Deforestation and Local Sustainable Development in Brazilian Legal Amazonia: An Exploratory Analysis

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ABSTRACT. This paper presents an exploratory analysis of socioeconomic and demographic patterns of small and medium-sized (in terms of population) municipalities in the "deforestation arc" of Legal Amazonia[1], Brazil. Using Principal Component Analysis (PCA) and Cluster Analysis (Two-Step-Cluster), this study explores 25 variables for 211 municipalities. In the PCA, these variables were reduced to five independent components (named *development, forest, size, growth and stagnation*), which explain around 73% of the total variability of the original database. Thereafter, the cluster analysis identified four groups, which present a well-defined spatial distribution pattern in terms of localization and contiguity. The multiple results demonstrate that the associations among *development* and *forest* components depend on the historic advance of the economic activities in the deforestation arc, as well as the territorial characteristics and spatial location of the municipalities. In addition, *size*, *growth* and *stagnation* provide relevant complementary information for understanding the sustainable development dynamics in Legal Amazonia. Finally, the paper further explores implications for public policies seeking local sustainable development in the region.
Key words: Amazonia, Deforestation, Local Sustainable Development, Multivariate Methods, Public Policies.

INTRODUCTION

The IPCC (Intergovernmental Panel on Climate Change) *Fifth Assessment Report* demonstrated that the second major source of human CO_2 emissions in 2013 came from deforestation and forest degradation, which were responsible for over 10% of the world´s greenhouse gas (GHG) emissions and were concentrated in tropical areas (IPCC 2014). These findings have supported a growing interest among the international community to hold developed countries more responsible, while also encouraging developing nations to contribute to mitigation in the forest sector (Chakravarty *et al.* 2012; Busch and Ferretti-Gallon 2014). In fact, the preservation of the tropical forests is particularly important given its potential contribution to mitigate the impacts of climate change (Busch and Ferretti-Gallon 2014) and the dreadful regional consequences of deforestation and forest degradation (Nobre *et al.* 2009).

In this context, REDD+ (Reducing Emissions from Deforestation and Forest Degradation and Enhancement of Carbon Stocks) has developed partnerships to disseminate knowledge and gather funds to subsidize forest protection initiatives in developing countries (REDD+ 2008; Angelsen 2012; UN-REDD 2015). Brazil is considered a key partner by REDD+[2] not only for hosting one-third of the current world´s rainforests (413.152 km^2), including 65% of the largest tropical forest in the world (INPE 2014), but also for its potential funding initiatives and capacity to further south-south cooperation. In addition, the ecological effects of deforestation in Brazil are potentially large and the global climate system might be significantly affected (Hougton *et al.* 2001; Soares-Filho 2006).

Deforestation and land degradation in Legal Amazonia are at the heart of the Brazilian efforts to mitigate climate change in the forestry sector. In 2004, the Brazilian government

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launched the National Action Plan for Prevention and Control of Legal Amazonia Deforestation (PPCDAm), which established strategies for three main areas: 1. monitoring and environmental control; 2. land tenure regulations; and 3. sustainable development. Assunção *et al.* (2012) have estimated that between 2005 and 2009 the PPCDAm policies avoided 27% to 62% of deforested area, which represents 270 to 621 CO^2 tons in the atmosphere. Based on these satisfactory results, the Brazilian government in 2009 has set an ambitious target to reduce deforestation by 80% below the historical baseline (19,500 km^2 per year) by 2020 (BRASIL 2009). The success of the Brazilian policies to protect Amazonia is also present in studies that highlight the monitoring enhancement and the Deforestation Detection System (DETER) implemented in 2004 (INPE 2015), the recent expansion of indigenous reserves and protected areas (Soares-Filho *et al.* 2010; Pfaff *et al.* 2015), the enforcement of logging laws (UCS 2011) and the partnerships with NGOs and the private sector (Green Peace 2009).

In Legal Amazonia, INPE (National Institute for Spatial Research) registered in 2014 a deforestation rate 5.54 times lower than was observed 10 years ago (INPE 2014). According to Nepstad *et al.* (2009, p. 1350), due to international pressure and the current reduction of deforestation rates, the end of deforestation in the Brazilian Amazonia is finally feasible and "could result in a 2 to 5% reduction in global carbon emissions". However, there is no guarantee it will be a definitive pattern. IPEA *et al.* (2011) reveals that the most effective actions of PPCDAm were focused on environmental monitoring and control, and actions that should ensure a durable reduction of deforestation have not occurred at a satisfactory effectiveness level. Furthermore, during the 2000s, the rate of deforestation in Amazonia was closely related to price variations of meat and soy in the international market (Hargrave and Kis-katos 2003; Macedo *et al.* 2011), and there was a strong correlation between the availability of agricultural credit and deforestation rates in Legal Amazonia (Andersen 1996; Barreto *et al.* 2009; Assunção *et al.* 2013). Despite the Brazilian efforts in the past decade, these studies suggest that the deforestation pace in Amazonia is still dangerously related to economic investment oscillations.

Mitigation and REDD+ success in Legal Amazonia depend on policies that take into account cross-scale interaction, multisector involvement, bottom-up approaches and local participation. Cross-scale interaction is a key requirement to face deforestation in Legal Amazonia and, for optimum results, the private sector, the government and civil society should work in harmony to establish goals regionally and locally (Sandbrook *et al.* 2010; Korhonen-Kurki *et al.* 2012; Sathler 2014). The lack of coordination among these stakeholders can hinder REDD+ governance in Brazil (Gebara *et al.* 2014). In addition, it is also important to stimulate the involvement of traditional communities by considering community-based forest management (CBFM) as part of a set of bottom-up strategies to protect the forest (Agrawal *et al.* 2008; Danielsen *et al.* 2010; 2013).

The design and implementation of these arrangements must be accompanied by local sustainable development. Otherwise, the protection of the forest will always require a lot of energy and an undefined amount of financial resources. According to Mer *et al.* (2011), preserving the integrity of the Amazonian biome, while promoting local sustainable development, is a key challenge for the global strategy to mitigate climate change and it is indispensable for the regional and local ecological equilibrium. Local sustainable development requires economic, social and environmental policies, as well as social engagement, knowledge and long- and short-term planning (Steurer 2010; Jacob *et al.* 2013). Initiatives that combine all of these elements can contribute to strengthen local capacities to face deforestation and forest degradation in the region. Moreover, the local level environmental changes in Legal Amazonia, especially in the hydrological cycle, surface temperature and length of dry season (Findell *et al.* 2006; Killem and Solórzano 2008; Nobre *et al.* 2009; Shukla *et al.* 2015), made it clear that there is a need for local solutions, which will have to be exponentially replicated in order to have a positive impact on regional and global scales.

In 2008, the federal government launched the Sustainable Amazonia Plan (PAS) that proposed an integrated set of guidelines to guarantee sustainable development in Legal Amazonia. It incorporated many strategic policies at the state level and these might affect sustainable development at the local level. However, municipalities of Legal Amazonia are not deeply involved in projects for promoting sustainable development and the preservation of the forest, and initiatives has spread more through top-down policies (PAS and PPCDAm) than through local interventions in Legal Amazonia.

Furthermore, assessing socioeconomic, demographic and environmental changes are fundamental to support the implementation of public policies that will take into account regional and local sustainable development in Legal Amazonia. In this context, several studies have contributed to understand the levels of poverty, inequality and social vulnerability in the region (Pinedo-Vasquez *et al.* 2001; Sears *et al.* 2007; Mangabeira 2010; Calentano and Vedoveto 2011; Guedes *et al.* 2012) and to explain the interactions between deforestation and socioeconomic patterns in Legal Amazonia (Rodrigues *et al.* 2009; Calentano *et al.* 2012).

Assessments should consider not only the larger cities and the most important regional centers, but also the small and medium-sized (in terms of population) municipalities, highlighting their demographic, socioeconomic and spatial specificities. Generally, small and medium-sized municipalities have distinct functions, synergies and capacities to produce social and environmental changes in both urban and rural areas when compared to municipalities that host cities at a higher level in the urban hierarchy. Many small and medium-sized municipalities in Legal Amazonia face serious environmental and social changes, as they serve as logistics bases to huge agro-industrial and mining projects, ensuring the frontier expansion and the internalization of economic activities. Public investments and the expansion of economic activities in these municipalities have caused important regional differences in their socioeconomic and demographic indicators. However, the links between deforestation and local sustainable development in the small and medium-sized Amazonian municipalities are understudied. In order to contribute to this debate, this paper brings an exploratory spatial analysis of environmental, socioeconomic and demographic patterns of small and medium-sized municipalities in the deforestation arc. The empirical analysis investigates the spatial patterns of deforestation and a set of variables directly or indirectly related to local development between 2000 and 2010 in Legal Amazonia.

METHODS

Data

This study explores data of 211 municipalities from Legal Amazonia that comprised the following conditions: a) deforested area higher than 200 Km^2 between 2001 and 2010; b) more than 20% forested area in 2000 (baseline year); c) Capitals and the municipalities with more than 140 thousands inhabitants were not considered. This threshold took into account the regional specificities of the small and medium-sized municipalities in Legal Amazonia, especially how cities and rural settlements are distributed in the territory, as well as previous studies about the regional urban hierarchy (IBGE 2008; Sathler *et al.* 2010). In addition to that, eight municipalities were excluded due to the lack of census data information.

In this analysis, twenty-seven initial variables represent nine different, but complementary dimensions, namely: territory, deforestation and forest, demographic, education, human development, economic, inequality, poverty and basic services (see Table 1).

Table 1 – Variables that characterize small and medium-sized municipalities, 2000-2010, Brazil – Legal Amazonia

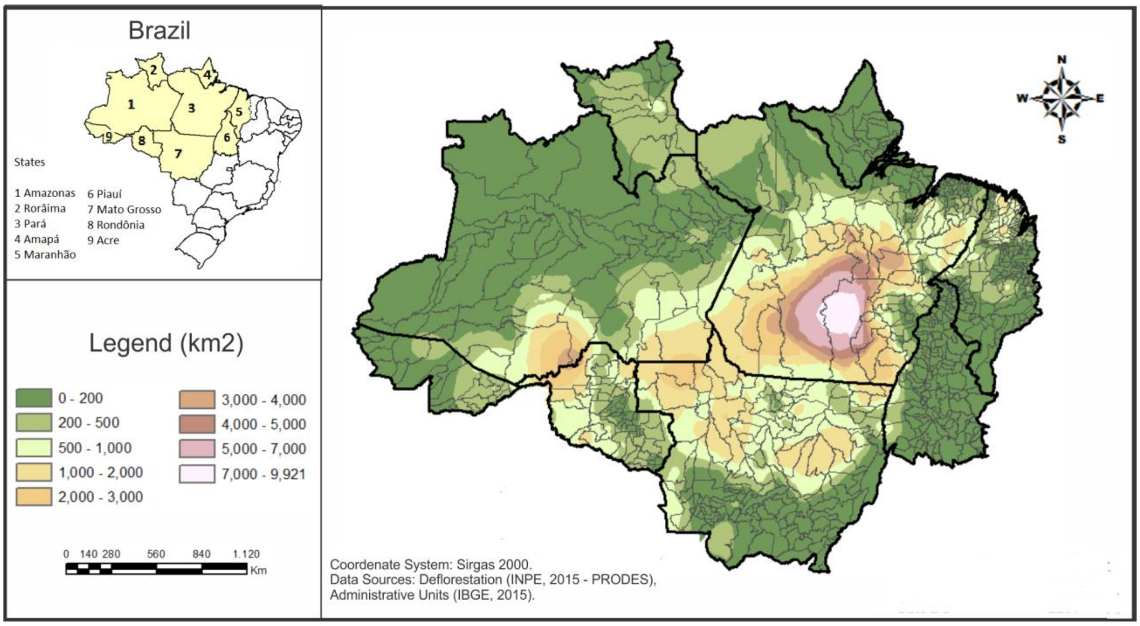
Dimensions	n	Variables / Units	Year or Period
Territory	1	Municipality area (km2)	2010
Deforestation and forest	2	Percentage of deforestation (%)	2001-2010
	3	Percentage of the municipality area in forests (%)	2010
Demographic	4	Population	2010
	5	Percentage of urban population	2010
	6	Urban population growth (% per year)	2000-2010
	7	Rural population growth (% per year)	2000-2010
	8	Percentage of immigrants (considering population in 2010)	2000-2010
	9	Percentage of out-migrants (considering population in 2010)	2000-2010
	10	Life expectancy at birth (years)	2010
	11	Fertility Rate (children)	2010
	12	Child Mortality Rate (per 1,000)	2010
	13	Dependency ratio (%)	2010
Education	14	Illiteracy rate (per 1,000)	2010
	15	Percentage of people with poverty vulnerability and without complete primary education (%)	2010
Human Development	16	Municipal Human Development Index	2010
	17	Municipal Human Development Index variation	2000-2010
Economic	18	Gross Domestic Product (R$)	2010
	19	Agricultural Gross Domestic Product (%)	2010
	20	Industrial Gross Domestic Product (%)	2010
	21	Services Gross Domestic Product (%)	2010
	22	Gross Domestic Product variation (% per year)	2000-2010
Inequality	23	GINI Index	2010
Poverty	24	Percentage of Poor people (%)	2010
Basic Services	25	Percentage of urban households with garbage collection (%)	2010
	26	Percentage of households with Electric (%)	2010
	27	Percentage of households with inadequate water and sanitation (%)	2010

Source: PRODES/INPE Brazil (2000-2010), IBGE (2000; 2010) and PNUD (2013).

The deforestation and forest open data were provided by INPE, as part of the Amazonia Deforestation Calculation Program (PRODES). Since 1988, PRODES has provided yearly data at the municipal level, which allows researchers to integrate environmental information with multiple social and territorial dimensions. Figure 1 shows the accumulated deforestation in Legal Amazonia between 2001 and 2010 (in square km) estimated by kriging interpolation[3]. The deforestation arc advances and presses the forest on many fronts towards the interior of the Amazonia. In ten years, the deforestation was significant not only in municipalities located in the most densely populated areas, near to the main roads and rivers of the southern and eastern Amazonia (consolidated deforestation frontiers) but also in municipalities located in the central Pará state (areas with more 4,000 km^2 deforested). Furthermore, in south Amazonas state, west Acre state and in the northern part of the region (new deforestation frontiers) there are many municipalities with more than 2,000 km^2 deforested. In Legal Amazonia, both consolidated and the new deforestation frontiers were active and registered expressive loss of forest in the 2000s. Moreover, the municipalities of the central part of Pará state generate great concern, since they concentrate a significant portion of deforestation in the region. Despite the deforestation deceleration, registered by INPE after

2004, the data demonstrated alarming information regarding the territorial extension of deforested areas. In order to associate deforestation with the other explored dimensions at the municipal level, this analysis has used the percentage of the deforested area instead of absolute deforestation.

Figure 1 – Accumulated Deforestation in Legal Amazonia, 2001-2010.



The *demographic* dimension is represented by 10 variables extracted from the Brazilian Microdata Population Censuses 2000 and 2010 (IBGE 2000; 2010). These variables provided information about population stock, mortality, fertility and age structure in 2010. The urban and rural population growth and last migratory stage[4] between 2000 and 2010 are also part of this dimension. The *education* dimension is represented by two variables: illiteracy rate and percentage of poor people[5] with no primary education. The *human development* dimension brings two important variables: the Human Development Index (HDI) in 2010 and the HDI variation between 2000 and 2010[6].

The *economic* dimension is represented by Gross Domestic Product (GDP) in 2010, GDP variation between 2000 and 2010, and percentage of agriculture, industry and services in the GDP. While the *inequality* dimension is represented by the Gini index, the *poverty* dimension is represented by the percentage of poor people. Finally, the *basic services* dimension includes three variables: garbage collection, electric and households without adequate water and sanitation.

Multivariate methods

In order to analyze this set of variables, this study applied a factor analysis based on Principal Component Analysis (PCA) for data reduction and a cluster analysis for identifying groups. Both methods are described in the next subsections.

Principal Component Analysis

The first multivariate method is a PCA, a variant of factor analysis. Factor analysis is a statistical method used to describe variability among observed, highly correlated variables in terms of a potentially lower number of unobserved variables called factors (Mingot 2007; Lima and Braga 2013). The PCA seeks to reduce a large number of *p* variables by a small number of *m* linear functions, which best summarizes large initial group of covariates (Mingoti 2007)[7]. In addition, principal components analysis is relevant to this study because many information vectors in the selected datasets are redundant. This characteristic might cause problems in further cluster analyses. Therefore, the PCA was used to transform a set of original and interrelated variables into a new set of orthagonal and non-related components (Rodrigues and Branco 2006).

Before implementing the PCA, a Kaiser Meyer Olkin (KMO) and a Bartlett test were performed in order to test the hypothesis that the variables are highly correlated. The KMO is a measure of adequacy that checks the fit of the data using all variables simultaneously. Acceptable values for continuing a PCA are around of 0.5 to 0.9. From the set of 27 variables, only two did not present value above 0.5, namely agricultural and industrial gross domestic products. These variables were not considered in the PCA. The next test, the sphericity Bartlett's, examines the hypothesis that the correlation matrix is an identity matrix, i.e. the main diagonal is equal to 1 and all other values are zero. In other words, there is no correlation between the variables. In this test, it was possible to reject the null hypothesis and argue that there is correlation among the variables considered. Once both tests are performed, the next step was the PCA application.

The results of the principal component analysis are described by a correlation matrix (Table 2), which is used to label the constructs estimated by the PCA. In certain cases, the rotation methods are used in order to facilitate the interpretation of the correlations between the original variables and the estimated components. Here, a *Varimax* rotation method was applied to minimize the number of variables in each component[8]. In the end, the PCA transforms the original set of covariates into standardized uncorrelated components with numerical values, or scores, ranging from $-\infty$ to $+\infty$, average centered on zero and standard deviation equal to 1 (Mingoti 2007). These uncorrelated components are then used in a cluster analysis.

Cluster Analysis

As a second step, a cluster analysis was applied in order to explore the possible spatial clusters among municipalities in Legal Amazonia based on the five standardized and uncorrelated components. The cluster analysis was performed by a *two-step* cluster, an algorithm designed to handle both continuous and categorical variables. First, the two-step pre-clusters the records into many small sub-clusters, and then it aggregates those sub-clusters into the desired number of clusters[9]. The records in one sub-cluster should end up in one of the final clusters so the pre-cluster step will not affect the accuracy of the final clustering (SPSS 2001). In general, inaccuracy from the pre-cluster step decreases as the number of sub-clusters from the pre-cluster step increases. However, too many sub-clusters will slow down the second stage clustering.

The number of optimal cluster is selected according to criterion suggested by Fraley and Raftery (1998). They proposed a Bayesian information criterion (BIC) as the criterion statistic for the Expected Maximization (EM) clustering method. Therefore, the two-step clustering estimates BIC for each number of clusters within a specified range, and uses it to find the initial estimate for the number of clusters. The second step refines the initial estimate by finding the greatest change in distance between the two closest clusters in each hierarchical clustering stage (SPSS 2001).

RESULTS

The 25 initial variables were reduced to five octagonal and independent components. These components are able to explain around 73% of the total variability of the original database (Table 2). In other words, around three quarters of the initial information of the 25 variables was compressed into five principal components. These five components were chosen according to the scree plot (Figure 2) and eigenvalues above 1 (Kaiser 1958).

Table 2 – Total variance explained by the principal components

Parameters	Components				
	PC1	PC2	PC3	PC4	PC5
Standard deviation	3,081	1,820	1,578	1,333	1,061
Proportion of Variance	0,380	0,132	0,100	0,071	0,045
Cumulative Proportion	0,380	0,512	0,612	0,683	**0,728**

Source: PRODES/INPE Brazil (2000-2010), IBGE (2000; 2010) and PNUD (2013).

Figure 2: Scree plot of the number of components

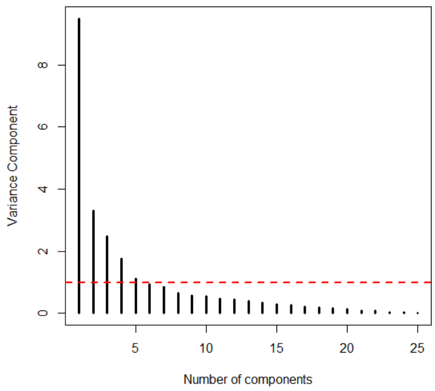


Table 3 demonstrates the correlation matrix of the rotated components by the Varimax method. The five principal components are described as follows:

- The first principal component (*development*) characterizes municipalities with high levels of poverty, inequality and social vulnerability. This component has a high positive correlation with the infant mortality (0.80), dependency ratio (0.79), illiteracy rate (0.80), percentage of poor population (0.86) and percentage of households without water piped and sewage network (0.78). It has a high negative correlation with the life expectancy (-0.83) and HDI (-0.89). The results also indicate a moderate negative correlation between this component and the percentage of urban population (-0.55), immigrants (-0.52) and out-migrants (-0.45). Very low levels of HDI in 2000 explain the positive correlation between the first principal component and HDI variation in the decade (0.75);
- The second principal component (*forest*) has a strong negative correlation with the percentage of deforestation (-0.82) and a positive correlation with the percentage of forest in 2010 (0.82). This component also has information about the municipality´s area, establishing a moderate positive correlation (0.61);
- The third principal component (*size*) characterizes municipalities with the highest values of population size (0.87) and GDP (0.75). Also, it has a moderate positive correlation with the percentage of urban population (0.56);
- The fourth principal component (*growth*) has a positive correlation with the Urban (0.69) and Rural Growth (0.73) rates. It presents a negative correlation with the out-migration (-0.68);
- The fifth principal component (*stagnation*) has a negative correlation with the GDP growth between 2000 and 2010 (-0.72). It also presents a moderate negative

correlation with the immigration (-0.59). This component characterizes municipalities with a high percentage of services in its GDP composition (0.73) because of its low levels of investments in the agricultural and industrial sectors.

Table 3 – Correlation matrix of the rotated components by the Varimax method, Legal Amazonia, 2000-2010.

Variables	Principal Components				
	PC1 Development	PC2 Forest	PC3 Size	PC4 Growth	PC5 Stagnation
Municipality area (km2)	0.02	0.61	0.38	-0.04	0.06
Percentage of deforestation (%)	0.27	-0.81	-0.07	0.06	0.19
Percentage of forest (%)	-0.03	0.81	0.07	0.09	-0.11
Population	0.13	0.11	0.87	0.12	0.20
Percentage of urban population (%)	-0.54	0.02	0.56	-0.25	-0.06
Urban population growth (% per year)	0.08	0.05	0.05	0.69	-0.34
Rural population growth (% per year)	-0.02	-0.01	0.11	0.73	0.00
Life expectancy at birth (years)	-0.84	0.34	-0.12	0.09	-0.04
Fertility Rate (children)	0.69	0.32	-0.2	0.08	0.10
Infant Mortality Rate (per 1,000)	0.80	-0.45	0.13	-0.11	0.03
Dependency ratio (%)	0.79	0.19	-0.04	0.10	0.36
Percentage of immigrants (considering population in 2010)	-0.52	0.12	-0.28	0.20	-0.59
Percentage of out-migrants (considering population in 2010)	-0.45	-0.07	0.12	-0.68	-0.15
Illiteracy rate (per 1,000)	0.80	-0.07	-0.16	0.01	0.26
Percentage of people with poverty vulnerability and without complete primary education (%)	0.87	0.21	-0.16	0.19	0.19
Municipal Human Development Index	-0.89	-0.08	0.17	-0.22	-0.18
Municipal Human Development Index variation	0.75	-0.27	-0.09	-0.04	-0.35
Gross Domestic Product (R$)	-0.38	0.13	0.75	0.12	0.01
Services Gross Domestic Product (%)	0.33	-0.04	0.2	0.17	0.73
Gross Domestic Product variation (% per year)	-0.15	0.07	0.00	0.31	-0.72
GINI Index	0.44	0.47	-0.14	-0.01	0.33
Percentage of poor people (%)	0.86	-0.01	-0.14	0.15	0.4
Percentage of urban households with garbage collection (%)	-0.46	0.42	0.11	-0.06	-0.31
Percentage of households with Electricity (%)	-0.43	-0.62	0.24	-0.32	-0.27
Percentage of households with inadequate water and sanitation (%)	0.78	-0.08	0.09	0.22	0.28

Source: PRODES/INPE Brazil (2000-2010), IBGE (2000; 2010) and PNUD (2013).

The five components were then classified according to a cluster method. The results of the cluster analysis are provided in Table 4. Based on the Bayesian Information Criterion (BIC), four clusters are the best solution for the used algorithm. The content of each cluster is analyzed according to the mean values of each cluster distributed across the five components obtained in previous PCA.

Table 4 - Cluster results (means and frequency) based on estimated principal components, 2000-2010.

Cluster	Development	Forest	Size	Growth	Stagnation	n
1	0.642	-1.602	-0.084	-0.017	0.687	35
2	0.140	0.125	0.480	0.275	-0.791	77
3	-0.972	-0.004	-0.312	-0.821	-0.086	52
4	0.367	0.993	-0.379	0.469	0.879	47

Source: PRODES/INPE Brazil (2000-2010), IBGE (2000; 2010) and PNUD (2013).

Cluster 1 groups the municipalities with the highest average in the PCA *development* component (0.64) and also has a high average value for *stagnation* (0.69). These 35 municipalities have the worst social indicators among the clusters. The *development* component also indicates that these municipalities have high fertility rate and dependency ratio. Cluster 1 is characterized by municipalities with low GDP variation between 2000 and 2010, low migratory attractiveness and an undiversified economy, essentially based on services. On average, these municipalities have strong negative correlation with the *forest* component, suggesting small territorial size, high percentage of deforested area in the analyzed period and also low percentage of forested area in 2010.

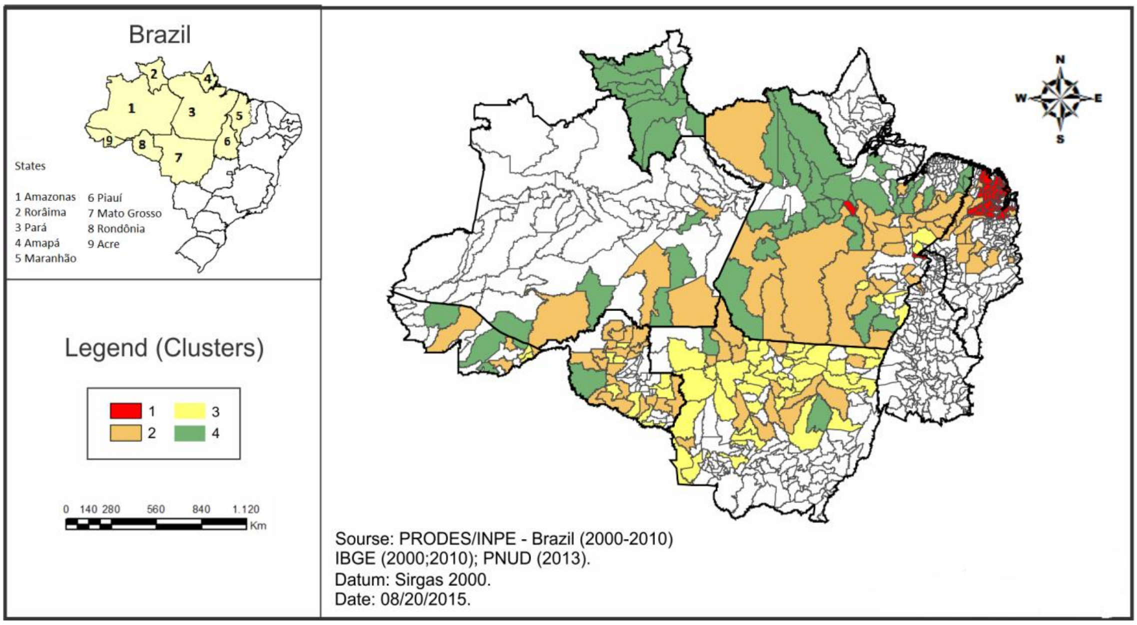
Cluster 2 aggregates 77 municipalities that exhibited on the average a high negative average of *stagnation* component (-0.79) and a moderate positive average of *size* component (0.48). Thus, it means that these municipalities have the highest values of GDP variation and a significantly migratory attractiveness. Additionally, their economies are not only concentrated in services. Despite the moderate positive average of *size* component, the cluster 2 aggregates municipalities with the highest population stocks and also the highest GDP values in Legal Amazonia.

Cluster 3 municipalities have the lowest average values of *development* and *growth* in Legal Amazonia (-0.97 and -0.82, respectively). These municipalities have the most favorable social indicators among the other groups. They exhibit low population growth in the urban and rural areas and high out-migration values between 2000 and 2010. The results demonstrate that the *stagnation* and *forest* components have values near to zero in this cluster. Cluster 3 also presents lower GDP variation and migratory attractiveness than cluster 2. Moreover, cluster 3 brings together municipalities with intermediate territorial size for the regional patterns and no large variations in the percentage of deforested areabetween 2000 and 2010.

Cluster 4 aggregates municipalities with high average values in the *forest* (0.99) and stagnation (0.87) components. The *development* (0.36), *growth* (0.47) and *size* (-0.38) components also have significant values for the description of this cluster. Therefore, these municipalities have a low percentage of deforested areas, high percentage of forest in 2010 and large territorial dimensions, but small populations and economies. This cluster is characterized by low economic growth and undiversified economy, concentrated in services. Given the moderate negative relationship between immigration and the *stagnation* component, the results suggest that the significant population growth in these municipalities might be explained by the low out-migration and strong natural growth between 2000 and 2010. The moderate level of the *development* component shows that cluster 4 has higher fertility and dependency ratio levels than clusters 2 and 3.

Figure 3 displays the spatial distribution of these clusters in Legal Amazonia, and it is possible to observe a well-defined pattern in terms of localization and contiguity. The municipalities that belong to cluster 1 present the lower territorial dispersion and are basically concentrated in the North part of the Maranhão state. On the other hand, the cluster 2 presents the highest territorial dispersion. They are located in the heart of the deforestation, especially in the East and South of the Pará state, and are also present in regions with important regional railways and massive agricultural projects, as in the central part of Mato Grosso and Maranhão, and in Rondônia state. The cluster 3 is located essentially in the Mato Grosso state, with little significant presence in Rondônia and eastern Pará. In the Mato Grosso region, it surrounds the municipalities of cluster 2, which have the greatest demographic and economic size and are located near to the 153 road. In addition to that, the cluster 4 municipalities are mainly located in the northern part of Legal Amazonia, mostly in areas where the transportation is made exclusively by the rivers. Some of these municipalities are also near to the deforestation arc.

Figure 3 – Spatial distribution of the clusters in Legal Amazonia, 2000-2010.



DISCUSSION AND POLICY RECOMMENDATIONS

Although several studies have advanced the general understanding of the conservation benefits (Börner *et al*. 2009; UNDP 2012) and the negative impacts of deforestation in Legal Amazonia (Moran 1993; Rodrigues *et al.* 2009; Calentano *et al.* 2012), it is also necessary to encourage further evaluation of how *local development levels* might hinder or contribute to forest protection. The general improvement of socioeconomic and demographic indicators related to human development may bring new perspectives for initiatives that seek to ensure a lasting cycle of prosperity in harmony with preservationists' interests in the region. *Local sustainable development* is the key requirement for an important paradigm shift in the region, which would imply the reduction of expenditures on monitoring and control of deforestation and the increase of income generated by forestry ecological services.

Jha and Bawa (2006) and UNDP (2011) have found a clear correlation between deforestation and human development by comparing variables among different regions of the world. In general, these macro analyses show that in tropical areas with high population growth, low human development is associated with high deforestation rates, while high human development is associated with low deforestation rates. However, at the regional scale, this study demonstrates that the associations between these variables are more complex and must consider the historic advancements of the economic activities in the deforestation arc, as well as the territorial characteristics and the spatial location of the municipalities.

In this context, spatial data integration and statistical analysis are crucial to assess deforestation and local development (Fonseca *et al.* 2009; Santos *et al.* 2014). The PCA and cluster analysis provide multiple results by integrating 25 environmental and census variables at the municipal level in Legal Amazonia. In the PCA, *development* and *forest* are the two strongest components, given their proportion of the variance (0.380 and 0.132 respectively), and were decisive for the clusters definition. In addition, *size*, *growth* and *stagnation* provide relevant complementary information for understanding the sustainable development dynamics in Legal Amazonia. These components show that there are different levels of demographic and economic pressures among clusters, while suggesting some important trends, such as the internalization of investments and demographic growth in the region.

Cluster 1 municipalities have low human development levels, high deforestation rates and low percentages of forested areas. Jha and Bawa (2006) have found this same pattern by investigating 30 of the most important world deforestation hotspots in the 1990s, but their results were concerned with areas characterized by high population growth. Instead, in this analysis, cluster 1 has exhibited high levels of environmental depletion even with an inexpressive population growth and high *stagnation* component. Moreover, cluster 4 municipalities have low levels of human development, high levels of *stagnation*, significant levels of natural population growth with the largest *forest* average among the four clusters. Given the cluster 4 specificities, it does not necessarily mean that there is a different association between these variables. Cluster 4 municipalities have the lower mean of *size* component, are located mainly in the new deforestation frontiers and present on average an expressive percentage of forested area. Also, their huge territorial area contributes to the relatively low percentages of deforestation registered between 2001 and 2010, although the absolute deforestation numbers are significant in the cluster 4 municipalities given their high *stagnation* and low *size* values. Additionally, the associations between *development* and *forest* components are less clear in clusters 2 and 3, whereas the penetration of economic activities and the historical advancement of the deforestation arc are crucial for both of these cluster configurations.

The results indicate well-defined differences between the explored demographic parameters, revealing some interesting patterns among the clusters. Significant migratory attractiveness and economic dynamism presented in cluster 2 as well as the high out-migration levels presented in cluster 3 suggest that these groups of municipalities were essential to the frontier evolution in this region. This finding corroborates previous studies, which demonstrate the predominance of the internal migration in the region (e.g. Perz 2002; Becker 2005). Furthermore, the information regarding urban and rural population growth, fertility rate and dependency ratio might indicate that cluster 1 and cluster 4 municipalities are delayed in the demographic transition when compared to cluster 2 and cluster 3. The pace of the demographic transition is strongly related to human development levels. Generally, developed regions are more advanced in this process than developing regions (Lee 2003; Reher 2011). In this study, the results are consistent with the demographic transition theory since human development levels are lower in clusters 1 and 4 compared to clusters 2 and 3.

Demographic transition and age structure changes are increasingly impacting the population distribution and also creating environmental pressures in both urban and rural areas in Legal Amazonia (Andersen *et al.* 2002; Perz *et al.* 2005). Changes in fertility and life expectancy have increased the proportion of adults and reduced the dependency rate, especially in the more developed municipalities (IBGE 2000; 2010). Therefore, development levels are associated not only with more opportunities that assure forest conservation, but also with demographic changes that might cause negative environmental impacts in the region, such as increases in consumption and land demands (Campos 2014; Mello and Sathler 2015). Also, young adults are likely to be relevant actors in labor migration (UN 2011; Kupiszewski 2013), which can impact the population distribution and increase the pressure on natural resources in Legal Amazonia.

Moreover, related literature suggests that variations in the household life cycle and the reduction of the dependency rate driven by the demographic transition represent a real problem for forest preservation in the rural areas (Bilsborrow and Stupp 1997; Bilsborrow and Carr 2001; Guedes 2010). According to complementary information provided by IBGE (2010), cluster 2 (63.30%) and cluster 3 (66.96%) municipalities have on average higher proportion of adults (15 to 64 years) than clusters 1 (61.43%) and 4 (58.98%) municipalities, and these figures are likely to increase in the next decade (Rigotti 2012). Thus, public policies must be aware of the opportunities and challenges arising from demographic transition and household changes in Legal Amazonia.

This investigation confirms the need for specific analysis in social and environmental studies for small and medium-sized municipalities in Legal Amazonia. In these municipalities, economic investments and the advancement of frontiers may cause significant local changes in some key explored variables, especially when they are starting from very low levels in the base year. In addition, the interpretation of some variables can change according to the population size or level of importance of the municipality in the regional hierarchy. For instance, in the small and medium-sized municipalities, high values of services in the GDP composition generally mean lower levels of economic diversification and lack of investments in other economic sectors. This information has a different meaning for the administrative capitals and big municipalities that have their economies based on more specialized and diversified services (IBGE 2000; 2010).

Moreover, further research on topological relations among deforestation, forest stock, and other mapped elements (roads, rivers, protected areas, economic activities and urban agglomerations) might reveal relevant insights for this discussion. Spatial distribution and proximity are essential for the understanding of the interactions among socioeconomic, demographic and environmental variables (Rindfuss and Stern 1998). Additionally, time-series data can be helpful to characterize the evolution of deforestation and social variables in the region.

The identification of patterns and improved understanding of the specificities and differences among the clusters may assist in the design of policies for local sustainable development, for the preservation and the regeneration of the forest. Cluster 1 municipalities deserve special attention in the implementation of local sustainable development initiatives, given their very low forest stocks and development levels. The policies should focus on promoting forest recovery, starting from the most sensible areas such as those surrounding springs and streams. Local development policies should support economic diversification by, for example, attracting more investments in non-traditional economic sectors, and the improvement of the existing services needs to be encouraged in concert with policies for forest regeneration. In the short-term, there is little or no possibility to implement environmental services that depend on significant forest stock in these municipalities.

Cluster 2 municipalities should continuously strengthen their environmental monitoring and control policies, considering their spatial location and the behavior of economic, social and demographic variables. Public policies must be aware of the dynamic reality of economic growth and demographic dynamic. Local governments should face the challenge of transforming economic growth in local sustainable development.

Cluster 3 municipalities present the best social indicators, which in theory can contribute to the sustainable development growth and also to combat deforestation. The stakeholders should promote actions to rehabilitate the deforested areas by emphasizing the protection of springs and riparian forests. Given that the deforestation arc has greatly damaged the forest stretching from the southern portion of Legal Amazonia into its interior, the results indicate the existence of some favorable conditions in these municipalities for the initiation of a strong movement for the recovery of forests and the enhancement of local sustainable development, advancing also from the southern portion toward the interior of Legal Amazonia. In these municipalities, the consolidated frontiers of deforestation should become the new frontiers of sustainable development.

Finally, cluster 4 municipalities have on average the worst social indicators among those that still have significant stocks of forest (clusters 2 and 3). The results indicate the absence of strong migratory movements in these municipalities, and a significant natural population growth in these areas. The municipalities of this group that are close to the deforestation arc require more careful work to maintain the forest stocks and improve living conditions.

In order to promote local participation in actions related to sustainable development and forest preservation, the Brazilian government should create and stimulate a network of municipalities in Legal Amazonia. Local governments´ networks are important to share knowledge and expertise, stimulate cooperation and attract funding (ICLEI 2012; Labaeye 2013). Since neighboring municipalities usually have close territorial characteristics and development patterns, the suggested network also could stimulate partnerships and integrate projects involving local governments with different capacities and distinct demographic, economic and functional sizes. This would help to break down barriers that hinder local sustainable development and the preservation of the forests. Additionally, municipalities can also integrate existing knowledge networks, such as ICLEI (Local Governments for Sustainability) and REGATTA (Regional Gateway for Technology Transfer and Climate Change Action in Latin American and the Caribbean).

Lastly, municipalities must continually improve their ability to interact with projects developed at the regional and national levels. According to MacCarney (2006), the lack of interaction of local governments with regional and national plans has been critical to the failure of public policies. In Legal Amazonia, municipalities should take advantage of the mobilizations, plans and actions developed for states and the national government. The Sustainable Amazonia Plan and its outcomes can assist municipalities to formulate and achieve their local developmental goals and partnerships between municipalities and the national government can maximize the local results of PPCDAm.

Endnotes

[1] Brazil's Legal Amazonia is a policy-defined region formed by 772 municipalities, distributed in nine states (Acre, Amazônas, Rondônia, Roraima, Mato Grosso, Pará, Maranhão, Tocantins and Macapá). The expression "deforestation arc" usually refers to the area along the eastern, southern and western edges of the forest (Fearnside 2008). However, this study consider all the municipalities that have registered more than 200 km^2 of deforestation between 2001 and 2010 as part of the deforestation arc, by incorporating also the northern edges of Legal Amazonia.

[2] Despite the natural leadership of Brazil in the REDD+ forums in the recent years, the country opted to not become an official partner of the UN-REDD Programme and the FCPF. The Brazilian Ministry of Environment (MMA) argues that deforestation-fighting strategies must be determined domestically. Notwithstanding, Brazil will be the first country to have its results of REDD+ recognized for UNFCCC according to MMA (BRASIL, 2015). For additional information see <http://redd.mma.gov.br>.

[3] According to Bohling (2005, p. 2) kriging is an "optimal interpolation method based on regression against observed z values of surrounding data points, weighted according to spatial covariance values".

[4] People with less than ten years of residence in the municipality should indicate the municipality and state (or foreign country) where they lived previously. Thus, the information collected refers to the last migratory stage, which may have occurred in the 10 years preceding the Census (Carvalho and Rigotti 1998).

[5] Percentage of people with per capita household income equal or less than R$ 140.00 (Brazilian Real) per month in 2010 (IBGE 2010).

[6] This index was created by the United Nations (UN) and incorporates three indicators: the per capita income, the literacy rates and the life expectancy. Although the index includes some information already present in the table, it is a complementary measure with great potential for comparability.

[7] According to Darlington (2010), there are numerous mathematical solutions to this problem. However, the establishment of three conditions provides a unique solution for any database: a) First, linear functions derived from such method should not be correlated; b) Second, the groups of m linear functions should include functions for smaller groups; and c) Third, the sum of squares weights that define each linear function must be equal to 1. According to these three conditions, the estimated principal components will be represented by *m* linear functions that decline in importance with increasing variance.

[8] In this method, the components are rotated until they match a simpler structure (Mingoti 2007). The number of components is estimated according to the eigenvalues and the empirical rule of Henry Kaiser. According to this rule, the number of components for the reconstruction of the initial information items must have eigenvalues higher than 1 (Mingoti 2007; Darlington 2010).

[9]This is the basic concept of two-stage clustering methods like BIRCH (Zhang et al. 1996). Therefore, first it applies a sequential cluster method to the dataset to compress the dense regions and form sub-clusters. In the second stage, it applies a cluster method on the sub-clusters to find the desired number of clusters.

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