Research

Deforestation and local sustainable development in Brazilian Legal Amazonia: an exploratory analysis

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ABSTRACT. We focus here on deforestation and human development dynamics among 211 small and medium-sized municipalities (in terms of population) in the Amazonian arc of deforestation, Brazil. First, we construct a typology of municipalities through principal component analysis and cluster analysis. Using this typology, we seek to identify changing deforestation frontiers in the study area based not only on forest loss levels, but also on sets of socioeconomic and demographic elements associated with human development. We find four well-defined macro-deforestation frontiers that exhibit distinct interactions between forest loss and human development levels. Our results show different levels of demographic and economic pressures in these frontiers while revealing some important trends such as the internalization of investments and demographic growth in the arc of deforestation. In addition, population growth and in-migration and out-migration patterns in the explored municipalities suggest a demographic complementarity among frontiers. Finally, we explore implications for public policies seeking to advance forest recovery and long-term conservation through sustainable development growth at the local and regional levels.

Key Words: *Amazonia; deforestation; local sustainable development; multivariate methods; public policy*

INTRODUCTION

In the Brazilian Amazon, regional and local sustainable development initiatives are vital to curb deforestation and forest degradation (Meir et al. 2011). Existing literature identifies sustainable development growth as a key element to forest recovery and long-term conservation in the tropics (Volpi 2007, UNDP 2014; B. A. Jingwa and S. A. Asongu, *unpublished manuscript:* https://mpra.ub.uni-muenchen.de/35898/). Preserving the functioning of the Amazonian biome while promoting sustainable development is indispensable for regional and local ecological balance, as well as for climate change mitigation at a global scale (Meir et al. 2011). However, policies addressing deforestation and forest degradation in the Brazilian Amazon have not focused on regional and local sustainable development by integrating actions seeking social inclusion and economic growth without depleting natural resources. Instead, they were mainly concerned with short- and medium-term strategies such as law enforcement, the expansion of protected areas, and repression actions through monitoring and control (Volpi 2007, Soares-Filho et al. 2010, Pfaff et al. 2015; Instituto de Pesquisa Econômica Aplicada, Deutsche Gesellschaft fur Internationale Zusammenarbeit, and Comissão Econômica para a América Latina e Caribe, *unpublished data:* http://repositorio.ipea.gov.br/bitstream/11058/885/1/Resultados%20avaliacao%20PPCDAm_seminario%20avaliacao_JH03x.pdf).

Successful policies seeking to decrease deforestation and recover forest generally take into account multilevel efforts, multisector involvement, and bottom-up approaches, including all levels of government (local, state, and national). This approach responds to the fact that deforestation produces distinct effects according to the scale of analysis (Fearnside 2008, Guedes et al. 2011), and deforestation drivers are also different at the local, state, and national levels (Brondizio and Moran 2012, Chakravarty et al. 2012). For optimum results, the private sector (soybean producers, ranchers, industries, and smallholders), public actors (executive,

legislative, and judicial branches), and civil society (nongovernmental organizations and social and community groups) should work collectively by establishing goals regionally and locally (Sandbrook et al. 2010, Korhonen-Kurki et al. 2012, Sathler 2014). Lack of coordination among these stakeholders can hinder policies addressing deforestation and forest degradation (Gebara et al. 2014). In addition, long-term sustainable development strategies combining economic, social, and environmental initiatives can contribute to strengthen communities in facing deforestation and forest degradation (Steurer and Trattinig 2010, Meir et al. 2011).

Deforestation accelerated significantly during the 1990s and early 2000s in the Brazilian Amazon, reaching an annual rate of 27,423 km² in 2004 (INPE 2004). These high rates were mainly promoted by infrastructure expansion (roads, ports, and hydroelectric plants) and emergence of new economic activities such as logging, ranching, soybean producers, mining, and industry (Fearnside 2007, Fearnside and Graça 2009, Ebanyat et al. 2010). In addition, major changes in the regional demographic context and urbanization were strongly associated with deforestation and forest degradation in the region (Vicentini 2004, Monte-Mor 2013). In this context, the ecological effects of deforestation, such as increasing land degradation and changes in species composition and atmospheric parameters, are potentially large and strongly affect agriculture and ecological services in the Brazilian Amazon (Findell et al. 2006, Killeen and Solórzano 2008, Sheil and Murdiyarso 2009, Shukla et al. 1990). Moreover, deforestation and forest degradation in the region significantly affect the global climate system (Houghton et al. 2001, Houghton 2005, Soares-Filho et al. 2006, Berenguer et al. 2014, Busch and Ferretti-Gallon 2014, IPCC 2014, Song et al. 2015).

In 2004, the Brazilian government launched the National Action Plan for Prevention and Control of Brazilian Amazon Deforestation (PPCDAm), which established strategies in three

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main areas: (1) monitoring and environmental control, (2) land tenure regulation, and (3) sustainable development (Ministério do Meio Ambiente 2013). Recent estimates demonstrate that PPCDAm policies prevented 27% to 62% of deforested area between 2005 and 2009 in the Brazilian Amazon, which represents 270 million Mg to 621 million Mg of carbon dioxide in the atmosphere (Assunção et al. 2012). In fact, the Instituto Nacional de Pesquisas Espaciais (INPE) registered in 2014 a deforestation rate 5.54 times lower than those observed 10 years earlier (INPE 2014). Based on these satisfactory results, the Brazilian government in 2009 set an ambitious target to reduce deforestation by 80% below the historical baseline (19,500 km²/ year) by 2020 (Ministério do Meio Ambiente 2013). Previous studies associate the success of the Brazilian policies to protect Amazonia with: monitoring enhancement and the Deforestation Detection System, or DETER, implemented in 2004 (Popkin 2016); recent expansion of indigenous reserves and protected areas (Nepstad et al. 2006, Soares-Filho et al. 2010, Pfaff et al. 2015); enforcement of logging laws (UCS 2011); governmental interventions in beef and soy supply chains (Nepstad et al. 2014); and partnerships with nongovernmental organizations and the private sector (Greenpeace 2009).

The recent reduction of net deforestation and the strengthening of international initiatives such as Reducing Emissions from Deforestation and Forest Degradation and Enhancement of Carbon Stocks (i.e., REDD+), might suggest that the end of deforestation in the Brazilian Amazon is finally feasible (Nepstad et al. 2009). Empirical evidence observed in many developed and some developing forested countries support this argument by identifying a forest transition curve along which deforestation increases with development until it stabilizes, after which the process is reversed by forest growth (Meyfroidt et al. 2010, Elias et al. 2011).

However, there is no guarantee that this recent deforestation reduction in the Brazilian Amazon will be a permanent pattern. The Instituto de Pesquisa Econômica Aplicada, Deutsche Gesellschaft fur Internationale Zusammenarbeit, and Comissão Econômica para a América Latina e Caribe (*unpublished data:* http://repositorio.ipea.gov.br/bitstream/11058/885/1/Resultados% 20avaliacao%20PPCDAm_seminario%20avaliacao_JH03x.pdf) reveal that the most effective actions of PPCDAm were focused on environmental monitoring and control. Actions that should have ensured a sustainable reduction of deforestation, such as initiatives seeking land tenure regulation and sustainable development growth, have not occurred at a satisfactory effectiveness level. Furthermore, during the 2000s, the rate of deforestation in the Brazilian Amazon was closely related to price variation in meat and soybean in the international market (Hargrave and Kis-Katos 2013, Macedo et al. 2012). In addition, there was a strong correlation between the availability of agricultural credit and deforestation rates in the Brazilian Amazon in this period (Andersen 1996, Barreto and Silva 2009, Assunção et al. 2013). Despite Brazilian efforts in the past decade, these studies suggest that deforestation rates in the region are significantly associated with changes in investments and capital availability.

In 2008, the federal government launched the Sustainable Amazonia Plan (PAS), which proposed an integrated set of guidelines seeking to promote sustainable development in the Brazilian Amazon (Ministério do Meio Ambiente 2008). This plan incorporated many strategic policies at the state level, which might affect sustainable development at regional and local levels. However, municipalities of Brazilian Amazon are not deeply involved in projects for promoting sustainable development and forest preservation (Sathler et al. 2015). In addition, conservation initiatives have spread more through top-down policies (PAS and PPCDAm) than through local interventions in the Brazilian Amazon (Madeira 2014).

Assessments of socioeconomic, demographic, and environmental changes are fundamental to support the implementation of public policies that take into account regional and local sustainable development in the Amazonian arc of deforestation, which comprises the area along the eastern, southern, and western edges of the forest (Barreto et al. 2008, Fearnside 2008). In this context, several studies have explored the regional levels of poverty, inequality, and social vulnerability in the Brazilian Amazon (Pinedo-Vasquez et al. 2001, Sears et al. 2007, Mangabeira 2010, Guedes et al. 2012, Garrett et al. 2017), as well as the negative social effects of deforestation in the region (Moran 1993, Rodrigues et al. 2009, Celentano et al. 2012) and the interactions between forest loss and socioeconomic patterns in deforestation frontiers (Rodrigues et al. 2009, Celentano et al. 2012). In general, these studies reveal that deforestation occurs on many fronts within the Amazonian arc of deforestation, which present distinct socioeconomic and demographic characteristics in a heterogeneous territory.

In the Brazilian Amazon, socioeconomic and environmental assessments of deforestation need to consider the whole urban hierarchy, which includes large cities, regional urban centers, and also the small and medium-sized (in terms of population) municipalities, highlighting their demographic, socioeconomic, and spatial specificities (IBGE 2008, Guedes et al. 2009, Sathler et al. 2009). Generally, small, medium, and large municipalities have distinct functions, synergies, and capacities to produce social and environmental changes in both urban and rural areas (Bolay and Rabinovich 2004), including deforestation (e.g., Aide et al. 2013, Brondizio and Moran 2012). In the arc of deforestation, public investments and the expansion of economic activities in small and medium-sized municipalities have caused important environmental and social changes (Becker 2005, Fearnside 2008, Ebanyat et al. 2010). However, deforestation and sustainable development dynamics in the small and medium-sized Amazonian municipalities are still understudied.

Here, we investigate the spatial patterns of deforestation and development between 2000 and 2010 (years of the two latest Brazilian demographic censuses) in the Amazonian small and medium-sized municipalities within the arc of deforestation. We focus on the following research questions. (1) Are there distinct and well-defined deforestation frontiers in the study area, and, if so, what are the main spatial patterns exhibited by forest loss and social variables in these frontiers? (2) How may our findings be used to improve the design of policies seeking regional and local sustainable development in the Brazilian Amazon?

To address these questions, we construct a typology of municipalities through principal component analysis (PCA) and cluster analysis (two-step cluster analysis). Using this typology,

Table 1. List of initial variables, 2000–2010. Sources: INPE (2014), IBGE (2000, 2010), and PNUD (2013).

Dimension	Variable number	Variable (units)	Year or period
Territory	1	Municipality area (km²)	2010
Deforestation and forest	2	Proportion of deforestation (%)	2001–2010
	3	Proportion of the municipality area in forests (%)	2010
Demographic	4	Population	2010
	5	Proportion of urban population (%)	2010
	6	Urban population growth (%/yr)	2000–2010
	7	Rural population growth (%/yr)	2000–2010
	8	Proportion of in-migrants (%)	2000–2010
	9	Proportion of out-migrants (%)	2000–2010
	10	Life expectancy at birth (yr)	2010
	11	Fertility rate (number of children)	2010
	12	Child mortality rate (per 1000)	2010
	13	Dependency ratio (%)	2010
Education	14	Illiteracy rate (per 1000)	2010
	15	Proportion 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 (GDP; R$)	2010
	19	Agricultural GDP (%)	2010
	20	Industrial GDP (%)	2010
	21	Services GDP (%)	2010
	22	GDP variation (%/yr)	2000–2010
Inequality and poverty	23	Gini index	2010
	24	Proportion of poor people (%)	2010
Basic services	25	Proportion of urban households with garbage collection (%)	2010
	26	Proportion of households with electricity (%)	2010
	27	Proportion of households with inadequate water and sanitation (%)	2010

we seek to identify changing deforestation frontiers in the study area based not only on the forest loss levels, but also on sets of socio-demographic and economic characteristics associated with sustainable development. We conclude by discussing the major implications of our analysis for public policies seeking decreased deforestation and increased forest recovery through regional and local sustainable development initiatives in the Brazilian Amazon.

DATA AND METHODS

Data
We selected 211 small and medium-sized municipalities in the Amazonian arc of deforestation based on the following criteria: (1) deforested area > 200 km² between 2001 and 2010, which represents a significant amount of forest loss in this period, according to INPE (2014); (2) > 20% forested area in 2000 (baseline year); and (3) exclusion of state capitals and municipalities with > 140,000 inhabitants. These requirements took into account the regional specificities of small and medium-sized municipalities in the Brazilian Amazon, especially how cities and rural settlements are distributed in the territory, as well as previous studies about regional urban hierarchy (IBGE 2008, Sathler et al. 2010). In addition, our analysis also incorporates the northern edges of the Brazilian Amazon as part of the arc of deforestation. According to these criteria, unselected municipalities are necessarily not located in the arc of deforestation or did not have the minimal required amount of forest in the baseline year.

In this analysis, 27 initial variables represent the following dimensions: territory, deforestation and forest, demographic, education, human development, economic, inequality, poverty, and basic services (Table 1).

Deforestation and forest data were provided by INPE as part of the Amazon Deforestation Calculation Program (PRODES). Since 1988, PRODES has provided yearly open data at the municipal level, which allows researchers to integrate environmental information with multiple social and territorial dimensions. The accumulated deforestation in the Brazilian Amazon between 2001 and 2010, which was estimated by kriging interpolation, is shown together with the main physical and anthropic elements in the region (Fig. 1). There was intense deforestation between 2001 and 2010 in the most populated areas near the main cities (such as Porto Velho, Ji-Paraná, Sinop, and Marabá), paved roads (BR-163, BR-155, and BR-364), and rivers (Madeira, Araguaia, and Tocantins rivers) of southern and eastern Amazonia. Deforestation between 2001 and 2010 was especially high in Central Pará state, which includes municipalities with > 4000 km² of deforested area. Moreover, the southern Amazonas state, Western Acre, and the northern Brazilian Amazon are dominated by municipalities with deforested area > 2000 km². Despite the deceleration in deforestation registered by INPE after 2004, Fig. 1 suggests alarming information regarding the territorial extension of deforested areas in the Brazilian Amazon. To associate deforestation with the other explored dimensions at the municipal level, our analysis uses the percentage

Fig. 1. Main physical and anthropological elements and accumulated deforestation (km²) between 2001 and 2010 in the Brazilian Amazon.
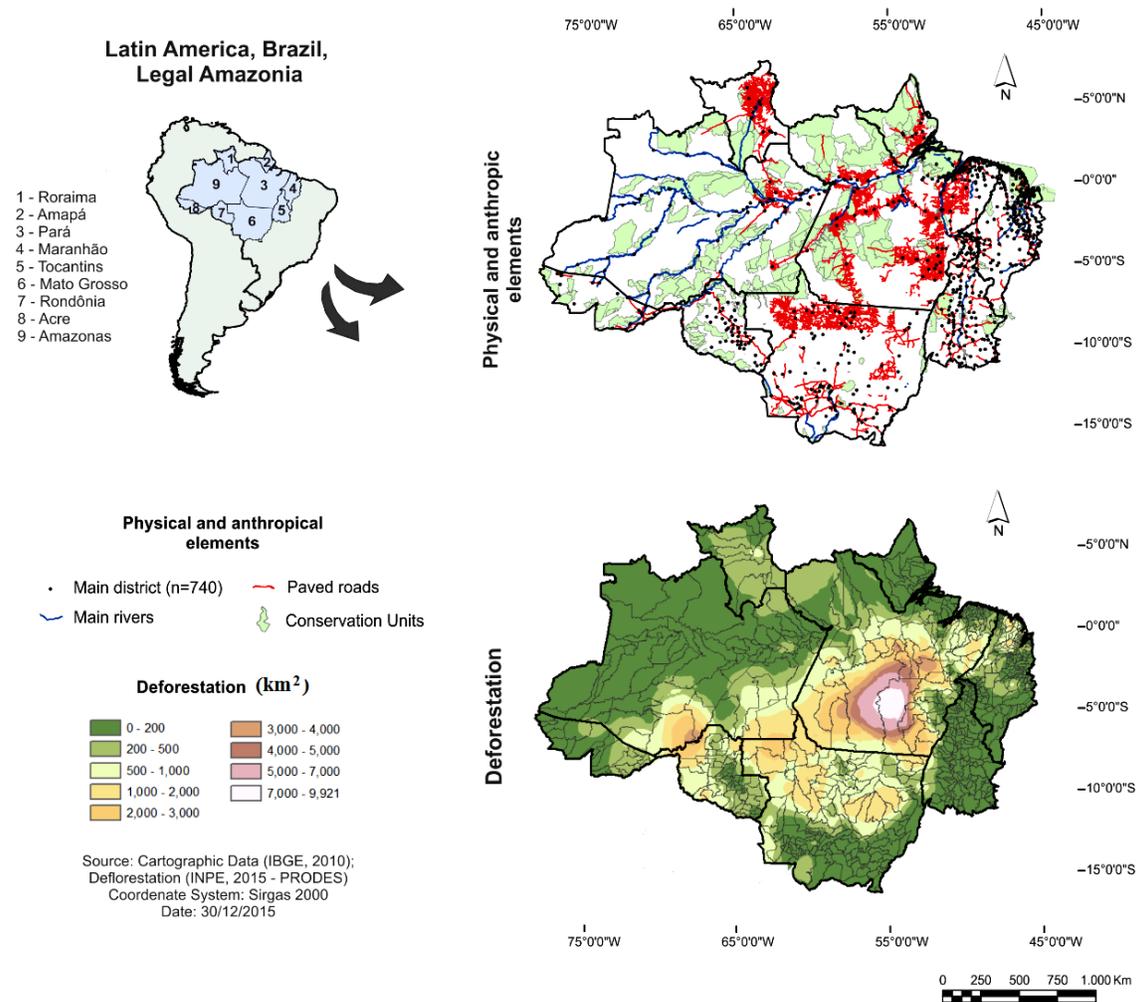
of deforested area instead of absolute area of deforestation. Given the high heterogeneity of the selected municipalities in terms of territorial size and forest stock, the percentage of deforested area offers more appropriate information for comparability.

In tropical forest, deforestation rates have been associated with demographic parameters such as population growth, migration, and age structure changes (Amacher et al. 2009, Carr 2009, Caviglia-Harris et al. 2013). In our analysis, 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, and urban and rural population growth between 2000 and 2010. The percentage of migrants is also part of this dimension and was obtained by referring to migration flows in the 10 years preceding the census (Carvalho and Rigotti 1998).

Furthermore, human development characteristics are associated with forest loss and forest recovery at the local level (Meir et al.

2011, Sathler et al. 2015). Education is represented by two variables: illiteracy rate and the percentage of poor people (defined as those with per capita household income ≤ R$ 140.00 per month in 2010) with no primary education (IBGE 2010). Other two variables are: the human development index (HDI) in 2010, and HDI variation between 2000 and 2010. This index was created by the United Nations and incorporates three indicators: per capita income, illiteracy rates, and life expectancy (PNUD 2013). Although HDI includes some information already present in Table 1, this index is a complementary measure with great potential for comparability.

Finally, most of the classic and recent literature on deforestation significantly addresses economic, inequality, poverty, and basic services aspects (Browder and Godfrey 1997, Fearnside and Graça 2009, Ebanyat et al. 2010, Hargrave and Kis-Katos 2013). 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. The inequality dimension is addressed by the Gini index, and the

Table 2. Total variance explained by the first five principal components. Data sources: INPE (2014), IBGE (2000, 2010), and PNUD (2013).

	Principal component (PC)				
Parameter	PC1 Development challenges	PC2 Forest	PC3 Size	PC4 Growth	PC5 Stagnation
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 of variance	0.380	0.512	0.612	0.683	0.728

poverty dimension is represented by the percentage of poor people. Three variables address basic services provided to households: garbage collection, electricity, and (lack of) adequate water and sanitation.

Multivariate methods

We used PCA and cluster analysis (Salvati and Zitti 2009, Bell et al. 2015) to analyze the data. PCA was used to transform a set of original and interrelated variables into a new set of octagonal and unrelated components (Lima and Braga 2013). PCA seeks to reduce a large number of variables by a small number of linear functions, which best summarizes the large initial group of covariates (Mingoti 2007, Lima and Braga 2013). PCA is relevant for our study because the information vectors in the selected data sets are redundant, which might cause bias in further cluster analyses.

Before using PCA, we performed Kaiser Meyer Olkin (KMO) and Bartlett tests. The KMO test is a measure of adequacy that checks the fit of the data using all variables simultaneously. In this test, acceptable values range from 0.7 to 0.9. From the set of 27 variables, only two did not present a value > 0.7 (agricultural and industrial GDP). Therefore, we did not include these two variables in the PCA. In addition, the sphericity Bartlett's test examines the redundancy between variables by comparing the correlation matrix with the identity matrix, i.e., the main diagonal is equal to 1 and all other values are zero. Moreover, we applied the Varimax rotation method to minimize the number of variables in each component.

PCA transformed the original set of covariates into five standardized uncorrelated components with numerical values ranging from $-\infty$ to $+\infty$, average centered on zero, and standard deviation equal to 1 (Mingoti 2007, Lima and Braga 2013). We then applied cluster analysis (using the two-step cluster algorithm) based on these five standardized and uncorrelated components to create a typology or classification of the municipalities included in the study. The cluster analysis subdivides data or objects into a number of different groups (clusters), which contain similar subjects (SPSS 2001, Everitt and Hothorn 2011). In this analysis, the two-step algorithm preclusters the records into many small subclusters, and then it aggregates those subclusters into the desired number of clusters. We selected the number of optimal clusters according to the criterion suggested by Fraley and Raftery (1998), who proposed a Bayesian information criterion for the expected maximization clustering method (SPSS 2001). We performed these multivariate methods using R version 3.2.3 software.

RESULTS

The five standardized uncorrelated components are able to explain ~73% of the total variability in the original data set, which corresponds to approximately three-quarters of the information contained in the original set of variables (Table 2). These five components exhibit eigenvalues > 1 (Fig. 2). The first two components (PC1 and PC2) present the highest proportion of variance (0.380 and 0.132, respectively) while the other components also provided relevant information for cluster definition.

Fig. 2. Scree plot of the number of components in the principal components analysis.
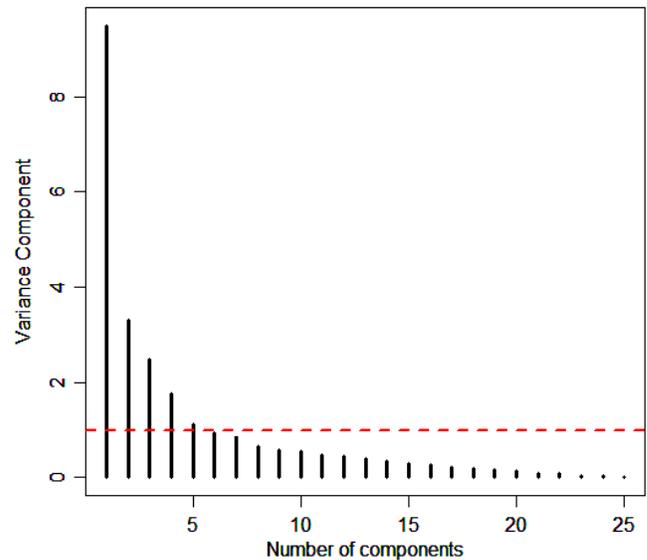
The first principal component (development challenges) characterizes municipalities with high levels of poverty, inequality, and social vulnerability. This component exhibits a high positive correlation with infant mortality (0.80), dependency ratio (0.79), illiteracy rate (0.80), percentage of poor population (0.86), and percentage of households without piped water and sewage network (0.78). It presents a high negative correlation with life expectancy (−0.83) and HDI (−0.89). The results also indicate a moderate negative correlation between the development challenges component and the percentage of urban population (−0.55) and the percentage of in-migrants (−0.52) and out-

Table 3. Correlation matrix of the rotated components obtained via varimax rotation, Legal Amazonia, 2000–2010. Data sources: INPE (2014), IBGE (2000, 2010), and PNUD (2013).

Variable	Principal component (PC)				
	PC1 Development challenges	PC2 Forest	PC3 Size	PC4 Growth	PC5 Stagnation
Municipality area (km²)	0.02	0.61	0.38	−0.04	0.06
Proportion of deforestation (%)	0.27	−0.81	−0.07	0.06	0.19
Proportion of forest (%)	−0.03	0.81	0.07	0.09	−0.11
Population	0.13	0.11	0.87	0.12	0.20
Proportion of urban population (%)	−0.54	0.02	0.56	−0.25	−0.06
Urban population growth (%/yr)	0.08	0.05	0.05	0.69	−0.34
Rural population growth (%/yr)	−0.02	−0.01	0.11	0.73	0.00
Life expectancy at birth (yr)	−0.84	0.34	−0.12	0.09	−0.04
Fertility rate (number of children)	0.69	0.32	−0.2	0.08	0.10
Infant mortality rate (per 1000)	0.80	−0.45	0.13	−0.11	0.03
Dependency ratio (%)	0.79	0.19	−0.04	0.10	0.36
Proportion of in-migrants (considering population in 2010, %)	−0.52	0.12	−0.28	0.20	−0.59
Proportion of out-migrants (considering population in 2010, %)	−0.45	−0.07	0.12	−0.68	−0.15
Illiteracy rate (per 1000)	0.80	−0.07	−0.16	0.01	0.26
Proportion 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 (%/yr)	−0.15	0.07	0.00	0.31	−0.72
Gini index	0.44	0.47	−0.14	−0.01	0.33
Proportion of poor people (%)	0.86	−0.01	−0.14	0.15	0.4
Proportion of urban households with garbage collection (%)	−0.46	0.42	0.11	−0.06	−0.31
Proportion of households with electricity (%)	−0.43	−0.62	0.24	−0.32	−0.27
Proportion of households with inadequate water and sanitation (%)	0.78	−0.08	0.09	0.22	0.28

migrants (−0.45). Very low levels of HDI in 2000 explain the positive correlation between the first principal component and HDI variation during the decade (0.75). The second principal component (forest) presents a strong negative correlation with the percentage of deforestation (−0.82) and a positive correlation with the percentage of forest in 2010 (0.82). It also exhibits a moderate positive correlation with municipality area (0.61). The third principal component (size) characterizes municipalities with the highest values of population size (0.87) and GDP (0.75). In addition, size presents a moderate positive correlation with the percentage of urban population (0.56). The fourth principal component (growth) presents a positive correlation with the urban (0.69) and rural (0.73) growth rates. It also presents a negative correlation with the percentage of out-migrants (−0.68). The fifth principal component (stagnation) exhibits a negative correlation with GDP growth between 2000 and 2010 (−0.72). Stagnation also presents a moderate negative correlation with the percentage of in-migrants (−0.59). This component is positively correlated with the services GDP (0.73), which characterizes municipalities with low levels of investments in the agricultural and industrial sectors in the Amazonian context (Table 3).

We constructed a typology of municipalities through the PCA and cluster analysis (Table 4). Based on the Bayesian information criterion, four clusters are the best solution for the algorithm used. The spatial distribution of these clusters forms four deforestation frontiers in the study area: stagnated, dynamic deforestation, consolidated, and internal deforestation (Fig. 3, Table 5).

The stagnated frontier (cluster 1) groups 35 municipalities with the highest average values for the development challenges component (0.64) and a high average value for the stagnation component (0.69). These municipalities have the most adverse social indicators among the clusters; they present, on average, the lowest values of HDI, as well as the highest values of infant mortality rate, illiteracy rate, and the percentage of people with poverty vulnerability and without complete primary education. The development challenges component also indicates that these municipalities have on average a high fertility rate and a high dependency ratio. This frontier is also 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 present negative values in the forest component, suggesting small territorial size, high percentage of deforested area between 2001 and 2010, and low percentage of forested area in 2010.

The dynamic deforestation frontier (cluster 2) aggregates 77 municipalities that exhibit a high negative average for the stagnation component (−0.79) and a moderate positive average for the size component (0.48). These municipalities present the highest values of GDP variation and a significant migratory attractiveness. Despite the moderate positive average for the size component, the dynamic deforestation frontier aggregates municipalities with the largest population stocks and the highest GDP values. In addition, these municipalities present on average a low forest component (0.125).

Table 4. Typology of municipalities and cluster results (mean and frequency) based on estimated principal components, 2000–2010. Data sources: INPE (2014), IBGE (2000, 2010), and PNUD (2013).

Typology	Development challenges	Forest	Size	Growth	Stagnation	N
Stagnated frontier (cluster 1)	0.642	−1.602	−0.084	−0.017	0.687	35
Dynamic deforestation frontier (cluster 2)	0.140	0.125	0.480	0.275	−0.791	77
Consolidated frontier (cluster 3)	−0.972	−0.004	−0.312	−0.821	−0.086	52
New deforestation frontier (cluster 4)	0.367	0.993	−0.379	0.469	0.879	47

The consolidated frontier (cluster 3) presents the lowest average values for the development challenges and growth components (−0.97 and −0.82, respectively). These municipalities have the most favorable social indicators among the groups and present, on average, the highest values of HDI and the lowest values of infant mortality rate, illiteracy rate, and the percentage of people with poverty vulnerability and without complete primary education. These municipalities exhibit on average 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 present average values near to zero in this frontier. The consolidated frontier also has lower GDP variation and migratory attractiveness than the dynamic deforestation frontier. Moreover, this frontier groups municipalities with intermediate territorial size for the regional patterns and no large variations in the percentage of deforested area between 2001 and 2010.

The internal deforestation frontier (cluster 4) aggregates municipalities with high average values for the forest (0.99) and stagnation (0.87) components. The development challenges (0.36), growth (0.47), and size (−0.38) components present moderate values in this frontier. These municipalities have on average a low percentage of deforested areas, high percentage of forest in 2010, and large territorial dimensions. In addition, these municipalities present on average small populations and economies. Therefore, the internal deforestation frontier is characterized by municipalities presenting, on average, low economic growth and undiversified economy. The moderate level for the development challenges component shows that the internal deforestation frontier has, on average, higher fertility and dependency ratio levels than do the dynamic deforestation and consolidated frontiers.

This typology of municipalities presents a well-defined pattern in terms of localization and contiguity (Fig. 3). Municipalities comprising the stagnated frontier (cluster 1) have the lowest territorial dispersion and are mainly located in the northern Maranhão state. In contrast, municipalities grouped in the dynamic deforestation frontier (cluster 2) present the highest territorial dispersion. These municipalities are located in the heart of the arc of deforestation, especially in the eastern and southern Pará state. These municipalities are also located in regions with important regional railways and massive agricultural projects such as in the central part of Mato Grosso and Maranhão, and in Rondônia state. The municipalities grouped in the consolidated frontier (cluster 3) are mainly located in Mato Grosso state, with little significant presence in Rondônia and eastern Pará. In Mato Grosso, municipalities grouped in the consolidated frontier

surround the municipalities of cluster 2 located near the 153 road. Finally, the municipalities grouped in the internal deforestation frontier (cluster 4) were mainly located in the northern Brazilian Amazon, especially in areas where transportation is exclusively by river. These municipalities are also present in Acre state, as well as in southern Amazonas and southern Pará.

DISCUSSION
Spatial data integration and statistical analysis provided multiple results by exploring 25 environmental, socio-demographic, and economic variables at the municipal level in the Amazonian arc of deforestation. In the PCA, development challenges and forest components were decisive for cluster definition, whereas size, growth, and stagnation components provided relevant complementary information for understanding the sustainable developmental dynamics in the study area. Our typology of municipalities revealed four deforestation macro-frontiers, i.e., stagnated frontier, internal deforestation frontier, dynamic frontier, and consolidated frontier, which correspond to distinct interactions between deforestation and human development levels. We present here a discussion on the main characteristics of these frontiers.

In the stagnated frontier, municipalities have, on average, the lowest human developmental levels, high deforestation rates, and low percentage of forested areas. In the 1990s, Jha and Bawa (2006) found this same pattern by investigating 30 of the most important world deforestation hotspots in areas characterized by high population growth. However, the stagnated frontier exhibited high levels of environmental depletion between 2000 and 2010, even with low population growth and severe economic stagnation.

In the internal deforestation frontier, deforestation is also clearly associated with low levels of human development. In fact, the arc of deforestation traditionally encompasses areas characterized by low levels of human development (Ministério do Meio Ambiente 2008, Meir et al. 2011). Population growth between 2000 and 2010 in this frontier was not mainly driven by migration, as observed in the dynamic deforestation frontier and in the hotspots investigated by Jha and Bawa (2006). Our findings show that the significant population growth exhibited by municipalities grouped in the internal deforestation frontier might be explained by low out-migration and strong natural growth in the assessed period. In addition, these municipalities present, on average, significant percentages of forested area and huge territorial area, which contributes to the relatively low percentages of deforestation registered between 2001 and 2010. The absolute deforestation figures are significant in the internal deforestation

Fig. 3. Spatial distribution and main characteristics of the frontiers in the arc of deforestation, Legal Amazonia, 2000–2010.
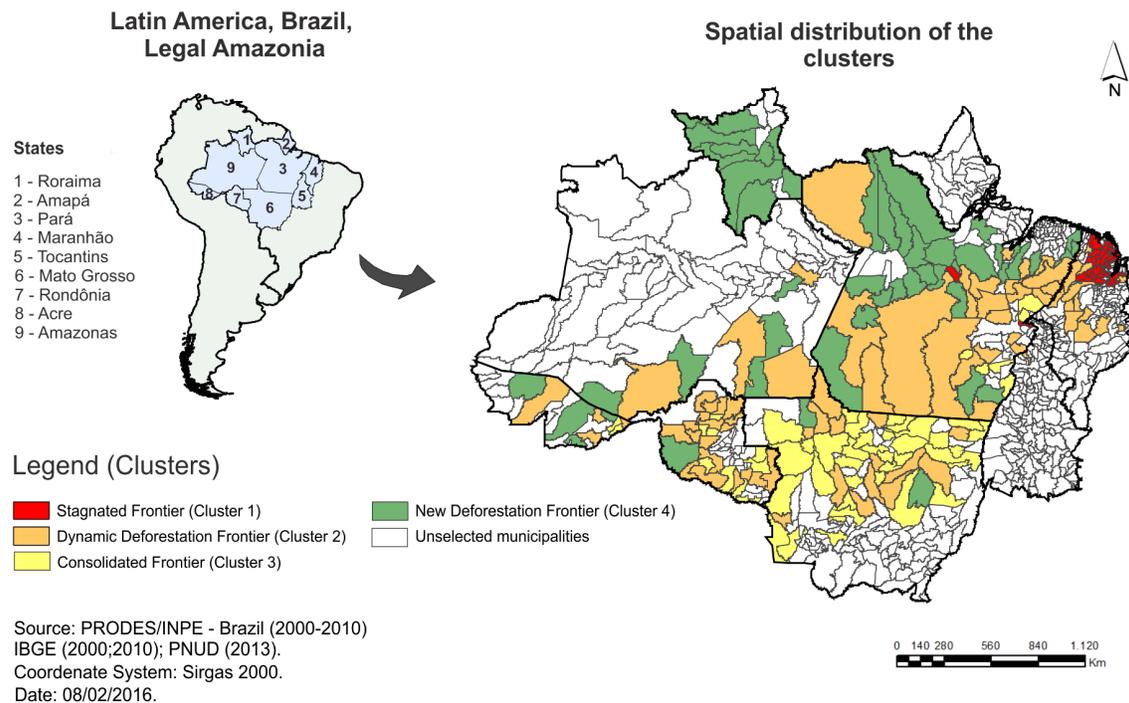
frontier, given its high values for the stagnation component and its low values for the size component.

The associations between forest loss and social variables are less clear in the dynamic deforestation frontier and in the consolidated frontier, in which the proliferation of economic activities and the historical advancement of the arc of deforestation were crucial for the cluster configurations. The dynamic deforestation frontier has presented significant economic growth between 2000 and 2010, which was mainly driven by agricultural and industrial activities (Fearnside and Graça 2009, Ebanyat et al. 2010). However, human development levels and social variables did not grow to the same degree, which may have increased environmental vulnerability in these areas. In addition, municipalities grouped in the consolidated frontier exhibited significant deforestation levels between 2001 and 2010, even presenting, on average, the highest regional levels of human development.

Our analysis also indicates well-defined differences between the explored parameters, revealing some interesting patterns among the frontiers. Significant migratory attractiveness and economic dynamism exhibited by the dynamic deforestation frontier, as well as the high out-migration levels presented in the consolidated frontier, suggest complementarity in the demographic dynamism between these areas. This finding corroborates those of previous studies that demonstrate the predominance of internal migration in the region (e.g., Perz 2002, Becker 2005). In addition, the information regarding urban and rural population growth, fertility rate, and dependency ratio might indicate that municipalities grouped in the stagnated frontier and in the internal deforestation frontier are delayed in the demographic transition

when compared to the other frontiers. Generally, the pace of the demographic transition is strongly related to human developmental levels and economic growth, with developed regions more advanced in this process than developing regions (Lee 2003, Reher 2011). Our results are consistent with demographic transition theory because human development levels are lower in the stagnated frontier and the internal deforestation frontier than in the other frontiers.

Development levels are associated not only with more opportunities that assure forest conservation, but also with demographic changes that might cause negative environmental impacts such as increases in consumption and land demands in the region (Campos 2014, Mello and Sathler 2015). Demographic transition and age structure changes are increasingly affecting the population distribution and are also creating environmental pressures in both urban and rural areas in the Brazilian Amazon (Perz et al. 2008). 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). In addition, young adults are likely to be relevant actors in labor migration (United Nations 2011, Kupiszewski et al. 2013), which can affect the population distribution and increase the pressure on natural resources in the Brazilian Amazon.

The related literature suggests that variations in the household life cycle and reductions in the dependency ratio driven by the demographic transition might threaten forest preservation in rural areas (Bilsborrow and Stupp 1997, Bilsborrow and Carr 2001, Moran et al. 2003, Guedes et al. 2011). According to complementary information provided by IBGE (2010),

Table 5. Key characteristics of the four clusters and main policy recommendations.

Variable	Stagnated frontier (*N* = 35)	Dynamic deforestation frontier (*N* = 52)	Consolidated frontier (*N* = 52)	Internal deforestation frontier (*N* = 47)
Key characteristics	Highest average in the nondevelopment (0.64) and stagnation (0.69) components; most adverse social indicators among the clusters, presenting on average the lowest values of Human Development Index and the highest infant mortality and illiteracy rates; high percentage of deforested forest area in the analyzed period and low percentage of forest in 2010	High negative average of stagnation component (0.79) and a moderate positive average of size component (0.48); highest values of gross domestic product variation and a significant migratory attractiveness; highest population stocks and gross domestic product values	Lowest average values of nondevelopment and growth components (−0.97 and −0.82, respectively); most favorable social indicators among the groups, presenting on average the lowest values of Human Development Index and the lowest infant mortality and illiteracy rates; intermediate territorial size and no large variations in the percentage of deforested area	High average values in the forest (0.99) and stagnation (0.87) components; low percentage of deforested areas; high percentage of forest in 2010 and large territorial dimensions
Main policy recommendations	Focus policies on promoting forest recovery, starting from the most ecologically vulnerable areas such as those surrounding springs and streams; local developmental policies should support economic diversification by attracting more investments in nontraditional economic sectors and improving existing services with no negative impact on forest regeneration	Continuously strengthen environmental monitoring and control policies in the short and medium terms; long-term policies should reduce expenditures on monitoring and control of deforestation and increase the income supported by forestry ecological services; policies must be aware of the intense economic and demographic changes; local governments should face the challenge of transforming economic growth in sustainable development, especially in mining areas that clearly require economic diversification polices	Stakeholders should promote actions to regenerate the forest, especially in areas most affected by cattle and soybean production; policies seeking economic development must stop depleting natural resources by implementing the Crop-Livestock-Forestry Integration System to increase the eco-efficiency of agricultural activities	Municipalities located in the southern arc of deforestation require more attention in maintaining forest stocks and improving living conditions, given the high deforestation rates presented by neighbors grouped in the dynamic deforestation frontier; policies strengthening conservation areas and traditional communities should be stimulated, seeking to curb the expansion of deforestation, especially in Amazonas state

municipalities grouped in the dynamic deforestation (63.30%) and consolidated (66.96%) frontiers have, on average, higher proportions of adults (15 to 64 years) than do municipalities grouped in the stagnated (61.43%) and internal deforestation (58.98%) frontiers, and these numbers are likely to increase in the next decade (Rigotti 2012).

Policy recommendations
Our results might assist in the design of policies seeking regional and local sustainable development for the preservation and regeneration of forests in the assessed municipalities. The stagnated frontier deserves special attention in the implementation of sustainable development initiatives, given its extremely low forest stocks and human development levels. Policies need to focus on promoting forest recovery, starting from the most ecologically vulnerable areas such as those surrounding springs and streams. Local developmental policies that support economic diversification might attract more investments in nontraditional economic sectors and improve the existing services with no negative impact on forest regeneration. Currently, forest stocks do not provide significant environmental services for populations living in the stagnated frontier, which might hinder human development growth.

In the dynamic deforestation frontier, the continuous strengthening of environmental and control policies is vital in the short and medium terms. In the long term, policies seeking sustainable development can promote an important paradigm shift in the dynamic deforestation frontier, which would imply the reduction of expenditures on monitoring and control of deforestation and the increase in income supported by forestry ecological services. Otherwise, forest protection will indefinitely demand a significant amount of financial resources invested in monitoring and control initiatives (Angelsen 2008, Böttcher et al. 2009, Sathler et al. 2015). In addition, public policies need to be aware of the intense economic and demographic changes in the dynamic frontier. Local governments will face the challenge of transforming economic growth in sustainable development, especially in mining areas that clearly require economic diversification policies, e.g., Canaã dos Carajás and Ourilândia do Norte in Pará state (SEICOM 2013). In addition, the immense distances between the main districts and areas presenting higher deforestation rates within some municipalities might hinder local actions in the dynamic deforestation frontier, especially those located in southern Amazonas (Apuí and Manicoré) and southern Pará (Novo Progresso, Altamira, and São Félix do Xingu).

The consolidated frontier presents the best social indicators among the frontiers in the arc of deforestation, which, in theory, can contribute to sustainable developmental growth by curbing

deforestation. In the consolidated frontier, it is urgent for stakeholders to promote actions to regenerate the forest, especially in the areas most affected by cattle and soybean production. Policies seeking economic development must stop depleting natural resources by implementing local strategies to increase the eco-efficiency of agricultural activities in this frontier (Pacheco et al. 2013). Because the arc of deforestation has greatly damaged the forest stretching from the southern portion of the Brazilian Amazon 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 sustainable development, advancing also from the southern portion toward the interior of the region. Therefore, the consolidated frontier of deforestation might become the new frontier of sustainable development.

The internal deforestation frontier presents the lowest development level among clusters that still have significant stocks of forest such as the dynamic deforestation frontier and the consolidated frontier. In the internal deforestation frontier, deforestation has not been driven mainly by external economic forces, which generally follow a linear logic of territorial occupation in the arc of deforestation. Instead, deforestation has been strongly associated with demographic and socioeconomic characteristics such as age structure, household patterns, economic activities, and land occupation (Moran et al. 2003, Guedes et al. 2011). In the internal deforestation frontier, the municipalities located in the southern arc of deforestation require more attention in maintaining the forest stocks and improving living conditions, given the high deforestation rates presented by neighbors grouped in the dynamic deforestation frontier. In this frontier, conservation areas and indigenous lands play an important role in preserving the forest (Nepstad et al. 2006, Soares-Filho et al. 2010). Therefore, policies strengthening conservation areas and traditional communities in this frontier are critical to curb the expansion of deforestation, especially in Amazonas state.

For example, recent studies have explored the positive effects of conditional cash transfers and payments for environmental services on rainforest preservation at the local level (Rawlings and Rubio 2005, Zbnden and Lee 2005, Persson and Alpízar 2013). In Amazonas state, the Bolsa Floresta program clearly associates improvements in human development with preservation practices at the local level, which have been reducing forest loss in the small and isolated communities (Börner et al. 2013, Piperata et al. 2016). Our results suggest that other Amazonian states may achieve interesting results by replicating the Bolsa Floresta program, especially in municipalities located in the internal deforestation and dynamic deforestation frontiers. In addition, the federal government may require environmental compensation from the beneficiaries of this program by partially increasing this benefit in some selected areas within the arc of deforestation. Further studies should assess the effects of cash transfer programs designed with no environmental compensation in the Brazilian Amazon, such as Bolsa Família.

As a complementary recommendation, municipalities must continually strengthen their interaction in projects developed at the regional and national levels. According to MacCarney (2006), the lack of interaction between local governments and regional and national efforts can lead to the failure of public policies. In the Brazilian Amazon, municipalities have the opportunity to take advantage of the mobilizations, plans, and actions developed for states and the national government. The Sustainable Amazonia Plan 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.

Finally, public policies seeking regional and local sustainable development need to address the recent demographic changes in the Brazilian Amazon by taking into account both opportunities such as the positive effects of the high percentage of adult population on the economy, and challenges such as the regional increase in consumption and land demands arising from demographic transition, household changes, and migration trends in the region.

CONCLUSION

By exploring 211 small and medium-sized municipalities (in terms of population) in the Amazonian arc of deforestation, we find four well-defined macro-deforestation frontiers that exhibit distinct interactions between forest loss, sociodemographic and economic characteristics, and human development levels: the stagnated frontier, the dynamic deforestation frontier, the consolidated frontier, and the internal deforestation frontier. Our analysis shows different levels of population and economic pressures in these frontiers while revealing some important trends such as the internalization of investments and demographic growth in the arc of deforestation. In addition, population growth and in- and out-migration patterns suggest a demographic complementarity among frontiers.

Our results support public policies seeking to address deforestation and forest degradation through regional and local sustainable development initiatives in the Brazilian Amazon. In the stagnated frontier, which is formed by municipalities presenting the lowest levels of human development and a high proportion of deforested area, public policies will face the challenge of promoting economic diversification at the local level and forest recovery in the most ecologically vulnerable areas in Maranhão state. The dynamic deforestation frontier, which presents the highest economic growth between 2000 and 2010, needs to strengthen its environmental monitoring and control policies continuously in the short and medium terms. In the long term, regional and local governments can mitigate the negative effects of economic growth by developing sustainable practices in these areas. In the consolidated frontier, which groups municipalities presenting the most favorable social indicators among the explored clusters, public policies can reduce environmental impacts and promote forest regeneration by increasing the eco-efficiency in large areas affected by cattle and soybean production, especially in Mato Grosso state. Finally, the internal deforestation frontier comprises stagnated municipalities that presents large territorial dimensions and high proportions of forest. In this frontier, governments can protect the forest by strengthening conservation areas and fostering sustainable development initiatives among traditional communities. In the internal deforestation frontier, monitoring and control policies are important in municipalities located in the southern arc of deforestation.

Our investigation confirms the need for specific analysis in social and environmental studies for small and medium-sized municipalities within the arc of deforestation. In these municipalities, economic investments and the advancement of frontiers might cause significant local changes in some key explored variables, especially those presenting low levels in the base year. In fact, small and medium-sized municipalities serve as logistics bases for agro-industrial and mining projects, ensuring frontier expansion and the internalization of economic activities (Becker 2005, Monte-Mor 2013). In addition, the interpretation of some variables can change according to the population size or the level of importance of the municipality in the regional hierarchy. For example, high values of services in the GDP composition in the explored municipalities are strongly associated with lower levels of economic diversification and lack of investments in other economic sectors. This finding has a different meaning for the administrative capitals and large municipalities that have economies based on more specialized and diversified services (IBGE 2000, 2010).

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

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