

Relating Change Patterns to Anthropogenic Processes to Assess Sustainability: A Case Study in Amazonia

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Abstract—This work focuses on identifying deforestation patterns and relating these to social processes in an extractive reserve of Acre (western Amazonia). Using multi-temporal satellite imagery deforestation is observed as a series of distinctive patches against the background of forest cover. The study of patterns emphasizes the important relationships existing between spatial patterns and social and spatially explicit processes. Since human processes are scale-dependant, a series of indexes were used to assess the structure, function, and change of the spatial distribution of patches at two different scale levels: global and regional. The global level analysis is concerned with the identification of patterns of land-use change in the entire reserve. The regional level analysis uncovers patterns by observing that local populations are organized in individual family groups occupying specific land areas here described as landscape units. Conclusions show that certain areas are being more deforested than others due to the synergic combination of different factors. This is leading to an unbalanced shift from an economy based solely on rubber extraction to other types of economy. This study can assist in determining development strategies for the reserves that take into account the different social and spatial patterns observed.

Introduction

The extractive reserves of Acre in the west of Brazilian Amazonia were conceived as part of a strategy for sustainable development, based on the extraction of renewable natural resources such as natural rubber, brazil nuts, oils, resins and fruits (Allegretti 1990, Almeida 1992). Such a strategy is considered necessary to act as a counter-balance to pressures for deforestation and cattle raising activities which have proved to be unsustainable. The study area selected for this study is the Sao Luis do Remanso Seringal (SLRS) located inside the Chico Mendes extractive reserve in the state of Acre. Compared to other areas of the reserve, the SLRS offers a “worst case” scenario in the study of land cover change and deforestation. The present study aims to analyse the dynamics of change operating in these remote areas over a certain time, namely between 1975 and 1989, a period where it is believed that deforestation in Amazonia was particularly intense due to public policies that stimulated the development of ‘new economic and agricultural’ frontiers.

Multi-temporal satellite images, from the Landsat MSS and TM sensors, were combined with the analytical capabilities of GIS to develop a methodology to measure, assess and monitor changes in the reserve landscape. Deforestation was observed as a series of

distinctive patches against the background of forest cover (fig. 1). The study of patterns described by patches emphasizes the important relationships existing between spatial patterns and spatially explicit processes, which in this particular case are of an anthropogenic nature. A

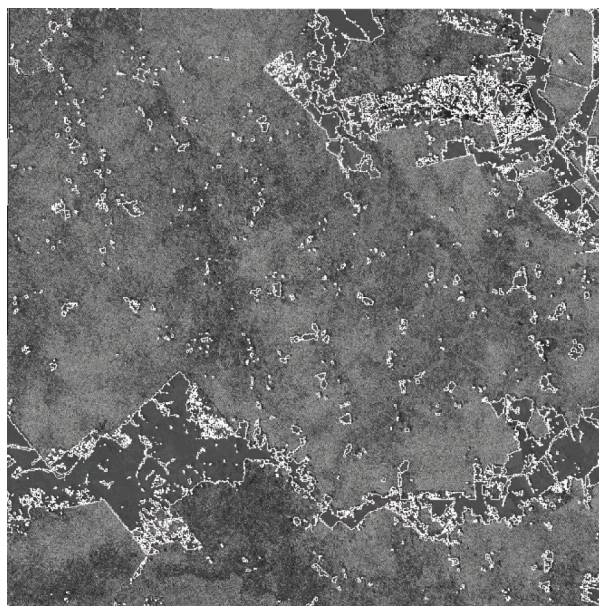


Figure 1. Landsat satellite image for 1989. Deforestation is seen as patches.

landscape ecology approach was adopted through the analysis of the relationships taking place between elements of the reserve's landscape and considering three main landscape characteristics: structure, function, and process. Human processes are scale-dependant. A series of indexes were used to assess the structure, function and processes of the spatial distribution of patches at three different scale levels: global, regional and local. For the purpose of this paper, only the global and regional levels are discussed.

The Global Level Analysis

The Global level analysis was carried out using the images available for the entire study area. The main objective of this analysis was to propose a series of indices to assess how the cleared patches identified were changing structurally over time, and to uncover patterns of spatial distribution of patches at different scales.

In that sense, three main indices were suggested:

- A Lacunarity index to assess patterns in the spatial distribution of patches at different scales and also to determine how gaps between cleared patches were changing over time.
- A Patchiness exponent to assess the distribution of patches according to their size.
- An Area-Perimeter Complicatedness exponent to assess drastic changes in patches' shape that might indicate changes in land use practices.

Lacunarity Index

The lacunarity indices were calculated for the raster data sets available for 1975, 1985, and 1989. In order to determine how the spatial distribution of clearings changed over time. This index is calculated by the use of a box size r that runs over the image, which previously converted into a binary map of forest and non-forest areas. The index calculates gaps between these two categories of cells. All binary maps had a grain size of 60 X 60 metres per cell. Lacunarity was calculated for $r = 5$ to 200 with an increment of box size of multiples of 5. Consequently, 40 lacunarity values were obtained for each map. Output was obtained as ASCII text files and imported into a spreadsheet where results were plotted on a log-log graph of lacunarity versus box size shown in figure 2.

Discussion and analysis of results

Higher lacunarity values denote heterogeneous and larger gap sizes, while bends in the lacunarity curves indicate more regularity in the spatial distribution and the range of gap sizes between patches. Lacunarity curves for the 1975, 1985, and 1989 data are straight, decreasing almost linearly until the lacunarity value of 1 is reached. Beyond this point, the curves bend slightly at $r = \ln 1.8$ for the 1975 and at $r = \ln 1.65$ for the 1985 and 1989 data sets (fig. 2) and the 1975 data presents the highest lacunarity values of all data analysed indicating larger gaps between patches for that period. However, at a box resolution of $r = \ln 1.5$, the 1989 lacunarity curve bends upwards exhibiting higher lacunarity values than the 1985 curve, indicating more heterogeneity between gaps for 1989 than for 1985.

At higher box resolutions the curves almost overlap and rapidly approach zero, indicating that while the number of cleared patches increases, the variance between gaps decreases.

Conclusions from Lacunarity Analysis

- The lacunarity index provided an insight as to how the cleared patches are spatially organised in the landscape. It was assumed that if gaps became more homogeneous at a given scale of observation, namely at 9 square km in average for all periods analysed, this reflected a specific pattern of spatial distribution due to social organization (family units) and land-use practices in the reserves. These results were, therefore, used

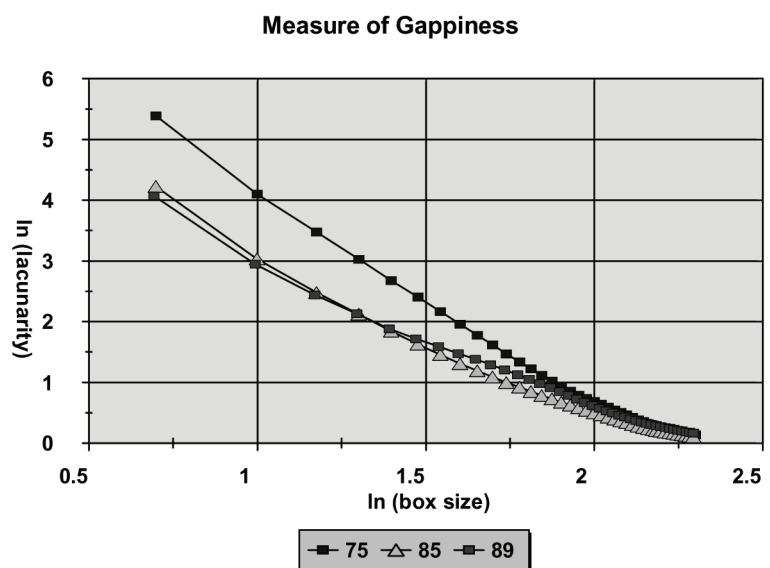


Figure 2. Lacunarity indices for 1975, 1985 and 1989 data.

to determine the extent at which to perform a more detailed analysis of the areas at a regional scale.

- Changes observed in the lacunarity indices of multi-temporal data provided a basis on which to assess changes in the spatial distribution of the cleared patches in the study area. The marked separation between the 1975 and the 1985 curves, suggests that between the mid 70s and mid 80s, the area was subjected to intense deforestation. The proximity of the 1985 and 1989 curves indicates that deforestation in the area of study during that period was not significant. However, higher lacunarity values for 1989 up from a scale extent of 6 square km ($r = \ln 1.5$) suggest that even though deforestation was not intense during that period, gaps between patches in 1989 became more varied than in 1985 due to the increment in size of some of the existing patches.

These results were considered to provide an insight on the temporal and scale dynamics operating in the deforestation process of the extractive reserves.

The Area-Perimeter Fractal Dimension Index

The fractal dimension index D describes how the quantity Q varies with scale. Q could represent the dimension of an area, perimeter, line, mass, etc. Usually, the fractal index is mathematically described by the equation,

$$Q(L) = L^D \quad (1)$$

where the exponent D represents the fractal dimension.

The use of the Area-Perimeter Fractal index in the global level analysis

In the context of the extractive reserves of Acre, patches with very complicated perimeters could be interpreted as representing a more or less “natural” habitat where rubber tappers are still involved in subsistence agriculture and depend largely on extractive activities for their survival. On the other hand, patches with regular edges (and usually greater in size) can be interpreted as being more significant in terms of agricultural practices and therefore, representing areas where there has been a shift from the traditional economic activities of extractivism to potentially more extensive clearings through agriculture and cattle ranching.

It is in that sense, the objectives of determining an Area-Perimeter Fractal index for the case study area are: to assess: drastic changes in patches’ perimeter (and extent) to identify shifts from an extractive-based economy to an agricultural-based economy over time and to determine similarities in economic practices by comparing fractal indices for the multitemporal data available

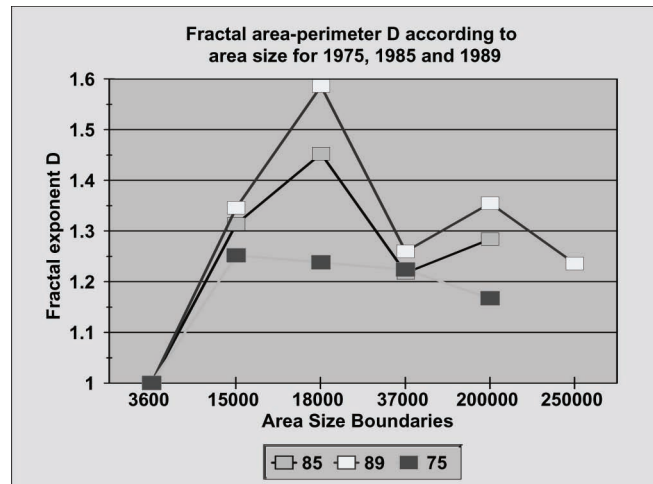


Figure 3. The Area-Perimeter Fractal index results for all periods.

Discussion of methodology and results

Data for this analysis was obtained by using a macro written in the Arc/Info programming language, AML, in order to export data on area size and perimeter length into ASCII text files for each period available. Calculation of the fractal indices was done in a QuattroPro spreadsheet by compiling data into groups of different area sizes, namely areas less or equal to 15,000, 18,000, 37,000, 200,000, and 250,000 square meters (fig.3). For the 1985 and the 1989 data, it was observed that patches with an area of less than 15,000 square meters (1.5 ha) presented low fractal indices, because these small areas tend to be composed of fewer pixels and present smooth edges. When area size increases from 15000 until 18000 square meters (1.8 ha), the fractal index increases considerably, suggesting complex patches’ perimeters and therefore, economic activities that resemble natural phenomena. At area size values of lower than 37,000 square meters (3.7 ha) the dimension D falls dramatically suggesting the presence of more rectangular edges characteristic of large mechanised agricultural plots. At higher area sizes, it was observed that the fractal index D increases slightly, showing evidence of new clearings adjacent to the larger patches that define slightly more complex perimeters.

Main Conclusions from the Global Level Analysis

Dynamics observed in the study area show land use changed in the reserve, mainly from a rubber based to a more agricultural based economy. Main deforestation processes occurred between 1975 and 1985, a period that coincided with the Brazilian military regimes. The decrease of gaps between cleared patches observed in the 1989 period can suggest the collapse of a future economy based in rubber extraction (table 1).

Table 1. Main conclusions of the global level analysis.

Objective	1975	1985	1989	Index used
Characteristics of gaps between patches	large and heterogeneous gaps due to sparse small patches	smaller gaps thus larger patches than in 1975, intense clearings during decade	not many new clearings, just increment of existing ones	Lacunarity
Patch shape as indications of predominant economic activities	more complex shapes at areas ≤ 18000 sqm, economy based in traditional extractive methods, patches of greater sizes seem to refer to more systematic and agricultural plot clearings with smooth geometric shapes.			Area-perimeter fractal index

Regional Level Analysis

While the global level analysis was concerned with the identification of patterns of land use change taking as a basis the entire study area, namely the Sao Luis do Remanso Seringal, a more localized level of analysis is presented underneath. The idea of examining patterns of land use change at a regional level is based on the observation that population in the extractive reserves is organized in individual family groups to which a certain extent of forest is allocated. The extent of forest used and the group's impact on it seems to vary according to three main criteria, such as are:

- number of economically active family members, reflected in the size and number of cleared patches
- accessibility to main transport routes from which goods can be traded and acquired
- main economic activities undertaken by each group i.e. rubber extraction or agricultural plots

Discussion of Methodology and Results

In order to define regional units of study, raster data on the Sao Luis do Remanso Seringal was subdivided into smaller sub-areas, here referred to as regional landscape units. The null hypothesis formulated in this analysis is that structural changes within and between pre-defined regional units were random. However, if patterns were identified, it was believed that these might reflect specific interrelationships between cleared patches and social processes that might explain how the study area is developing and changing at a regional level. In that sense, a complementary goal of performing a regional analysis is to locate spatially the occurrence of specific processes that describe how each one of these regions is changing over time. Furthermore, by grouping units that presented similar changes over time, spatial and temporal patterns of regional land use change were identified. This analysis was carried out in four main stages by:

- Defining the extent of regional landscape units.

- Determining regional key descriptor attributes.
- Determining a series of metrics based on spatial distribution of clearings, access to main transport routes and main land use activities. In fact, these metrics define the structural characteristics of each unit considered (Forman and Godron 1986). Metrics are tested towards their contribution to the analysis by a correlation matrix, whereby metrics considered not to offer additional information were discarded. With the use of a Principal Components Analysis technique, metrics were grouped into orthogonal composite factors
- By identifying spatio-temporal patterns of change at the regional level, units are grouped according to their similarity using a Nonhierarchical Cluster classification technique. Here, units are classified according to the intrinsic combination of the structural metrics considered in the Principal Components analysis. By categorising and mapping the classified clusters for all data periods available, the spatial location and "temporal evolution" of similar units was determined

Definition of the Extent of Regional Landscape Units

In the present case extent is considered as the size of the regional landscape unit on which to base the regional analysis. Due to the sparse nature of the spatial distribution of clearings observed in the study areas it was determined that each landscape unit should exceed the 1 km x 1 km extent recommended in the ITE Land Classification System for Great Britain (Haines-Young 1992).

One of the findings of the Lacunarity index used at the global level analysis was that cleared forest patches appeared less randomly distributed at a scale of 9 square kilometres for the 1975 data and at 12 square km for the 1989. This knowledge led to the formulation of the hypothesis that at that scale of observation, a specific pattern of social spatial organisation was observable in the region. To confirm these results, a complementary

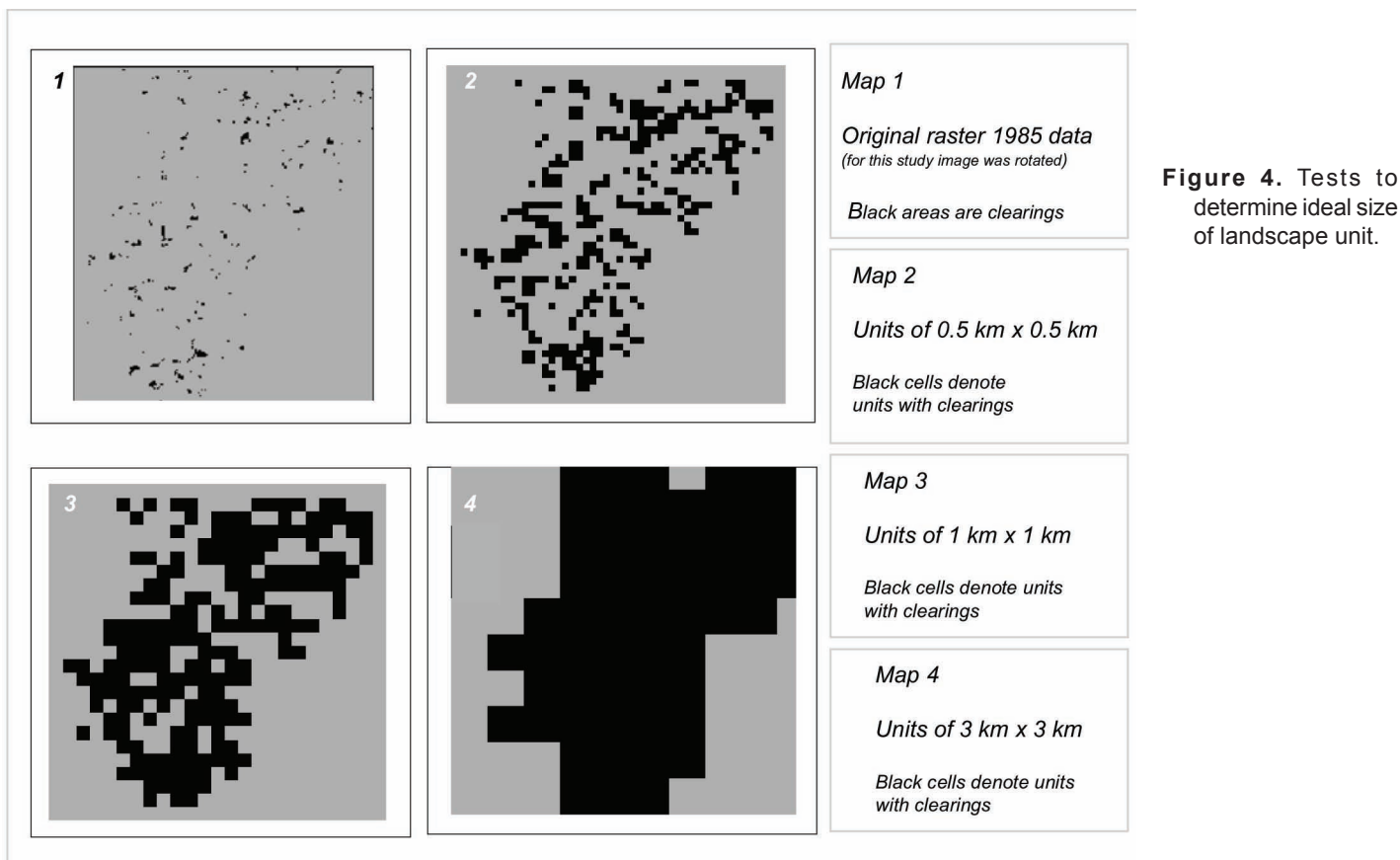


Figure 4. Tests to determine ideal size of landscape unit.

study to determine the extent of regional landscape units through the development of hierarchical binary maps was conducted using the analysis and programming capabilities of Arc/Info.

This process was only performed on one of the data sets, namely the 1985 data set, as a single unit extent would be applied to all the data sets available. The 1985 represented an intermediate period of data collection and, therefore, was believed to provide an average unit extent between all the data available. The analysis was conducted considering three scenarios, where the study areas were subdivided in units of approximately 3km x 3km, 1km x 1km and 0.5km x 0.5 km. In that sense, the final results were three raster maps with cells denoting the presence and absence of clearings at different analysis resolutions, presented in figure 4.

Determination of Key Descriptor Attributes of Regional Landscape Units

Key descriptor attributes were defined by considering the hypotheses drawn from the observation of the links operating at a regional level delineated in the conceptual model of the reserves. Descriptor attributes were defined in relation to four main characteristics: patch, patch distribution, patch accessibility, and patch shape. Within each

key descriptor attribute related structural attributes were considered (fig.5).

In order to extract the relevant key descriptor attributes from each landscape unit and to obtain these in a compatible format to be further analysed, the study was conducted using the Arc/ Info programming language, AML, in three main stages.

1. The study area was subdivided into the desired landscape units, namely 9 square kilometres.
2. Complementary programmes (.amls) were written to extract all relevant metrics from the data sets and write results into an ASCII text file.
3. Results were analysed through a Principal Components statistical method.

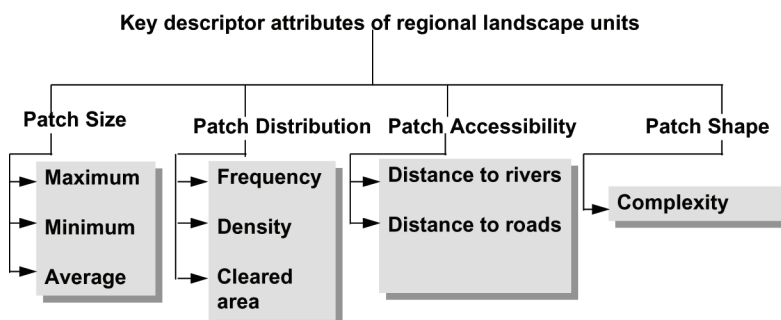


Figure 5. Structural Key Attributes considered at the Regional level analysis.

The Principal Components Analysis of the Variables Considered

Principal Components Analysis is a technique used for simplifying the information in a set of variables by identifying “principal components of variation” within the data. Results obtained from Principal Components analysis “re-describes” a given data set in terms of a smaller set of variables. So, components can be described as “composite variables” or “families” of relatively closely correlated variables. Thus, Principal Components Analysis identifies the similarities in spatial patterns or attributes of a data set, by “constructing new variables that are pair wise uncorrelated” (Mather 1976). Variables considered in PCA are assumed to be normally distributed where inter-correlated variables are grouped as new composite variables and are represented as orthogonal vectors in “theoretical space” where they are referred to as “eigenvalues.” Eigenvalues describe the percentage of variability within the total data set that can be “accounted for” or “described by” the component (Ebdon 1985, Johnston 1980). The first component is, therefore, the assemblage of variables that has the maximum variation when correlated to all other variables in the data set. The first principal component represents the most important axis of variation within the data set, but its strength depends on the particular variables included. Generally, most of the variation contained in the data set can be explained by the three first principal components.

The analysis provided NINE principal components, from which only the first three components presented eigenvalues greater than 1.0. The percentage variance explained by these three components was 87 percent for the 1975 data, 86 percent for the 1985 data and 83 percent for the 1989 data. Thus, Component I explained 36 percent of the variance for the 1975 data, 37 percent of the 1985 data, and 31 percent of the variance in the 1989 data. Components II explained around 28 percent

and Components III and IV explained 13 percent and 10 percent respectively for all data sets. Even though some variables scored highly in more than one component, it was assumed that variables would be considered as mainly contributing to the component where they exhibit the highest loadings. In that sense, a categorisation of each component was made possible.

In order to make comparisons between the results of the PCA obtained for all periods of the Sao Luis do Remanso Seringal possible, a within-group categorisation of the PCA loadings was attempted (table 2). This was done by selecting the highest loadings of each variable and establishing to which component it was allocated. Table 1 illustrates the results of this categorisation by highlighting, loadings that have a value of 0.6 or greater in the same component for the three periods analysed. In that sense, it was concluded that the Component I was composed of variables related to the size and impact of the cleared patches, so it was categorised as an “Intensity of clearing” indicator. Component II included variables related to frequency and density of clearings per landscape unit, therefore, it was identified as referring to “Spatial Distribution of patches”. Components III and IV related mainly to the shape of clearings through the fractal complicatedness index D, and to the location of the units in relationship to the main existing access routes. Therefore, Components III and IV were interpreted as reflecting categories of “Land use and accessibility.” However, low loadings observed for the variable Distance to Roads at all instances considered suggest that the presence of the BR317 running outside the reserve’s boundaries has not a really significant effect in the intensity, size and distribution of clearings. Nevertheless, it should be noted here that this observation refers only to clearings within the reserve’s boundaries, as the satellite images available (fig.1) show intensive deforestation in areas adjacent to the highway.

Table 2. Loadings and Categorization of components I, II, III, and IV for all periods for the Sao Luis do Remanso Seringal.

Variables	Component I			Component II			Component III			Component IV			C
	75	85	89	75	85	89	75	85	89	75	85	89	
AvgSize	-0.8	0.68	0.91	-0.5	0.63	0.06	0.17	0.02	0.03	-0.0	0.27	-0.1	I
MinSize	-0.7	-0.02	0.25	-0.5	0.76	0.63	0.19	0.38	-0.5	-0.0	-0.3	-0.1	
MaxSize	-0.9	0.85	0.75	-0.1	0.22	0.54	0.06	-0.1	-0.2	0.02	0.34	-0.1	
PerClear	-0.9	0.96	0.92	0.35	0.00	-0.2	0.00	-0.1	-0.1	0.11	0.15	0.0	
Freq	-0.4	0.73	0.35	0.88	-0.5	-0.9	-0.6	0.10	-0.1	0.09	-0.3	0.09	II
Density	-0.4	0.73	0.34	0.88	-0.5	-0.9	-0.1	0.10	-0.1	0.08	-0.3	0.06	
D_Compli	0.12	0.28	0.10	0.13	0.69	-0.0	0.83	0.39	0.54	-0.1	-0.3	-0.8	III/IV
DistRiv	0.23	0.06	0.31	-0.1	0.21	0.18	0.25	-0.7	0.69	0.9	-0.4	0.32	
DistRoa	0.22	0.02	-0.3	0.45	-0.5	-0.4	0.58	0.57	-0.3	-0.2	0.09	-0.5	

Main Conclusions from the PCA in Relationship to Spatial Dynamics in the SLRS

It is considered that the PCA offers an understanding of the main sources of variance between the structural characteristics of cleared patches within the units analysed. Conclusions from this study are that the regional landscape units defined for the Sao Luis do Remanso Seringal study present high variability (differences) when analysed in terms of the “intensity of clearings,” followed closely by attributes related to the “spatial distribution of their cleared patches” and are less affected by categories reflecting “Land use and accessibility.”

The multitemporal comparison of the components results serves as an exploratory tool to formulate hypothesis related to the processes involved in regional land use change within the units of study, suggesting for example that in 1985, the variation between the patches’ size and shape was more affected by its accessibility i.e. greater patches were located near rivers, whilst for the 1975 and 1989 data, the patches’ shape was more related to its accessibility and was independent from the patches numbers and spatial distribution.

Regional Landscape Change Patterns in the SLRS

In order to better relate the PCA results with landscape change patterns in the extractive reserves, these were grouped into clusters according to the similar combination of components scores. As a result, landscape units were mapped according to a cluster membership, determined by a value ranging from 1 until 5 (fig. 6). The description of the each cluster membership is described in table 3.

This mapping process uncovered spatial patterns formed by the distribution of similar regional units within the SLRS context. These patterns were not obvious from the observation of the raw image data and are considered relevant to define areas of critical sensitivity to deforestation and to provide understanding as to how similar areas are connected or isolated.

Results were interpreted following basic criteria, namely, by taking into consideration the number of units that were assigned to each cluster for each period of study. In that sense, it was determined that for 1975, units that presented small cleared patches and sparse distribution were dominant. By 1985, units that presented small clearings were still more common, however, a substantial increment in units presenting large cleared patches is observed. By 1989, the great majority of units presented

large cleared patches sparsely distributed across each unit, indicating that clearings became widespread in the entire Sao Luis do Remanso Seringal context. When performing a spatial analysis of the clustered units with the GIS system, the following results were obtained for each year of study.

Conclusions

The general conclusion drawn from this study is that the reserve’s landscape was dominated by small and numerous patches in 1975, which by 1989 had become dominated by large and sparsely distributed patches. This provided evidence of the disappearance of small clearings or the clumping of existing clearings between 1975 and 1989.

At a regional level, it was established that regions of the SLRS were being affected differently by deforestation and that this phenomena reflected social and economic processes taking place in the area. Two main processes responsible for the different regional deforestation patterns were identified and are described below:

1. Two main poles of deforestation located at the south and the north-west of the study area were determined.

A cluster of regional units that suffered the greater deforestation was located towards the south-east of the study area in the proximity of the BR317 highway. A second area where considerable deforestation was observed, though not as extensive as the previous one, was identified in the north-west of the reserve, near the confluence of the Acre River and one of its main tributaries. This evidence shows a pattern of greater deforestation linked to the presence of main access routes, suggesting that these are the main regions from where populations are gaining access into the area.

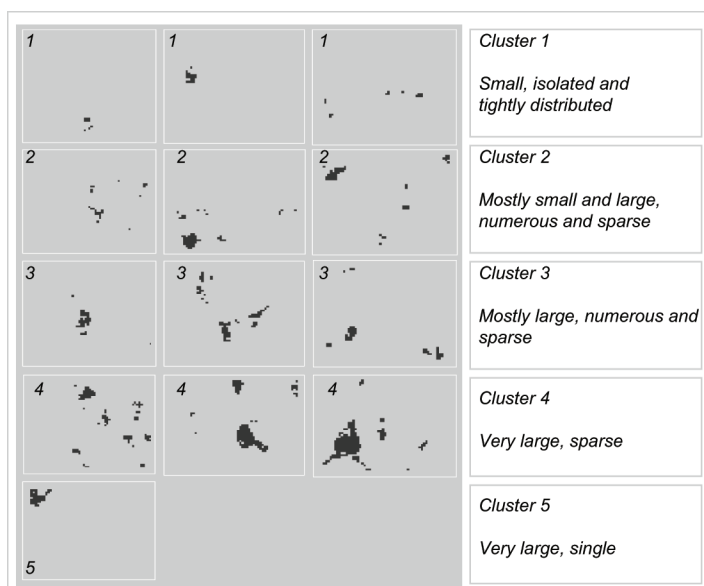
2. The main direction of deforestation of the reserve was determined as originating from the main highway into the forest interior.

By observing the spatial distribution of clusters for the three periods considered (fig. 7) it was observed that units seem to suffer a more dramatic deforestation in the direction away from the main highway into the reserve’s interior, whilst units located inside the reserve seem not to change as dramatically through time. In that sense, the main deforestation direction was established to be from the south-east to the north-west of the SLRS. At the south-east of the study area runs the BR317 highway.

The main conclusion from this analysis is that the BR317 highway seems to encourage greater deforestation than the presence of main rivers in the area.

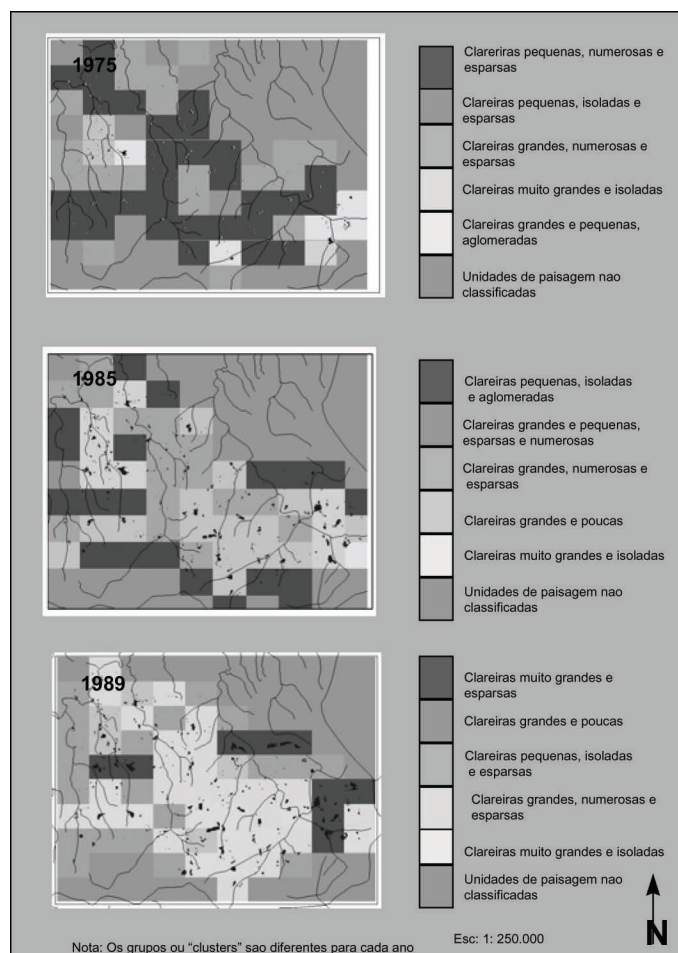
Table 3. Description of cluster categorisation for each period.

Categorisation of clusters by year						
Clusters	1975	tot	1985	tot	1989	tot
1	Small patches, high density and sparsely distributed	29	Small patches, low density, tightly distributed	21	Dominated by very large patches, sparsely distributed.	9
2	Small patches, low density and sparsely distributed	19	Dominated by small patches with some large patches, high density and sparsely distributed	16	Large patches very sparsely distributed	20
3	Dominated by large patches, high density and sparsely distributed	2	Dominated by large patches, high density and sparsely distributed	14	Small and large patches, high density and sparsely distributed	5
4	Very large single patch	1	Very large patches sparsely distributed	8	Large patches, high density and sparsely distributed	22
5	Dominated by large patches, low density and tightly distributed	5	Very large single patch	1	Large patches, low density and tightly distributed	10
Total		56		60		66

**Figure 6.** Sample of clusters categories for the 1985 period.

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**Figure 7.** Spatial land use change patterns obtained for each period.

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