Deforestation Hotspots in the Brazilian Amazon: Evidence and Causes as Assessed from Remote Sensing and Census Data

Nilson Clementino Ferreira,* Laerte Guimarães Ferreira, and Fausto Miziara

Image Processing and GIS Laboratory (LAPIG), Social and Environmental Studies Institute (IESA), Federal University of Goiás, Goiania, Brazil

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ABSTRACT: The main goal of this study, conducted in an area comprising 221 municipalities, in which 90% of the deforestation in the Legal Amazon takes place, was to understand the role of the agrarian structure in the conversion of forest into pasture and agriculture fields. Linear regression results indicate that 54%–62% of the variation in deforestation occurred between 1997 and 2004, respectively, and are explained as a function of changes in the amount of appropriated land in 1995. Likewise, up to 80% of the deforestation can be well explained by the variation in land concentration. In fact, strong spatial correlations were found between deforestation hotspots and land appropriation and land concentration. On the other hand, these critical areas have insufficient governance, particularly at the federal level. As the results of this study clearly demonstrate, strong governance and institutional integration, with emphasis on the territorial ordainment, are mandatory in order to reduce the rapid pace of deforestation in the Brazilian Amazon.

KEYWORDS: Deforestation hotspots; Spatial statistics; Land tenure structure

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* Corresponding author address: Nilson Clementino Ferreira, Image Processing and GIS Laboratory (LAPIG), Social and Environmental Studies Institute (IESA), Federal University of Goiás, Campus II, Cx. Postal 131, Goiania, Goiás, CEP 74001-970, Brazil.

E-mail address: ncferreira@uol.com.br

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1. Introduction

The Amazon region, due to its territorial dimensions, large fluvial system, and an extensive forest cover, has a major influence on global carbon exchange, energy balance, and climate regulation (Potter et al. 2001; Costa and Foley 2000; Houghton et al. 2000; Williams and Melack 1997). On the other hand, rapid changes in land cover, driven by governmental projects aimed to foster land occupation and economic activities, have been taking place in the Amazon ecosystems since the early 1970s (Skole et al. 1994). Interestingly, even after the boom of such initiatives and the adoption of environmental policies concerning the conservation of the natural resources in the 1990s, the pace of forest conversion did not decrease. In fact, clearcutting rates are continuously increasing, currently approaching nearly 2 Mha (million hectares) yr^{-1} (INPE 2000, unpublished manuscript).

Although these deforestations have been closely monitored since 1978 with the help of remote sensing technology (e.g., Skole and Tucker 1993), and significant attempts have been made in order to understand their causes and possible trends (e.g., Pfaff 1999; Alves et al. 2003), the relationship between deforestation and land tenure remains largely unexplained.

Within this context, and assuming that land appropriation is a major driving force behind deforestation, a major goal of this study was to understand, on a large-scale basis and through the integrated analysis of social and economical variables and deforestation data obtained via remote sensing imagery, the role of the land ownership structure on the Amazon deforestation. In particular, the deforestation distribution patterns along the years, and their spatial dependence on land appropriation, land concentration, and land use, were investigated. Likewise, the current institutional context (i.e., governance) of the Amazon region and its geographical relation to potential deforestation hotspots was also evaluated.

2. Study area

The area of study, encompassing 221 municipalities located in the forested portions of the Brazilian Amazon, corresponds to approximately 3.25 million km^2 (i.e., 81% of the Legal Amazon region), and is responsible for about 92% of all the deforestations that have occurred so far. Particularly important in choosing this area was also the availability of a complete time series of census data from 1970 to 1995 as well as deforestation data since 1997 (Figure 1).

The selected area, entirely located inside Brazil, is limited by six South American countries: Bolivia, Peru, Colombia, Venezuela, Guiana, and Suriname. The total population is around 9 378 787 people, from which about 73% are found in urban areas, while the remaining 27% live in rural areas.

Another important characteristic of the study area is the 879 023.22 km^2 of sustainable use and integral protection conservation units and indigenous land, which correspond to about 27% of the area under analysis and 63% of all the protected areas in the Legal Amazon.

Regarding land conversion, in 1997 it corresponded to 6.7% of the study area, while in 2004 it reached 10.31%. On average, the annual deforestation rate is about 17 800 km^2 (Figure 2).

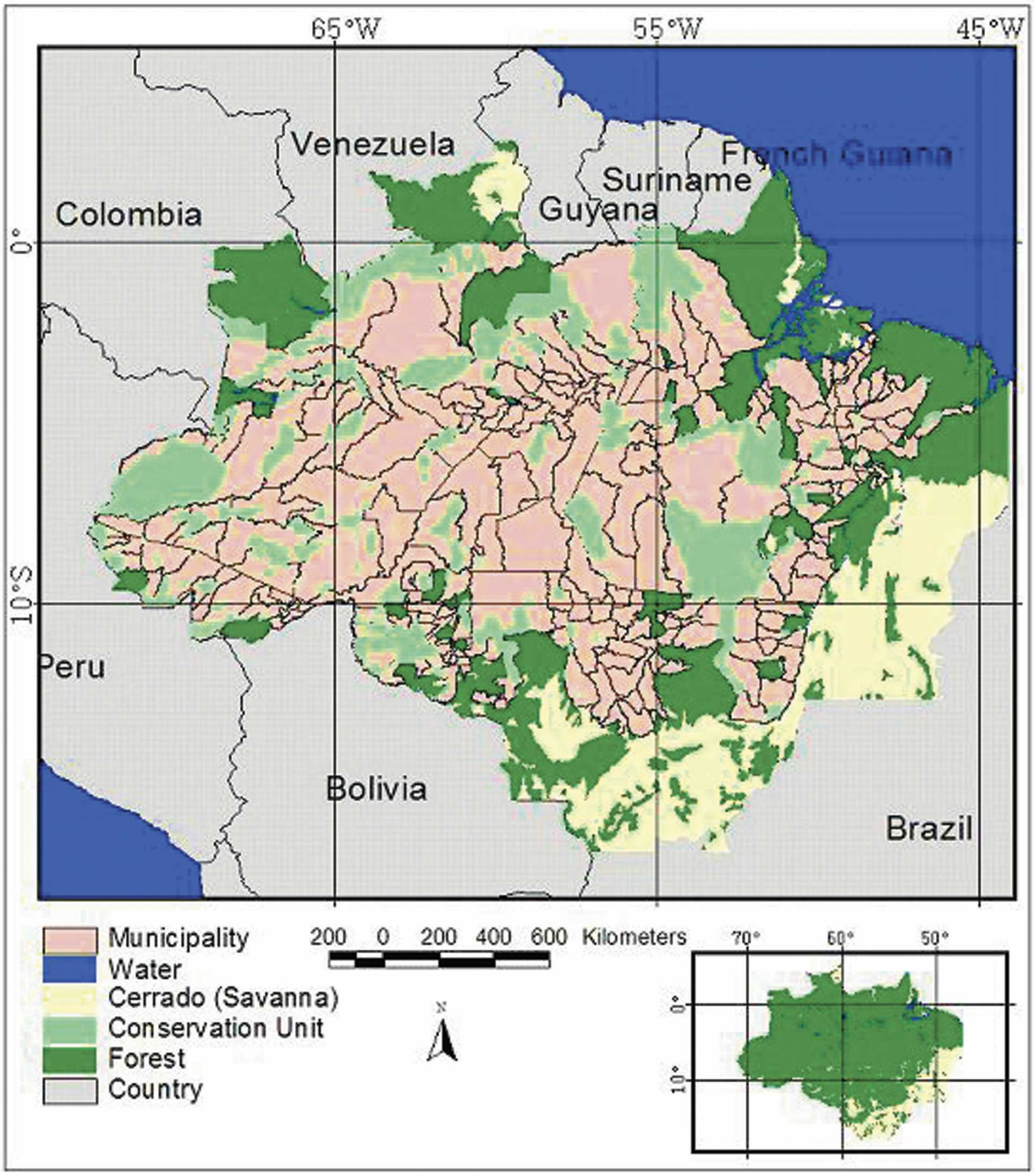

Figure 1. Study area and highlight of the 221 municipalities it comprises (shown in pink).

3. Data description

3.1. Deforestation data

The deforestation data utilized in this study were those obtained from the Brazilian Space Research Institute (INPE) Deforestation Monitoring Program (PRODES) and Detection in Real Time (DETER), and the Amazon Protection System (SIPAM) Integrated Warning Deforestation System (SIAD) initiatives.

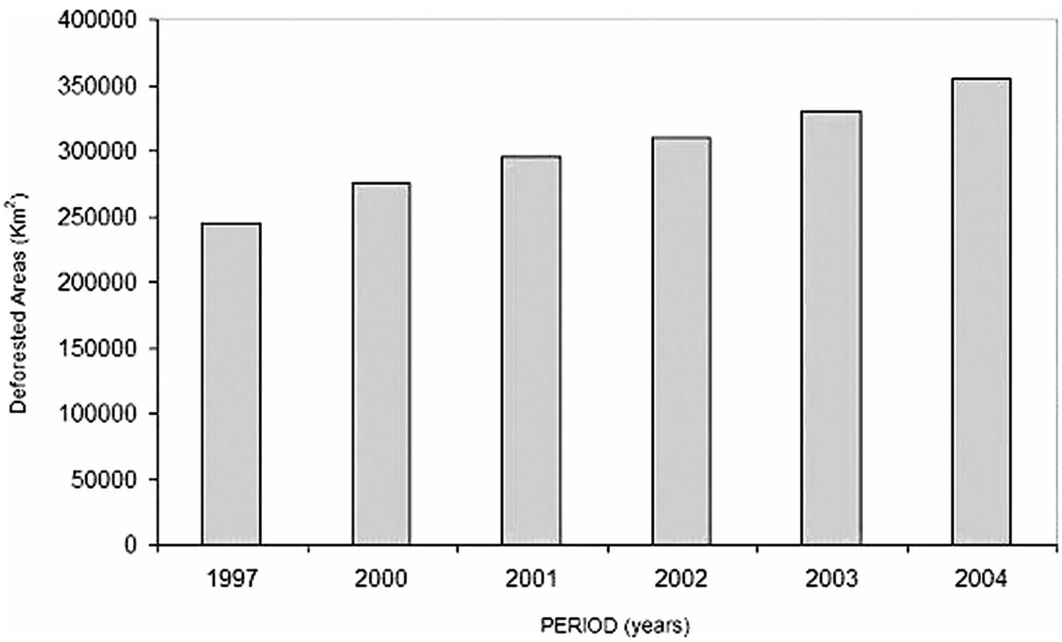

Figure 2. Deforestation in the study area between 1997 and 2004 (source: INPE/PRODES data).

The PRODES data, available in vector format for the year of 1997 and from 2000 through 2004, are based on Landsat imagery (Shimabukuro et al. 2000), while the DETER (Anderson et al. 2005) and the SIAD data (Ferreira et al. 2006), available since 2004, are based on Moderate Resolution Imaging Spectroradiometer (MODIS) 250-m reflectance-based endmembers and vegetation index images, respectively.

3.2. Census data

Information on land ownership (i.e., land owner or land occupant), agricultural revenue, and land use (cultivated and natural pastures, and temporary and permanent crops) was obtained from the agricultural and cattle-raising census data, and made available by the Brazilian Institute of Geography and Statistics (IBGE; www.ibge.gov.br) at the municipality level, for the period between 1970 and 1995.

Additional cartographical data, such as municipal limits, road network, map of conservation units, and location of public institutions [e.g., the Brazilian Institute of the Environment and Renewable Natural Resources (IBAMA), etc.] were obtained from the digital compilations prepared by the IBGE for the SIPAM.

4. Data analysis

The comprehensive thematic, cartographic, and census datasets were organized into a geographical information system (GIS) and integrated with the municipal

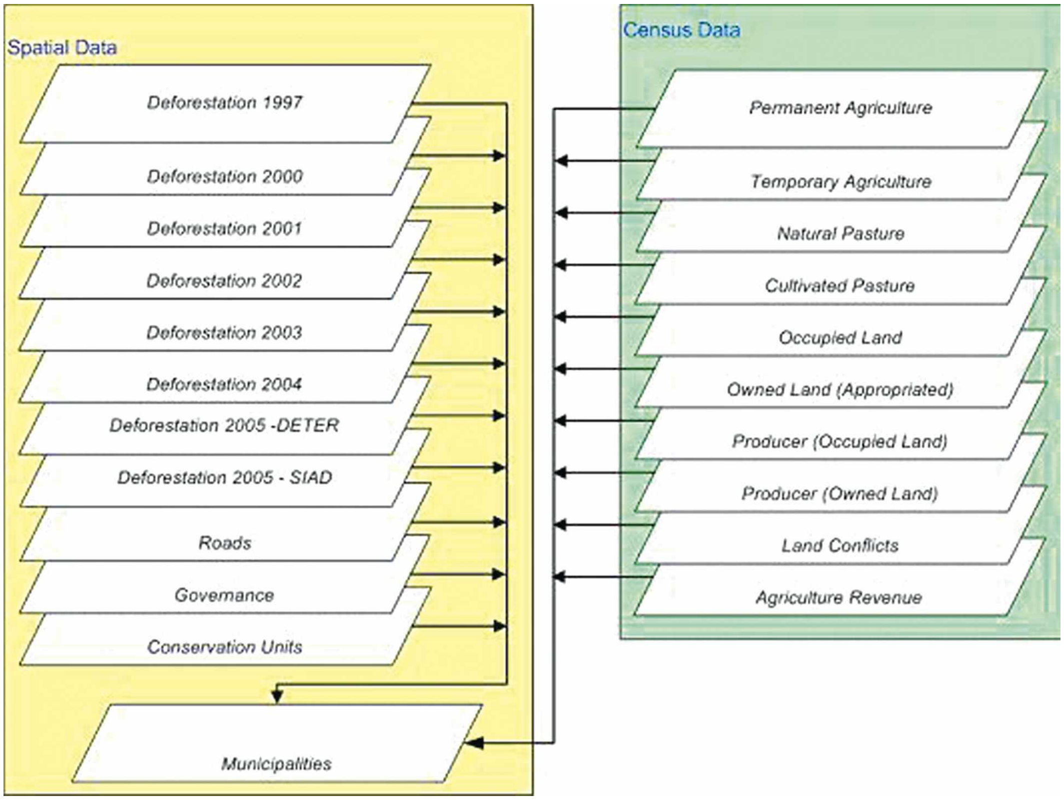

Figure 3. Integration data model regarding the cartographic, thematic, and census datasets.

layer in order to establish a common basis between deforestation, conservation units, institutions, and road maps with the spatialized social–economical variables (Figure 3). The main approaches and steps followed in this study are depicted in Figure 4.

The relationship between land appropriation and deforestation was assessed through linear regressions, taking into account only the percentage of appropriated land for each municipality not coincident with conservation units or Indian reserves. The deforestation and land appropriation amounts were also evaluated regarding the land use classes (e.g., natural and cultivated pastures, etc.).

The identification of critical areas (*hotspots)* concerning land concentration[1] and deforestation as well as the analysis of the respective spatial correlations was based on the use of the Getis–Ord measure, which identifies clusters of low and high values regarding local spatial associations (Getis and Ord 1992). The Getis–Ord approach can be described as a ratio between the summation of neighboring values

[1] The average land concentration for each municipality was obtained through the ratio between the appropriated area and the number of land owners.

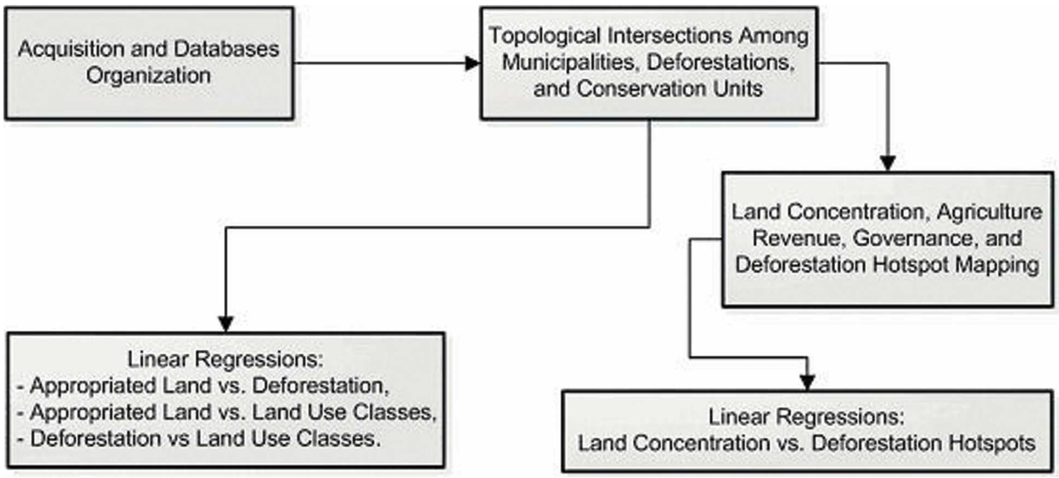

Figure 4. Flowchart diagram depicting the main approaches and steps in the present study.

in a certain area and the summation of all values in the sample, as shown in Equation (1):

$$G_i = \frac{\sum_j w_{ij}(d)x_j}{\sum_j x_j}, \tag{1}$$

where $w_{ij}(d)$ are the elements in the contiguity matrix for a distance d.

Hotspot maps were produced for land concentration and agricultural revenue, according to the 1995 agricultural census, governance, and the deforestation detected between 1997 and 2000, 2000 and 2001, 2001 and 2002, 2002 and 2003, and 2003 and 2004, based on Landsat imagery (i.e., PRODES initiative), and between 2004 and 2005 using the MODIS products (i.e., DETER and SIAD initiatives).

The correlation between deforestation and land concentration was estimated based on linear regressions of the respective G_i cluster values associated with each municipality.

The degree of governance in the study area was assessed through the IBAMA and Brazilian Institute of Colonization and Agrarian Reform (INCRA) offices that are in charge of conducting and enforcing the federal government environmental and agrarian reform policies, respectively, and the SIPAM communication network, located in a variety of governmental institutions and distributed all over the Brazilian Legal Amazon.

Specifically, the geographical area of influence of each institution branch/terminal, regardless of their jurisdictions, was mapped through a set of Thiessen polygons (Thiessen and Alter 1911; Gold 1991). The respective governance hotspots were determined based on the inverse of the area of these polygons.

5. Results and discussion

5.1. Land appropriation

In the study area, appropriated land (i.e., owned) predominates over occupied areas. As seen in Figure 5, this difference continuously increased since 1970. Interestingly, while the land appropriation showed a systematic and strong increment, the occupied areas varied much less and at a slower pace, suggesting that land appropriation, besides the replacement of small land occupants, occurs mainly on public pristine lands.

5.2. Land appropriation and deforestation

The relationships between land appropriation in 1995 and the accumulated deforestation in 1997, 2000, 2001, 2002, 2003, and 2004 are presented in Table 1. It is worthwhile to notice that the deforestation dependence on the appropriated land increases slightly from 1997 to 2004, as indicated by the r^2 values and the respective angular coefficients of the regression lines, indicating a certain time lag between variations in the agrarian structure and deforestation.

The spatialized regression residuals for the deforestations that occurred until 1997 are shown in Figure 6. As seen in this figure, deforestation behaves as predicted in 54% of the municipalities, that is, according to the variations in the

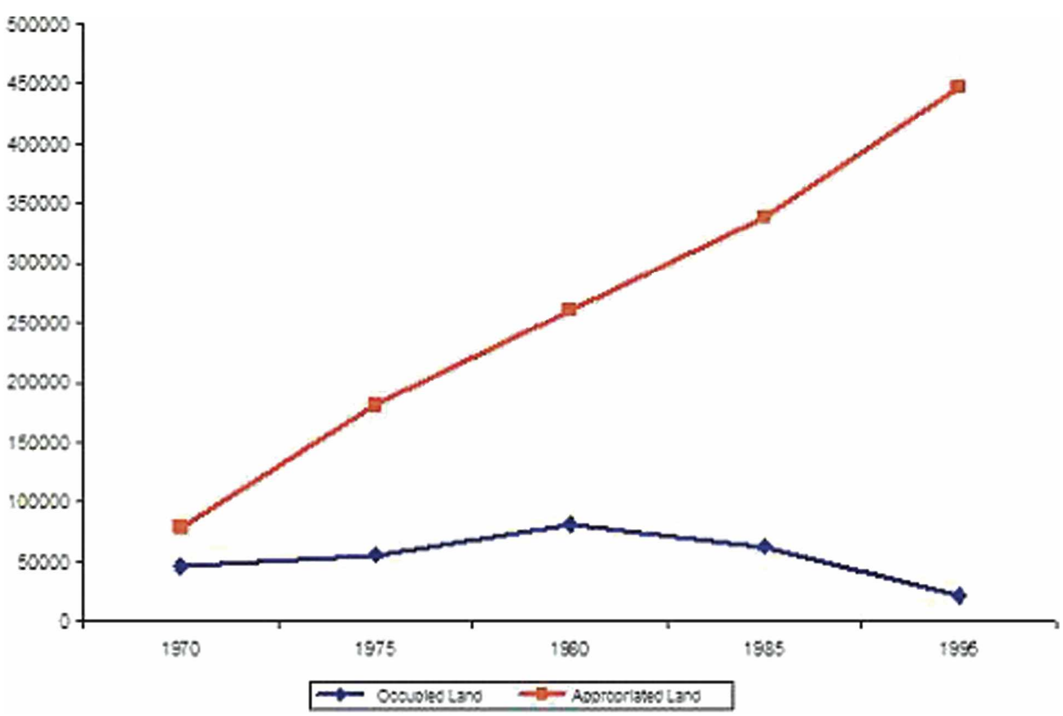

Figure 5. Evolution of appropriated and occupied land in the study area for the period between 1970 and 1995 (source: IBGE).

Table 1. Relationship between land appropriation (*x*) and accumulated deforestation (*y*).

Year	Model ($y = ax + b$)	r^2
1997	$y = 0.5278x + 0.0027$	0.5410
2000	$y = 0.6094x + 0.0016$	0.5888
2001	$y = 0.6237x + 0.0071$	0.5986
2002	$y = 0.6411x + 0.0096$	0.6067
2003	$y = 0.6564x + 0.0141$	0.6162
2004	$y = 0.6769x + 0.0203$	0.6255

land appropriation values, while only 2% of the samples behave as outliers in relation to the proposed model.

5.3. Land use, land appropriation, and deforestation

As observed in Table 2, deforestation and land appropriation are most strongly correlated to cultivated pastures. In fact, in relation to other land cover types, such as permanent crops, cultivated pastures demand fewer resources and infrastructure and are more easily consolidated.

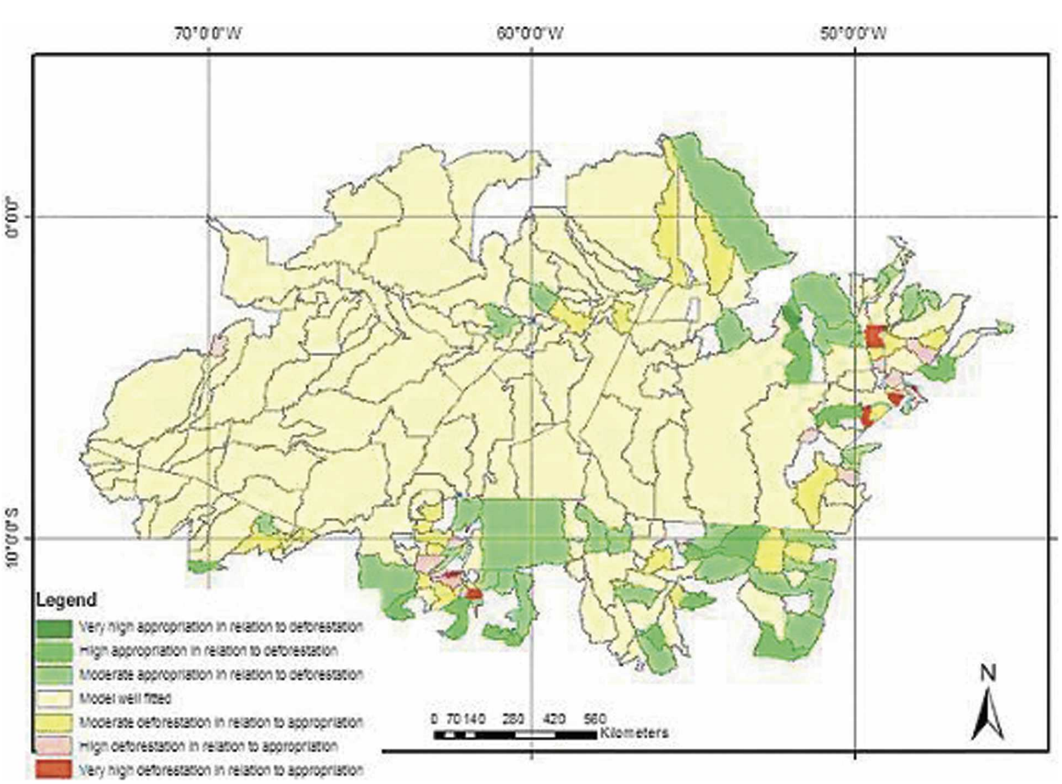

Figure 6. Residual map yielded by the regression model between land appropriation (1995) and the deforestation detected until 1997.

Table 2. Linear regression results regarding the correlations among land use, land appropriation, and deforestation

Land use (y) and land appropriation (x)		
Land use	Regression model $y = ax + b$	r^2
Permanent crops	$y = 0.0201x + 0.0011$	0.1079
Temporary crops	$y = 0.0316x + 0.0015$	0.0952
Native pastures	$y = 0.0427x + 0.0038$	0.1122
Cultivated pastures	$y = 0.3998x - 0.0288$	0.7757

Year	Deforestation (y) and temporary crops (x)		Deforestation (y) and cultivated pastures (x)	
1997	$y = 1.1529x + 0.1623$	$r^2 = 0.033$	$y = 1.0973x + 0.0475$	$r^2 = 0.605$
2000	$y = 1.3734x + 0.1923$	$r^2 = 0.036$	$y = 1.2888x + 0.0589$	$r^2 = 0.628$
2001	$y = 1.4115x + 0.2038$	$r^2 = 0.036$	$y = 1.3254x + 0.0654$	$r^2 = 0.630$
2002	$y = 1.4426x + 0.2129$	$r^2 = 0.036$	$y = 1.3686x + 0.0698$	$r^2 = 0.631$
2003	$y = 1.4824x + 0.223$	$r^2 = 0.036$	$y = 1.3996x + 0.0767$	$r^2 = 0.630$
2004	$y = 1.5417x + 0.2363$	$r^2 = 0.036$	$y = 1.4376x + 0.0863$	$r^2 = 0.623$

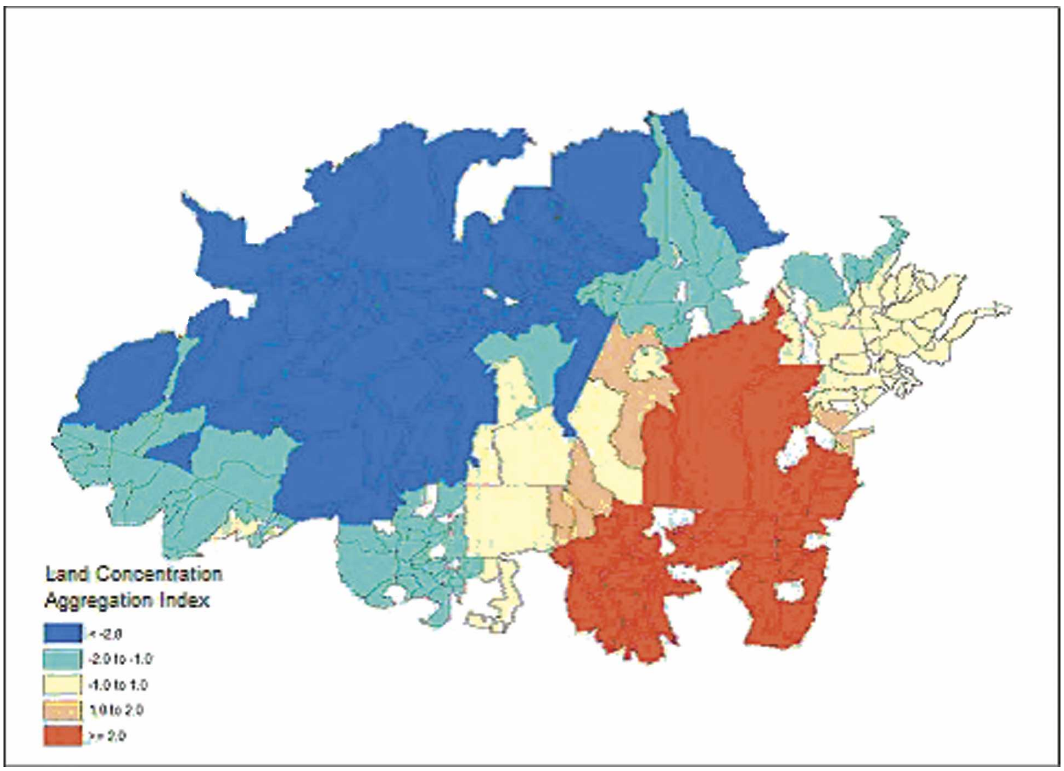

Figure 7. Hotspot map of land concentration, where municipalities with values equal to or greater than 2 (in red) are classified as hotspots, while municipalities with values equal to or smaller than −2 (in blue) are classified as coldspots.

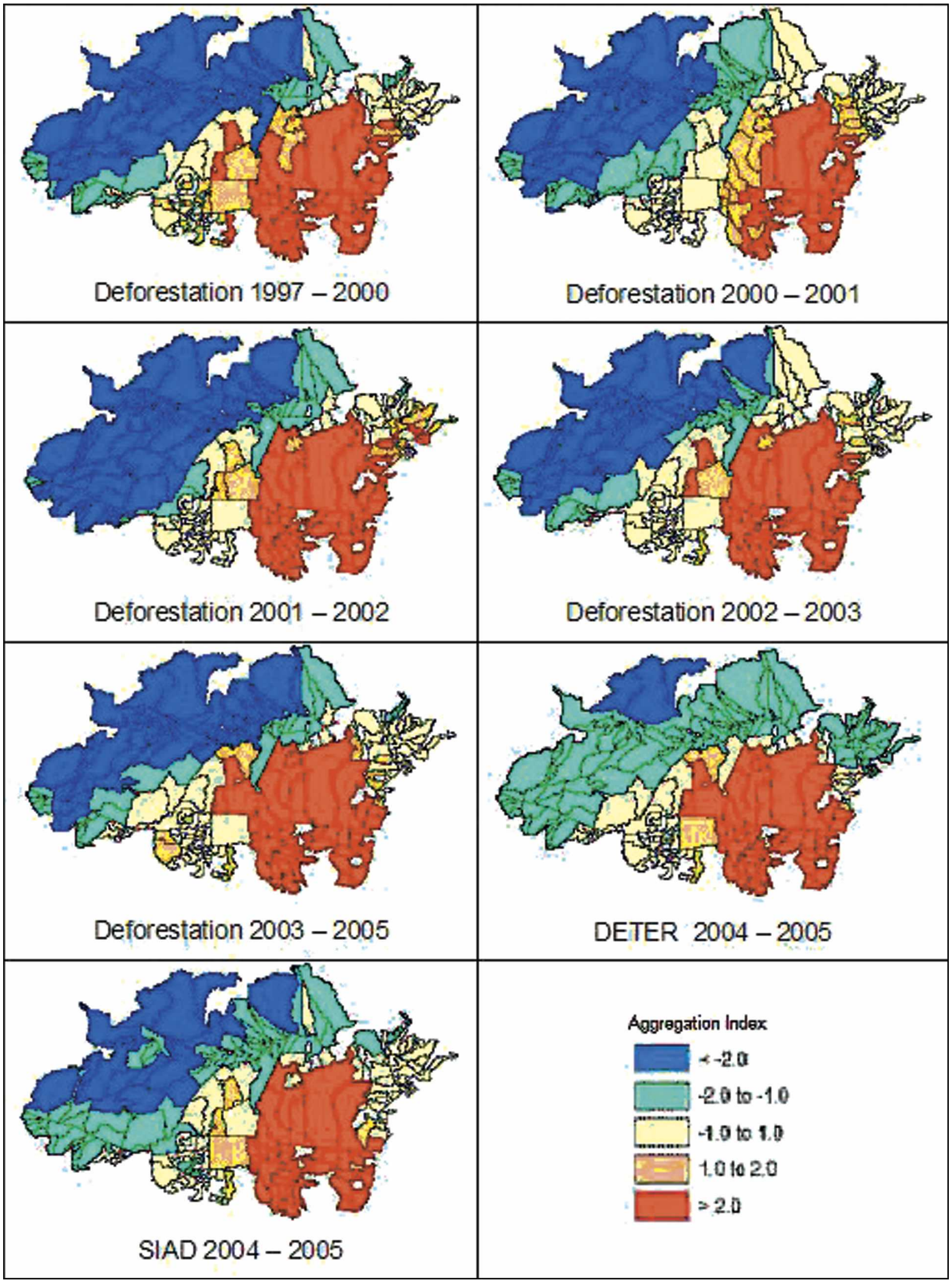

Figure 8. Deforestation hotspot maps, where the municipalities with values equal to or greater than 2 (in red) are classified as hotspots, while municipalities with values equal to or smaller than −2 (in blue) are classified as coldspots.

Table 3. Linear regression results between the land concentration (x) and deforestation (y) hotspot G_i cluster values.

Period	Model ($y = ax + b$)	r^2
1997–2000	$y = 0.7724x + 0.3835$	0.7188
2000–2001	$y = 0.6989x + 0.16$	0.7874
2001–2002	$y = 0.9826x + 0.3792$	0.8572
2002–2003	$y = 0.7095x + 0.248$	0.8029
2003–2004	$y = 0.7454x + 0.2903$	0.7341
2004–2005 DETER	$y = 0.6509x + 0.2372$	0.6753
2004–2005 SIAD	$y = 0.8024x + 0.2422$	0.7591

5.4. Land concentration and deforestation

A significant characteristic of the agrarian structure of the Brazilian Amazon is the size of the rural properties. In some areas, a small number of farmers own significant extensions of land. According to the 1995 IBGE agricultural census, the average land concentration in the nine Amazonian states is about 255% larger than in the other 18 states in Brazil.

The close dependence between land concentration and deforestation is confirmed by the hotspot analysis. In the map shown in Figure 7, it is possible to observe that the land concentration hotspot (areas in red) comprises 42 municipalities located in the state of Mato Grosso and in the southern region of the Pará State.

The hotspot maps regarding the deforestations that occurred between 1997 and 2000, 2000 and 2001, 2001 and 2002, 2002 and 2003, 2003 and 2004 (PRODES data), and 2004 and 2005 (DETER and SIAD data) are shown in Figure 8, while the correlation between deforestation and land concentration, according to the regression of the respective hotspot G_i values, is shown in Table 3.

The results depicted in Table 3 indicate a strong correlation between land concentration and deforestation; that is, areas with high land concentration are also likely to be more severely affected by deforestation.

Indeed, 48% of the deforestation detected in the study area for the period between 2000 and 2004 took place in 42 municipalities with a hotspot aggregation index equal to or greater than 2, while 75.8% of the deforestation was concentrated in the 94 municipalities with aggregation indices equal to or greater than −1 (Table 4).

The deforestation and land concentration hotspots are strongly correlated to

Table 4. Percentage of deforestation according to the hotspot G_i aggregation indices.

	Index > = 2 (42 municipalities)	Index > = −1 (94 municipalities)
2000	40% of the deforestation	70% of the deforestation
2001	50% of the deforestation	73% of the deforestation
2002	55% of the deforestation	84% of the deforestation
2003	49% of the deforestation	76% of the deforestation
2004	46% of the deforestation	76% of the deforestation
μ	48% of the deforestation	75.8% of the deforestation
σ	±5.52%	±5.21%

each other (Figures 7 and 8), as well as to the agricultural revenue hotspots (Figure 9). In other words, deforestation tends to be more prominent in rather productive and concentrated ownership regions.

5.5. Governance

Figure 10 shows the IBAMA hotspot map (see the area in red in the map). Overall, the IBAMA hotspots comprise 57 municipalities, which are responsible for only 2.05% of the deforestation occurring each year in the study area.

In relation to the INCRA offices, it was not possible to derive a hotspot map, as their locations are restricted to the state capitals. Alternatively, in Figure 11, each INCRA office is located over the land concentration hotspot map. The hotspot map of the SIPAM communication terminals, which play a key role in the institutional integration and represents the overall governance existent in the region, is shown in Figure 12. As observed with the IBAMA and INCRA offices, the hotspot map of the SIPAM communication terminals is poorly correlated to the deforestation and land concentration hotspot maps.

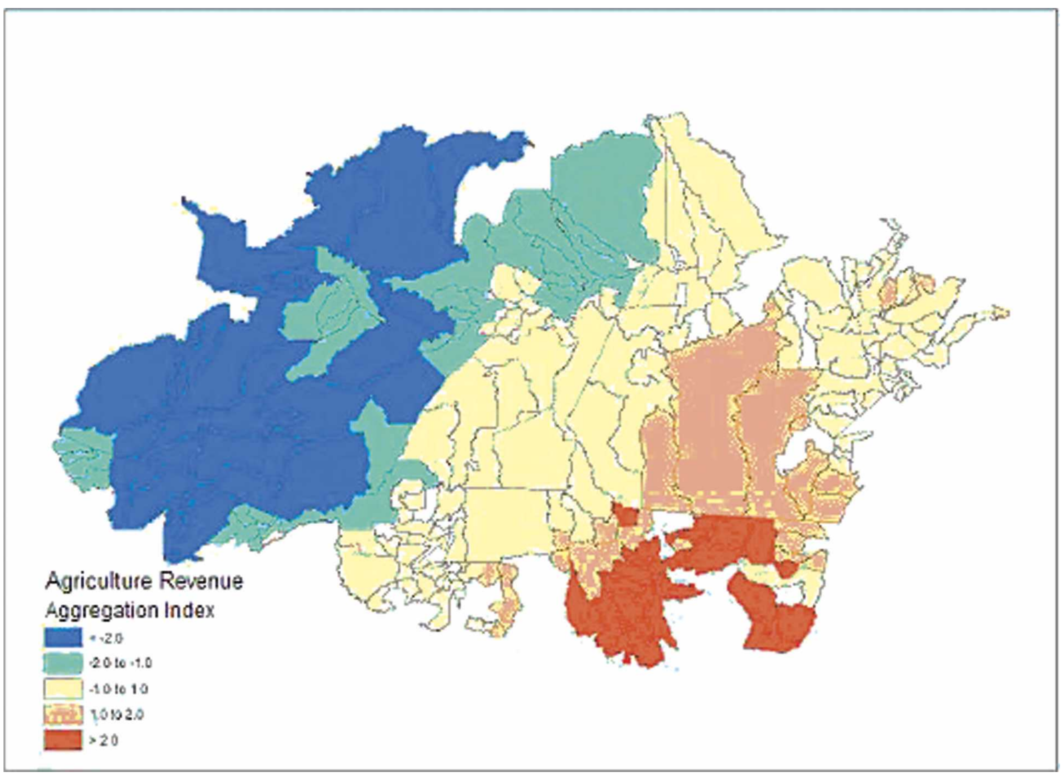

Figure 9. Agricultural revenue hotspot map, where the municipalities with values equal to or greater than 2 (in red) are classified as hotspots, while the municipalities with values equal to or smaller than −2 (in blue) are classified as coldspots.

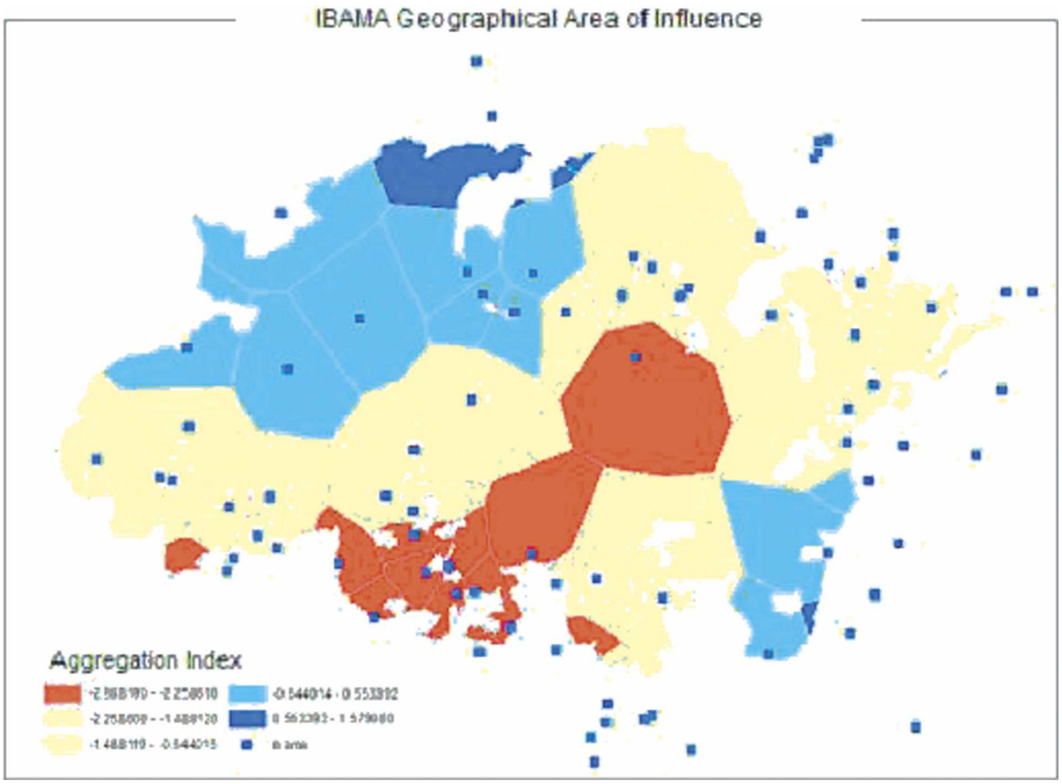

Figure 10. Hotspot map depicting the region of influence of the IBAMA in the area of study. Polygons with values equal to or smaller than −2 (in red) are classified as hotspots, while the polygons with values equal to or greater than 0.5 (in blue) are classified as coldspots.

6. Concluding remarks

In this paper, we evaluated remotely sensed deforestation data with respect to their social–economical and institutional context. According to our results, clear-cutting in the Amazon forest is strongly correlated to land use (mainly cultivated pastures), as well as to appropriated land and land concentration. In fact, 48% of the land conversions in the study area until 2004 have occurred in the 42 municipalities with the largest land concentration aggregation values (i.e., hotspot indices). Likewise, linear regression results, considering the land concentration and deforestation values inside the hotspots, indicated that up to 80% of the deforestation can be well explained by the variation in land concentration.

Thus, regions with agrarian situation dominated by large properties are more prone to further conversions. In addition, land concentration is also closely correlated to rural conflicts (Martins 1996). Indeed, in 2004, according to the Catholic Church Land Pastoral Commission, 118 conflicts and disputes (threats to life, violation of human rights, attempted murders, etc.), including 26 deaths and involving 13 398 families of land occupants, were registered in the area of study (CPT 2005).

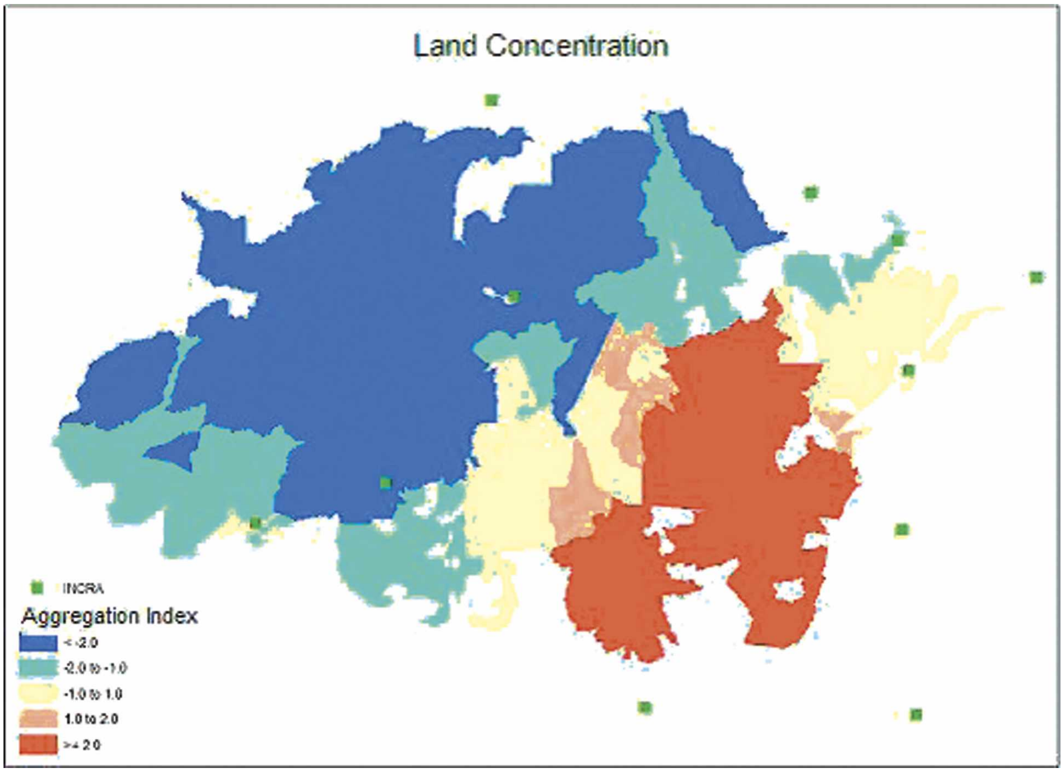

Figure 11. INCRA offices (green squares) located relative to the land concentration hotspot map.

On the other hand, the majority of the development projects carried out in the Amazon systematically oversees the role of the agrarian structure, which is a mandatory issue concerning deforestation monitoring, environmental licensing of rural properties, and regional territorial planning and ordainment.

In relation to the presence of the state, a primary requisite for the proper organization of the territory, forest preservation, and reduction of the violence is still highly variable, and in most cases, insufficient. For instance, INCRA, the government branch in charge of implementing the agrarian reform, has its presence in the study area restricted to the state capitals.

In relation to the IBAMA, the Brazilian federal environmental agency, its main area of influence corresponds to 57 municipalities, where annual deforestation is only about 2.05% of the total amount occurring in the entire study area. To circumvent this geographical limitation, the IBAMA carries out every year huge fiscalization operations with the use of cars, helicopters, planes, etc. A more feasible and efficient alternative would be to redistribute its offices, allocating them according to the deforestation hotspots.

Another aspect to be considered, of social dimension, regards the eviction of small farmers and occupants due to the appropriation of their lands by large landholders. With this respect, it is extremely important that both the government and nongovernmental organizations promote specific measures in order to assure

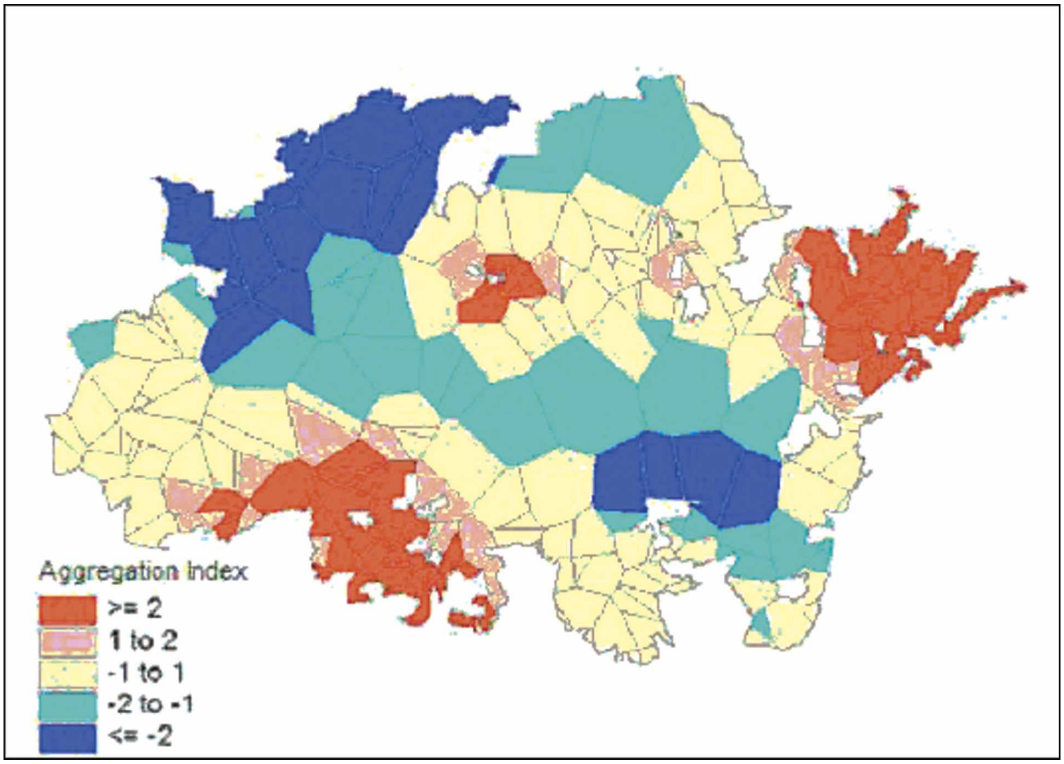

Figure 12. Hotspot map of the SIPAM communication network. Polygons with values equal to or greater than 2 (in red) are classified as hotspots, while the polygons with values equal to or greater than −2 (in blue) are classified as coldspots.

thousands of families their rights to the land. Such efforts may significantly contribute to reduce deforestation, as well as to minimize the serious social problems in the urban areas in Brazil.

It is also worthwhile to emphasize the role of territorial planning for a more sustainable land use and occupation in the Amazon. In fact, the severe clear-cutting detected by satellite imagery evidences the lack of institutional integration, through the sharing of data and information, and the absence of territorial policies and governance.

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