	B	B	B	B	B	C
Watersheds	Cupa	Res	Tor	Ara	Bra	Cupu	Ita	Jac	Par	Pir	Ipa
Slightly altered-old-growth forest	82.3	83.5	85.5	64.8	74.0	69.3	62.8	47.5	62.9	52.2	33.7
Succession forest	11.1	12.6	12.7	21.4	17.9	20.4	16.8	36.3	25.1	21.4	30.4
Crop land, pasture	4.4	2.7	0.9	8.6	5.6	5.2	11.8	10.0	7.2	13.8	20.5
Bare soil	2.1	1.1	0.8	4.1	2.2	2.6	8.5	5.9	3.8	12.4	13.9
						2009					
Groups	A	A	A	B	B	B	B	B	C	C	C
Watersheds	Cupa	Res	Tor	Ara	Bra	Cupu	Ita	Par	Ipa	Jac	Pir
Slightly altered-old-growth forest	75.0	71.7	76.3	48.9	58.2	52.7	51.3	51.9	30.7	33.3	38.8
Succession forest	14.4	20.6	19.7	26.0	22.9	25.5	20.5	30.4	29.0	35.6	21.9
Crop land, pasture	6.4	5.3	2.5	16.4	12.0	13.8	16.9	11.3	20.8	18.6	18.7
Bare soil	3.7	2.4	1.5	7.3	6.1	5.2	11.0	3.7	17.9	12.2	20.3

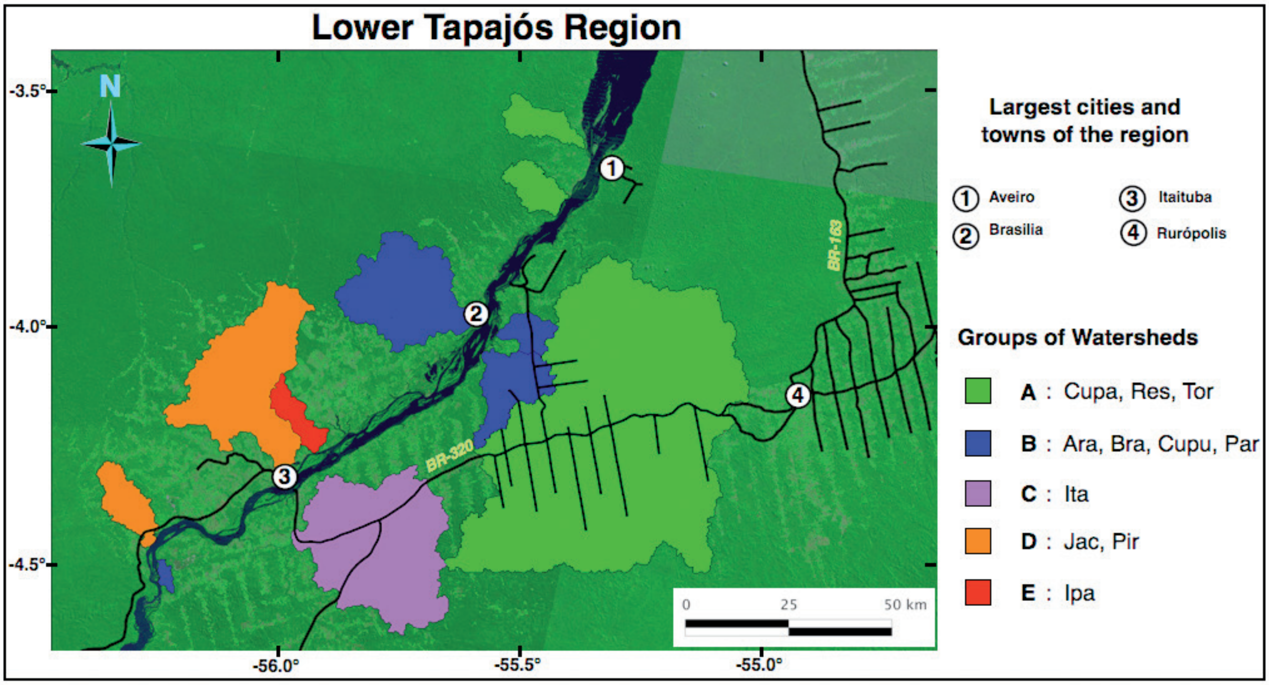

Figure 6. Presentation of groups of watersheds based on similarities in the temporal and spatial evolution of land cover and land use. in ascending order of deforestation. Acronyms as in Figure 1. This figure is in color in the electronic version.

the study period. This group distinguished itself from others because the slightly altered old-growth forest cover persisted as a dominant class over time. In addition, Group A did not show differences in LCLU over the time periods studied. Group B, composed of the **Ara, Bra, Cupu** and **Par** watersheds underwent important changes between 2001 and 1986 and was found to be significantly different from Group A. Over the three years studied, LCLU changes in the Group B watersheds were similar, as no significant differences were found between them. Group C is made up only of the **Ita** watershed. In 1986, this watershed was similar to the more disturbed **Jac** and **Pic** watersheds. The level of disturbance in **Ita** however stabilized over time and its LCLU came to resemble Group B in 2001 and 2009. The **Ita** watershed thus evolved in a manner that is distinct from others. Group D, composed of the **Jac** and **Pir** watersheds, showed a rapid increase in anthropogenic classes since 1986. At the beginning of the study period, the area in anthropogenic classes was smaller when compared to the most disturbed watershed (**Ipa**), however the rate of change in the **Jac** and **Pir** watersheds was faster than in other groups. The difference between the Group D watersheds and the **Ipa** watershed decreased over time, until in 2009 when no difference was observed between them. Finally, Group E, made up solely of the **Ipa** basin, was significantly different than other groups, due to higher levels of disturbance, until 2009.

DISCUSSION

Evolution of LCLU at a regional scale

The general trends observed over the last three decades in the 11 watersheds under study include major losses in slightly altered old-growth forest cover and a corresponding increase in other classes: succession forest, crop land and pasture, and bare soil. Succession forest is the most common anthropogenic class of land use in all years studied and across all watersheds. This observation echoes the findings of Moran *et al.* (1994), in the Altamira region (south-west of Pará), reflecting the fact that family farming systems are based on temporary, subsistence crop cultivation, and require the regrowth of secondary vegetation so that cultivation can continue a given plot, after several years (Gutman *et al.* 2004). Slashing and burning of new areas is often necessary, as farmers in the region do not use chemical fertilizers, which would allow them to cultivate the same area for longer periods.

A number of LCLU changes studies have taken place in other frontier regions of colonization of the state of Pará. A study was conducted in the Altamira region by Moran *et al.* (1994) and another one in the Bragantina region (north-eastern Pará) by Watrin *et al.* (1998). These studies reveal the same general trends we observed, namely the reduction of slightly altered old-growth forest and increases in anthropogenic classes although the extent of change is different across regions. For example, slightly altered old-growth forest loss was limited in the Bragantina region, while losses were much larger in the Altamira region, and are even greater in the region covered by this study. This could be explained by the fact that Bragantina is one of the oldest regions of colonization in the Amazon. In this regard, Watrin *et al.* (1998) suggest that levels of deforestation were indeed greater when settlers first arrived, but has since stabilized over time. The evolution of LCLU for family farming follows the same general trend in the different regions of study, but seems to be offset in relation by the initial dates of colonization of a given area.

For the state of Pará, INPE (2010a) estimated that the average annual rate of deforestation between 1988 and 2000 was of 0.51%, while we found it to be of 0.87% for the region studied between 1986 and 2000. Between 2001 and 2009, the rate increases to 0.57% for Pará, while for the same period we measured a rate about three times as high of 1.48% in the study region for the same period revealing the extremely rapid rate of colonization. Furthermore, the INPE data exhibits increases in the rates of deforestation since 2002 in the state of Pará in general and specifically in the region studied. These rates reached a peak in 2004, a particularly devastating year throughout the Brazilian Amazon.

The evolution of LCLU at the watershed scale

With major changes in LCLU observed in the region over the last three decades, our statistical analyses demonstrate that there are important differences in the spatial and temporal LCLU patterns observed in the 11 watersheds, revealing complex and heterogeneous dynamics. This local scale reading of the evolution of LCLU highlights elements that would otherwise remain hidden in a regional scale analysis. For example, some watersheds have very low levels of disturbance over time, while others were subject to increased rates of disturbance, having undergone large transformations in LCLU since 1986. Based on the results of the statistical analyses, five main groups of watersheds were formed, based on similar LCLU changes.

There are a number of studies that highlight the influence of roads on the transformation of the Amazon forest. Roads offer access to new lands, which can then be cut and converted to crops or pastures (Chomitz and Gray 1996; Nepstad *et al.* 2001; Soares-Filho *et al.* 2004). Numerous researchers have also reported that high population numbers are related to the intensification of changes in nearby areas (Walker and Homma 1996; McCracken *et al.* 1999; DeFries *et al.* 2010). The presence of road and urban centers may explain, in part, the LCLU changes observed in the five groups of watersheds studied (Figure 6). Indeed, the highest levels of disturbance of the **Ipa** watershed (Group E) correspond to the fact that this watershed is located next to the Transamazonian highway and is in the vicinity of Itaituba, the largest city in the region. Since the beginning of the period studied, this watershed has shown disturbance patterns that distinguish it from the others considerably. It should be noted, however, that it did not show significant changes in LCLU throughout the period studied. This observation could be explained by the temporal limits of the study. Indeed, it is likely that the Transamazonian highway, built at the beginning of the 1970s, already had an impact on LCLU in this watershed prior to the study time frame. Similarly, the city of Itaituba had a population of nearly 62 000 inhabitants in 1970 and thus the impact of populations pressures in this watershed also likely predated the time period studied. It seems that on the whole, proximity to the highway and to the city may contribute to the unique evolution of LCLU observed in the **Ipa** watershed. This conclusion corroborates the findings of a pan-tropical study by DeFries *et al.* (2010), which highlights how already established population centers are a factor in determining increased deforestation rates.

The Group D watersheds, namely **Jac** and **Pir**, had significant changes in LCLU between 1986 and 2001. In 2009, higher levels of disturbance were measured, compared to past years, making LCLU in these watersheds similar to that of the **Ipa** watershed (Group E). The **Pir** watershed encompasses the sprawl area of the city of Itaituba, which again reinforces DeFries *et al.* (2010)'s observation that urbanization is a driver of deforestation. The **Jac** watershed is about 35 km upriver from the city of Itaituba but is nonetheless heavily influenced by the Transamazonian highway (Figure 6). The opening of this major roadway is likely to have contributed to increased deforestation of old growth forest by allowing new colonists to settle and practice subsistence farming.

The portion of anthropogenic classes in the **Pir** watershed is lower than in the **Ipa** watershed, even though both are close to Itaituba and the Transamazonian highway. While the disturbances in both watersheds were observed in the areas close proximity to the highway or the city, the difference in their evolution could be explained by the large size of the **Pir** watershed. Additionally, the anthropogenic disturbances intensified over time throughout the entire **Pir** watershed (Figure 7A). The evolution of the **Jac** watershed was also marked by extensive transformations in LCLU, despite it being farther from Itaituba than the **Pir** watershed. The high percentage of deforested area in the Pir watershed could be explained by the small size of this watershed run through by the Transamazonian highway.

As previously observed, the **Ita** watershed (Group C) shows lower levels of disturbance over time than the **Jac, Ipa** or **Pir** watersheds. Over the study period, the **Ita** watershed however underwent considerable LCLU change, which were likely catalyzed by the creation of the two largest roads of the

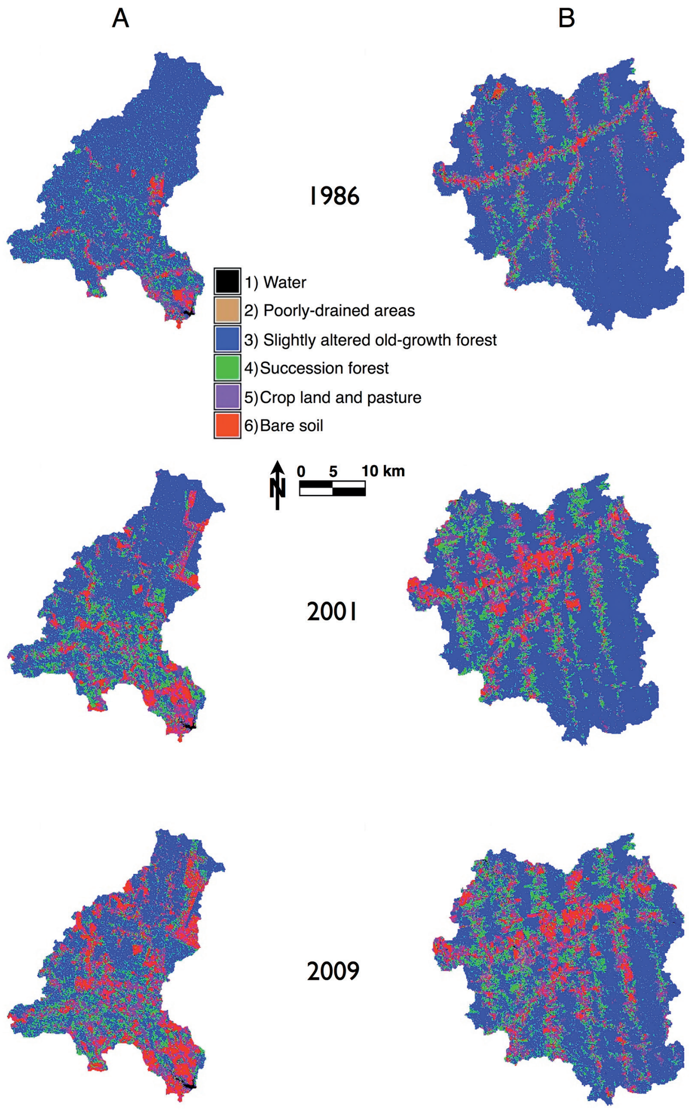

Figure 7. Evolution of land cover and land use in the Pir watershed (A) and in the Ita watershed (B). This figure is in color in the electronic version.

region (the Transamazonian and the BR-163) that extend through this watershed (Figure 6). Indeed, changes are mostly observed near the highways and the secondary roads that branch off (Figure 7B). Such land-use configurations around roads are indicative of planned settlements that were established during the colonization plan in the 1970s. The fact that the **Ita** watershed is far from one of the urban centers of the region may explain why the LCLU changes are less intense than those of the watersheds previously discussed.

In 1986, the Group B watersheds, **Ara, Bra, Cupu** and **Par**, exhibited limited disturbances. While changes became more significant over time, the levels of disturbances in these watersheds were however considerably lower than those in the previously discussed watersheds. This observation could first be linked to the fact that these four watersheds are not close to either of the major highways of the region. It seems possible that the areas underwent lower levels of change because they are farther from the infrastructures that allow access to and the subsequent conversion of lands. It should however be noted that there are secondary roads that are close to or in these watersheds. Furthermore, the lower level of changes could be due to the considerable distance between the **Ara, Cupu** and **Par** watersheds and any city or town. The **Bra** watershed however, is close to the smaller town of Brasilia Legal, which had over 550 inhabitants in 2004. It would seem that the proximity of the **Bra** watershed to an "urban" area is not related to increased LCLU changes when compared to the other watersheds in this group. The large size of the **Bra** watershed may have masked the effect of anthropogenic disturbances related to its proximity to the town of Brasilia Legal.

Finally, the Group A watersheds, namely **Cupa, Res** and **Tor**, underwent little LCLU change in 2009 and no significant differences were measured between the years studied. The **Res** and **Tor** watersheds are neither close to roadways nor to urban areas (Figure 6). It is also notable that these regions were outside the zones targeted by the colonization plan of the 1970s. The distance between these watersheds and major roads or urban centers very likely contributes to the lack of anthropogenic disturbance over the course of this study. The **Cupa** watershed is crossed by the Transamazonian highway and a multitude of its secondary roads (Figure 6), and is located 45 km from Ruropolis, a municipality with close to 40,100 inhabitants in the year 2010. While the combination of proximity to major roads and proximity to urban centers led to important changes in LCLU in the other watersheds studied, the situation appears to be inverted in the **Cupa** watershed. This is most probably due to the massive size of this watershed. Indeed while this watershed underwent extreme LCLU changes, however slightly altered old-growth forest cover is still the dominant class in terms of percent area. Consequently, the overall evolution of changes has been similar to that of the **Res** and **Tor** basins.

Although the factors "roadways" and "population centers" are factors that explain, in part, the temporal and spatial evolution of LCLU in watersheds, they alone cannot explain the differences observed in the study region. In this regard, Liverman *et al.* (1998) state that while many studies highlight the relationship between the intensity of LCLU changes roadways and populations, there are some limitations, notably not being able to account for the underlying and indirect causes of LCLU transitions. In addition, many elements can be related to the factors "roadways" and "population centers." For example, some studies have analyzed the impacts of the presence of populations while considering their rate of growth, their organization, and their density (Wood and Skole 1998; Carr 2004). These researchers demonstrated that all of these population indicators influence LCLU changes. Furthermore, it is possible to observe different impacts according to the nature of the roadways (primary or secondary), their frequency of use, and the populations that they serve (Nepstad *et al.* 2001; Laurance *et al.* 2002).

CONCLUSIONS

The analysis of 11 watersheds in the lower Tapajós region over a three decade period revealed that there have been drastic spatial and temporal differences in LCLU, highlighting dynamics that can only be observed at the local level rather than at the regional or global levels. The expansion of already established population centers is a dominant factor contributing to the increase in deforestation rates of nearby old-growth forest. Away from the sprawling urban areas, the opening, expansion or paving of roads trigger an increase in family farming activities, which in turn accelerates deforestation rates. While the Forestry Code, applicable to the entire Amazon since 1965, requires landowners to preserve 80% of the forest on their properties, none of the 11 watersheds studied comply to that code as of 2009. In fact, some watersheds have less than 50% forest cover. In order to properly manage forestry resources, measures should take into account the complexity and the diversity of local dynamics, such as those observed in this study.

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