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Assessing the regional context of migration in the Brazilian Amazon through spatial regression modeling☆

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ABSTRACT

The Brazilian Amazon contains the most active rainforest frontier in the world, and its socioeconomic, demographic and spatial dynamism has been a topic of interest for academics and policy makers for decades. In this paper, we use spatial statistical modeling to examine the context of migration in the Brazilian Amazon by investigating its socioeconomic, demographic, spatial and environmental heterogeneities at the municipal level between 2000 and 2010. First, we visualized the spatial distribution of net-migration, in-migration and out-migration rates among municipalities in the Brazilian Amazon. Then, we explored the presence of spatial autocorrelation using Global Moran's *I* Index, and use spatial modeling techniques to investigate the associations between response variables (in-migration and out-migration) and selected explanatory variables. We identified several in-migration frontiers in the region, especially in Center Mato Grosso and Southeast Pará, while out-migration seems more diffuse in the Amazonia territory. Global Moran's *I* scores indicate that most of the selected variables exhibit spatial dependence, and the spatial regression models present better estimates of the coefficients by incorporating the spatially lagged autoregressive parameter. Our results also confirm the spatial heterogeneity and multidimensional character of in-migration and out-migration in the Brazilian Amazon. Economic growth, regional inequality and the environmental dynamism of the rainforest frontier appear to be closely associated with the intensity of migration flows in the region. We also find that less-populated municipalities have a central role in regional migration dynamics, forming relevant in-migration frontiers and ensuring territorial robustness for migration in the region.

1. Introduction

The Brazilian Amazon contains the most active rainforest frontier[1] in the world, and its socioeconomic, demographic and spatial dynamism has been a topic of interest for academics and policy makers for decades (Schmink and Wood, 1984; 1992; Browder & Godfrey, 1997; Becker, 2005; Fearnside, 2008; Sathler et al., 2009; Guedes et al., 2012). Since the 1970s, intense cycles of regional economic growth were followed by deep social changes and major shifts in the Amazonian population distribution (Ebanyat et al., 2010; Fearnside, 2008; Ramos, 2014). The consequent expansion of the territorial heterogeneities has created a dynamic context in which interregional and intraregional migration flows have assured the evolution of the rainforest frontier and the consolidation of the urbanization process in the region (Caviglia-Harris, Sills, & Mullan, 2012; Monte-Mór, 2013; Padoch et al., 2008).

Migration patterns in rainforest frontiers are, in general, complex and multidirectional (Caviglia-Harris et al., 2012), typically driven by different multilevel factors associated with the regional context and the migratory network structures (Entwisle et al., 2007). The effects of macro level government policies and private investments usually play an important role for migration in these areas (Carr, Suter, & Barbieri, 2006). Likewise, micro-level factors influence generations of migrants, as is the case with local labor markets (Shively & PAGIOLA, 2004;

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Shrestha and Bhandari, 2007), age structure (Barbieri, Carr, & Bilsborrow, 2009), household composition (Bilsborrow, 2002; Brondizio et al., 2002) and local environmental depletion (Celentano, Sills, Sales, & Verissimo, 2012; Rodrigues et al., 2009). In addition, network analyses reveal that social ties, personal goals and household strategies are also relevant to shape migration patterns in rainforest frontiers (Randell & VanWey, 2014).

In the Brazilian Amazon, the regional migratory history has been strongly associated with deep economic changes. In the 1970s, infrastructure expansion (roads, ports and hydroelectric plants) and the emergence of new economic actors (mining, industry, ranching and soybean producers) triggered intense migration from other parts of Brazil toward the Amazonian frontier (Ebanyat et al., 2010; Fearnside & Graça, 2009). Since the 1980s, intraregional migration has been predominant and the evolution of the rainforest frontier was manly shaped by economic actors already stablished in the region (Becker, 2005; MMA, 2008). In addition, the latest Brazilian censuses (IBGE, 2000; 2010) demonstrate that recent economic changes have enormously increased Amazonian territorial disparities (Lira, Silva, & Pinto, 2009; Prates and Bacha, 2011), unequally impacting regional development, and featuring increased intraregional migration (Cunha, 2011).

Major shifts in the regional demographic context have also occurred in the past decades, such as rapid urbanization (Monte-Mór, 2013; Vicentini, 2006) and changes in population age-structure (Paiva & Wajnman, 2005). In the Brazilian Amazon, both intra-municipal (rural-urban) and inter-municipal migration have been key determinants to rapid regional urban growth (Padoch et al. 2008). The urban population in the Brazilian Amazon was 45.5% in 1970, and continued to grow by reaching 55.8% in 1980, 68.9% in 2000 and 72.5% in 2010 (IBGE, 1980; 1991; 2000; 2010). In this context, Becker (1990; 1995) uses the terms "urban forest" and "urban frontier" to describe the role of cities as nodes of economic development and territorial occupation. Moreover, the demographic transition is changing dramatically the age structure in the Brazilian Amazon by decreasing the percentage of children, pushing it into an increase in the percentage of young adults (Carvalho & Wong, 2006; Paiva & Wajnman, 2005), which may have an effect in intraregional migration flows (Cunha, 2011).

Understanding migratory dynamism is vital for policies seeking sustainable development at the local and regional levels. Recent literature describes internal migration as a positive force for development, as migrants transfer knowledge to receiving municipalities, spread investments and remittances, and are an incentive for business opportunities (UNCSD, 2012; World Bank, 2016). However, migration is often related to social challenges and expressive changes on physical landscapes in tropical forests. In the Brazilian Amazon, increasing Gross Domestic Product (GDP) from fostering economic activities in rainforest frontiers have not pushed social indicators at satisfactory levels (Sathler et al., 2018). Furthermore, previous literature widely considers migration as an important contributor to deforestation and land degradation in the Brazilian Amazon (Amacher, KOSKELA, & OLLIKAINEN, 2009; Carr, 2009; Caviglia-Harris et al., 2012). Environment depletion via soil degradation has been one of the leading causes of internal migration further into the rainforest frontier (Caviglia-Harris et al., 2012). At the local level, *boom and bust* economic cycles were also relevant drivers for in-migration and subsequent out-migration in the Brazilian Amazon (Rodrigues et al., 2009).

Integrating recent environmental and demographic data is fundamental to studies seeking a better understanding of the association between migration, social variables and environment depletion in the Brazilian Amazon.Despite these relevant findings, migration data provided by the latest Brazilian census (IBGE, 2010) is clearly underutilized. In this paper, our empirical analysis uses spatial statistical modeling with census data to examine the context of migration in the Brazilian Amazon by investigating its socioeconomic, demographic, spatial and environmental heterogeneities at the municipal level between 2000 and 2010. Initially, we explored and visualized the spatial autocorrelation among factors using Global Moran's *I* Index. Subsequently, we use spatial modeling techniques to investigate the associations between response variables (in-migration and out-migration) and selected explanatory variables.

We focus on the following specific questions:

(1) Is there any spatial dependence in the explored variables, and, if so, how should this characteristic be appropriately addressed in the spatial regression models?
(2) Which contextual factors significantly explain in-migration and out-migration rates in the Brazilian Amazon?

The next section presents the data and methods; the following section shows the results of the spatial analysis; finally, we provide a discussion of the regional context of migration highlighting its major implications for public policies seeking sustainable development in the Brazilian Amazon.

2. Data and methods

2.1. Data

We investigate the associations between migration and contextual socioeconomic, demographic, connectivity, and environmental factors, from 740 municipalities in the Brazilian Amazon. These municipalities are distributed in nine states (Acre, Amazônas, Rondônia, Roraima, Mato Grosso, Pará, Maranhão, Tocantins and Macapá) forming the "Legal Amazon". The emancipated municipalities in Legal Amazon between 2000 and 2010 (n = 15), as well as their municipalities of origin (n = 16) were not considered in this analysis due to data incompatibility in some variables. The Legal Amazon extends for 5,016,136.3 km^2, which corresponds roughly to 59% of the Brazilian territory.

In this study, internal migration rates were operationalized as in-migration and out-migration rates, calculated with data from the latest Brazilian census, in 2010 (IBGE, 2010). We used in-and-out migration rates as response variables for two main reasons. First, net-migration models may confound changes in migration propensities with changes in population stocks, producing a misspecification in the investigated associations (Rogers, 1990). Second, having distinct migration models make it possible to separate factors associated with "deciding to leave" (out-migration) from factors associated with "destination selection" (in-migration), exploring in some detail a complex process that involves numerous decisions (Chort & Rupelle, 2016; Tabor et al., 2015; Williams and McMillen, 1980). In-migrants and out-migrants were identified from a sample of individuals who were 5 years old or older in 2010, and who declared to have resided in a different municipality in 2005 (IBGE, 2010); and subsequently aggregated in a migratory matrix at the municipal level. Internal migration rates were calculated using municipal population at the end of the period (2010). Fig. 1 presents the study area, highlighting the main physical and anthropic elements, such as districts, rivers, paved roads and conservation units.

Based on a review of the subject's literature, this study focuses on six main dimensions to potentially explain internal migration in the Brazilian Amazon: a) demographic, b) economic, c) development, d) inequality, e) connectivity, and f) environment. Thirty-nine initial variables were explored, but only twelve are included in the models due to multi-collinearity and confounding issues. These variables express the municipal context at the end of the analyzed period (2010) or the variation between the two last Brazilian censuses (2000–2010) at the municipal level. Data sources include the Brazilian census micro-data (IBGE, 2000; 2010), PNUD indicators (2010), Brazilian 1:250.000 maps (IBGE, 2016) and INPE (2000–2010). Table 1 displays summary statistics of response and explanatory variables, organized by topic.

Studies typically associate migration with population stock, urbanization and age structure, highlighting the impacts of the demographic

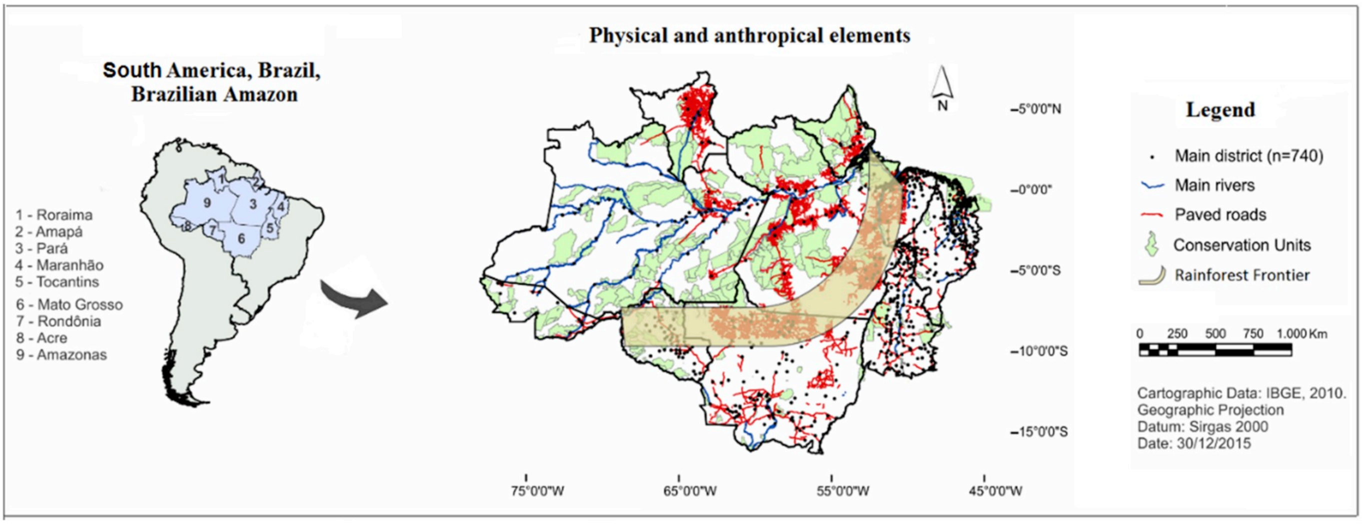

Fig. 1. Study area and main geographical elements in the Brazilian Amazon, 2005–2010.

context on migration as well as the migration effects on demographic variables (UN, 2011; Karahan & Rhee, 2014). In this analysis, the demographic dimension is represented by three variables: population, urban population growth (2000–2010), and the percentage of the population between 20 and 39 years old. In addition, most of the classic and recent literature on internal and international migration significantly addresses the economic and development dimensions (Massey et al., 1993; De Haas, 2010), which are represented in this study by the following four variables: variation in Gross Domestic Product (GDP) (2000–2010); the percentage of services GDP; human development index (HDI)[2]; and variation in HDI (2000–2010). Furthermore, there is a consolidated literature addressing internal migration and social inequality in developing countries (Kanbur & Rapoport, 2005; Black et al., 2006; Chiswick and Miller, 2015). In this study, the social inequality dimension at the municipal level is represented by the Gini index. In addition, the connectivity dimension includes two variables: distance to the closest major center (distance between centroids of an observed municipality and the closest municipality with a larger population) and distance to a paved road. We calculated these variables by using the main districts of municipalities as a locational reference (Fig. 1). Finally, we incorporated two variables in order to represent the environment dimension in this analysis given the migration impacts on deforestation as well the environment depletion effects on migration (Amacher et al., 2009; Carr, 2009; Caviglia-Harris et al., 2012; Rodrigues et al., 2009): deforested area (2005–2010) and the percentage of forested area in 2010. These open data were provided by National Institute for Spatial Research (INPE), as part of the Amazonia Deforestation Calculation Program (PRODES). Since 1988, this program has provided yearly data at the municipal and regional level, which allows researchers to integrate environmental information with multiple social and territorial data in the Brazilian Amazon.

2.2. Methods

Initially, we construct three maps demonstrating the spatial distribution of the response variables (in-migration and out-migration

Table 1
Summary statistics (mean, standard deviation, median, minimum and maximum values) of response and explanatory variables; n = 740 municipalities in the Brazilian Amazon, 2000–2010.
Source: IBGE (2000; 2010). PNUD (2010). INPE (2000–2010).

Variables	Mean ± Std	Median	Minimum	Maximum
Response variables				
In-migration rate (%)	9.80 ± 6.18	8.61	0.56	36.48
Out-migration rate (%)	9.69 ± 4.55	9.18	1.25	31.78
Explanatories				
Demographic				
Total population	32,435 ± 101,574	14,805	1037	1,802,014
Urban population growth (2000–2010) (% by year)	1.76 ± 9.01	2.30	−48.87	95.75
% Population between 20 and 39 years	31.46 ± 2.76	31.16	23.71	43.81
Economic and Development				
Variation in GDP (2000–2010)	7.38 ± 3.73	6.84	−4.27	39.63
% Services GDP	58,37 ± 13.73	59.03	13.43	92.60
HDI	0.61 ± 0.06	0.61	0.49	0.79
Variation in HDI (2000–2010)	3.31 ± 1.01	3.23	1.07	8.01
Social Inequality				
Gini Index	0.56 ± 0.06	0.55	0.38	0.80
Connectivity				
Distance to the closest major center (km)	68,66 ± 115.05	37.98	1.17	1454.20
Distance to a paved road (km)	19,38 ± 42.55	0.00	0.00	347.19
Environment				
% Deforested area (2005–2010)	6.96 ± 14.25	2.01	0.00	97.86
% Forested area (2010)	25.17 ± 28.32	13.07	0.00	98.73

rates) and net-migration rates in the Brazilian Amazon. In addition, we investigate our data using the global Moran's I index, including both the response (in-migration and out-migration rates) and the twelve explanatory variables. This index provides a summary spatial correlation measure, where a value of 0 indicates no spatial correlation and a value of 1 a complete clustering pattern. An observation is surrounded by neighbors with similar values when the observed I is higher than its expected value (E[I]). If the observed I is lower than its expected value, the observation tends to be surrounded by neighbors with different values (Schabenberger and Gotway, 2005; Sparks and Sparks, 2010).

In the regression analysis, we first inspected the data and run a series of correlation matrices among all variables. In addition, we used the Variance Inflation Factor (VIF) test in order identify those variables that would contribute to statistical multicollinearity in both models (i.e. in-and-out migration). Based on this preliminary analysis, we selected twelve explanatory variables by representing the five explored dimensions.

Subsequent data transformation included normalizing all predicting variables, subtracting the corresponding mean and dividing by the standard deviation. Moreover, Ordinary Least Squares (OLS) models were run to model linear relationships for both in-and-out migration rates. A series of Moran's I among the models' residuals were also conducted, in order to obtain the intensity and significance of the spatial relationships within the error terms. Spatial patterns were also confirmed through Breusch-Pagan tests, via heteroscedasticity.

Once spatial associations were confirmed, Lagrange Multiplier (LM) diagnostics were conducted following Anselin's methodology (Anselin, 2004; 2007). Table 2 shows the results from the LM tests. In this table, both spatial lag (LMlag) and spatial error (LMerr) models' LM tests resulted significant for both in-migration and out-migration. Therefore, robust model forms (i.e. RLMerr and RLMlag) might provide a better fit (Anselin, 2004; 2007). The higher RLMlag statistic indicates the lag specification as a better alternative for both models (Anselin, 2004).

Moreover, we estimated the spatial regression models through the maximum likelihood principle according to equation (2). These models were built based on the spatial weights matrix W (Ward and Gleditsch, 2008). In this analysis, we incorporated the spatial effects by including a spatially lagged response variable as an additional predictor:

$$y = \rho Wy + x\beta + \varepsilon \tag{2}$$

where Wy is the spatially lagged component on the response variables for weights matrix W; χ is a matrix of observation on the explanatory variables; ε is a vector of error terms and ρ is the spatial coefficient ($\rho = 0$ indicates no spatial dependence). Finally, we use Akaike Information Criterion (AIC) to estimate the higher relative quality of spatial models than OLS models. This criterion is based of maximum likelihood function, and lower values denote best model fit (Burnham and Anderson, 2012).

3. Results

Fig. 2 presents the spatial distribution of the response variables (in-migration and out-migration rates) and net-migration rates in the Brazilian Amazon. According to this figure, there are five major groups of municipalities exhibiting high in-migration rates between 2005 and 2010: in the Center Mato Grosso, in the Southeast Pará, alongside the road Belém-Brasília (Tocantins state), in significant parts of the Northern Amazon (Amapá and Northeast Amazonas) and some fragmented municipalities in the Northern Rondônia, Northen Mato Grosso, South Pará and South Amazonas states. In addition, Acre, Amazonas, Northern Pará and Maranhão clearly present lower in-migration rates. In general, out-migration rates are higher in Mato Grosso, Rondônia and Tocantins states, and are significant in the interior areas, such as Northern Pará, Eastern and Weastern Amazonas. Furthermore, there is a well-defined cluster of municipalities presenting high positive net migration rates in the Southeast Pará, Northern Rondônia, Southwestern Amazonas, Northern Mato Grosso, Rorâima and Amapá. In the regional interior, many municipalities located in the border of the Amazon river also present positive net migration rates, while negative values prevail in areas far from the main regional transportation axes and paved roads.

Table 3 presents the observed and expected values of global Moran's I index for both explanatory and response variables. As Table 3 shows, urban population growth and distance to the closest major center do not exhibit any significant spatial pattern at the 0.05 level. The percentage of forested area (0.833), distance to a paved road (0.658), HDI (0.575), the percentage of deforested area (0.565) and in-migration rates (0.512) present the highest degree of spatial autocorrelation, while total population (0.077) and variation in GDP (0.198) exhibit the lowest Moran's I scores.

Table 4 presents the results for in-migration and out-migration modeling using both OLS and SLM models. In these models, we used normalized variables. Therefore, comparisons in terms of weight and direction between explanatory and response variables, and across models, is applicable. In general, after controlling for spatial structure in the data, several variables decrease their weight in the models. In addition, some variables decrease their significance or even became not significant. In the SLM explaining in-migration, the coefficient parameter (Rho = 0.513, $p < 0.001$) indicates that the sample data presents a positive and highly significant spatial dependence. This model reveals a highly significant improvement in total fit over the OLS model according to its AIC value (4236.37 vs 4383.17). After controlling for the spatial lag autocorrelation, we see overall decreases in the coefficients weights in the significant variables, such as population, the percentage of population with 20–39 years, variation in GDP, the percentage of services GDP and HDI. Demographic, economic, development and connectivity dimensions contribute with at least one significant variable in the SLM explaining in-migration rates, while inequality and environment variables do not present any significance. In this SLM, the percentage of population with 20–39 years presents a significant positive association with in-migration rates while population has a significant and negative coefficient. In addition, urban population growth is not significant among the demographic variables. In the economic and development dimensions, variation in GDP and HDI present a positive and significant association with in-migration rates, while the percentage of services GDP is negative and statistically significant associated with this response variable. In addition, variation in HDI is not significant at the 0.05 level. In the connectivity dimension, the distance to the closest major center exhibits a negative and significant association with in-migration rates, while the distance to a paved road is not significant. In the environment dimension, the percentage of deforested area (2005–2010) and the percentage of forested area are not statistically significant.

Turning to the SLM explaining out-migration rates, the coefficient parameter (Rho = 0.469, $p < 0.001$) reveals a positive and highly significant effect. This model also presents a lower AIC value compared to OLS model (3900.48 vs 4018.07), showing an improvement in terms of total fit. Demographic, economic, development and environment variables have clearly dominated the SLM explaining out-migration rates. Examining the p-values between the OLS and SLM reveals that

Table 2
Lagrange multiplier diagnostics for spatial dependence.
Source: IBGE (2000; 2010). PNUD (2010). INPE (2000–2010).

	In-migration	Out-migration
LMerr	84.94***	127.88***
LMlag	154.60***	136.70***
RLMerr	4.48*	5.35*
RLMlag	74.14***	14.18***
SARMA	159.08***	142.06***

***$p < 0.001$; **$p < 0.01$; *$p < 0.05$.

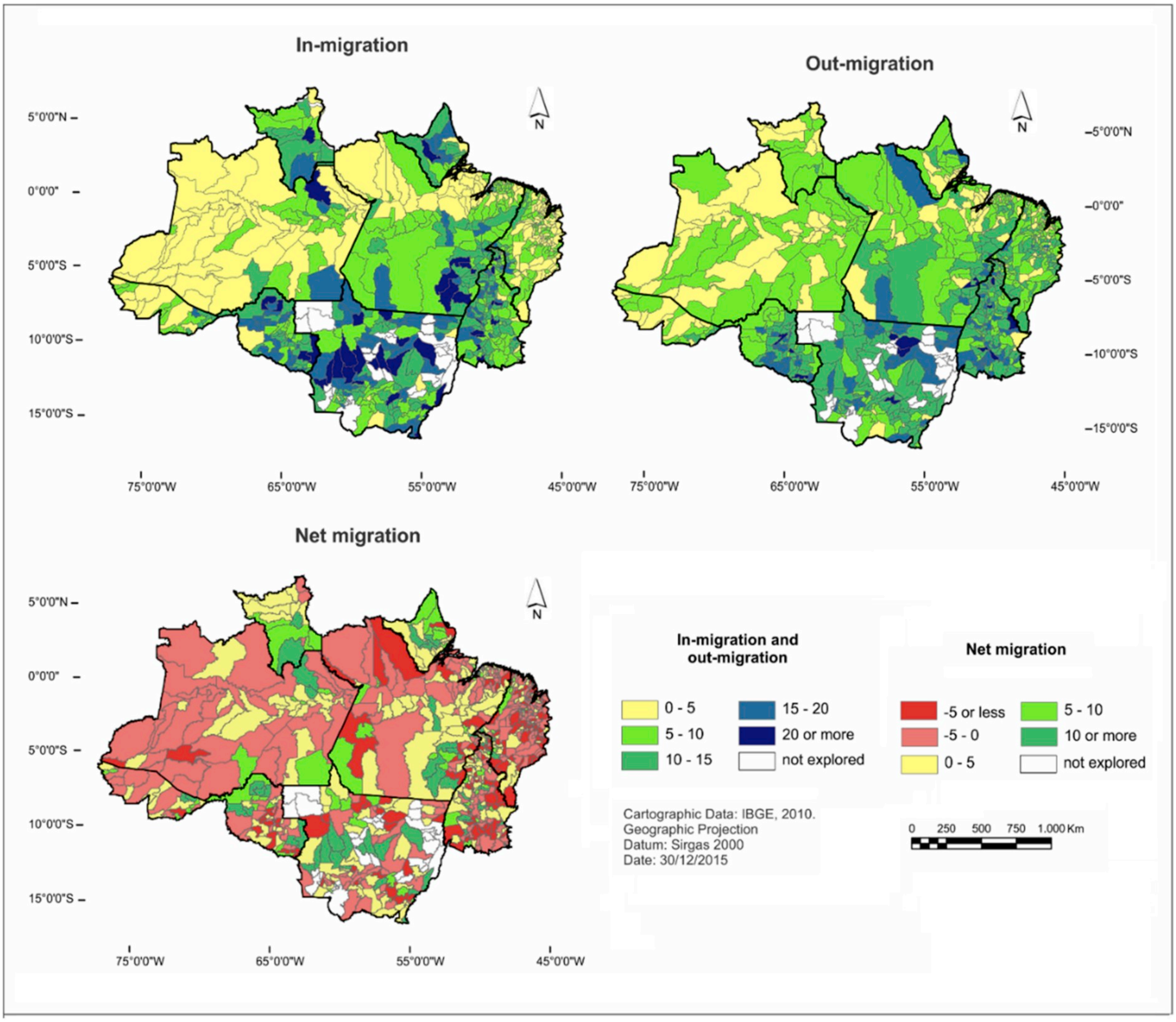

Fig. 2. Response variables (in-migration and out-migration rates) and net-migration rates in the Brazilian Amazon, 2005–2010.

distance to the closest major center is no longer significant when considering the lag specification. In the demographic dimension, population, urban population growth and the percentage of population with 20–39 years are negatively and significantly associated with out-migration rates. In the economic and development dimensions, variation in GDP and the percentage of services GDP present a negative association with out-migration rates, while HDI presents a significant positive association with the response variable. In addition, variation in HDI is not significant at the 0.05 level. There are no significant variables in the inequality and connectivity dimensions. Finally, the percentage of deforested area (2005–2010) presents a significant and positive association with out-migration rates, while the percentage of forested area exhibits a significant and negative association with this response variable.

4. Discussion

Migration dynamics in rainforest frontiers is complex and multidirectional (e.g. Entwisle et al., 2007; Caviglia-Harris et al., 2012). Our results indicate that there is significant spatial patterning in both in-migration and out-migration rates among the explored municipalities in the Brazilian Amazon. Fig. 2 reveals in-migration frontiers in the region, especially in Center Mato Grosso and Southeast Pará. In contrast, we find vast areas that presented low in-migration rates in the same period, mainly in the Amazonas, Acre, Maranhão and Northern Pará. In these areas, low in-migration rates are usually associated with low GDP growth and economic stagnation in the Brazilian Amazon (Sathler et al., 2018). Out-migration rates were higher in Mato Grosso, Rondônia and Tocantins states, by exhibiting a more diffuse pattern. In general, high demographic loss among Amazonian municipalities are associated with regional inequality and economic constraints in the Brazilian Amazon (Guedes et al., 2012, Sathler et al., 2018). In addition, out-migration rates in the regional interior were relevant (higher than 5%), even in Amazonas state and Northern Pará, where migrants have to cross huge distances to change residence.

The spatial regression models present better estimates of the coefficients by incorporating the spatially lagged autoregressive parameter. We find that both in-migration and out-migration rates in a specific municipality are affected by the respective rates from the neighbors. In addition, Global Moran's *I* scores confirm that most of selected variables exhibit spatial dependence. Previous studies suggest that the concentration of investments and demographic growth in the rainforest frontier, while maintaining large stagnated areas in the Central and Northern Amazon, have stimulated the observed spatial dependence among the selected variables (Sathler et al., 2018; Guedes et al., 2012). Moreover, the models confirm the multidimensional character of in-migration and out-migration rates in the Brazilian Amazon, given the observed associations with multiple contextual variables at the municipal level.

The *Demographic* dimension is crucial in the spatial regression

Table 3
Global Moran's *I* scores for variables in the analysis, Brazilian Amazon.

Variables	Observed I	E[I]	Z[I]
Response variables			
In-migration rate (%)	0.512***	−0.001	21.430
Out-migration rate (%)	0.487***	−0.001	22.992
Explanatories			
Demographic			
Total population	0.077*	−0.001	4.021
Urban population growth (2000–2010) (% by year)	0.006	−0.001	0.405
% Population between 20 and 39 years	0.393***	−0.001	17.067
Economic and Development			
Variation in GDP (2000–2010)	0.198***	−0.001	8.301
% Services GDP	0.380***	−0.001	16.002
HDI	0.575***	−0.001	24.377
Variation in HDI (2000–2010)	0.433***	−0.001	18.179
Inequality			
Gini Index	0.430***	−0.001	18.405
Connectivity			
Distance to the closest major center (km)	0.038	−0.001	1.721
Distance to a paved road (km)	0.658***	−0.001	28.577
Environment			
% Deforested area (2005–2010)	0.565***	−0.001	24.235
% Forested area (2010)	0.833***	−0.001	35.831

E[I] = the expected value of Moran's *I*.
Z[I] = the observed I value's standard deviate under the H0 of no association;
***$p < 0.001$.
**$p < 0.01$.
*$p < 0.05$.

models, especially in the SLM explaining out-migration in which all the three incorporated variables present significant coefficients. First, the significant negative association with population in both spatial regression models highlights the relevance of less-populated municipalities in regional migration dynamics. The opening of new economic fronts in the Amazonian rainforest frontier, which has attracted people to unexplored areas and less-populated municipalities (Becker, 2005; Cunha, 2011), partially explains the significant negative association between in-migration rates and population. Furthermore, in the Brazilian Amazon, large agricultural and industrial projects in the rainforest frontier can potentially cause higher variations in in-migration and out-migration rates among less-populated municipalities given their strong socioeconomic impact and the distinct proportional effect of migration flows on municipal population (Hutcheson & Sofroniou, 1999).

Fig. 2 shows that less-populated municipalities were vital for the conformation of notable in-migration frontiers in the Brazilian Amazon. In the Center Mato Grosso, Sinop, Lucas do Rio Verde and Soriso, which are three medium-sized cities located alongside the BR-163 road, provided most of the logistic needs for the intense soybean expansion throughout less-populated municipalities, such as Brasnorte, Nova Maringá, Campos de Júlio and Nova Ubiratã (Fearnside & Graça, 2009). In the 2000s, soybean production promoted high levels of economic growth in these municipalities, which showed a high percentage of deforested areas by previous ranching activities (INPE, 2002; Sathler et al., 2018). In addition, huge mining projects established in the Southeast Pará have driven strong migration flows in some municipalities close to Marabá (PMP, 2018, pp. 1–70), which had 233,669 inhabitants in 2010 and presented a growing steel industry in the 2000s. (IBGE, 2010). On the southern border of Marabá, Parauapebas, a middle-sized municipality with 153,908 inhabitants in 2010, hosts the world's largest iron ore mine, by holding 2.97 billion tonnes of iron ore in proven and probable reserves (VALE, 2013). In this area, smaller municipalities presenting extremely high in-migration rates, such as Santa Maria das Barreiras (24.92%), Camaru do Norte (28.07%), Ourilândia do Norte (23.54%), Canaã dos Carajás (30.20%) and Sapucaia (24.64%), have formed one of the most dynamic economic and demographic fronts in the Brazilian Amazon. Within these two in-migration frontiers, medium-sized cities were vital to serve as logistics bases to huge agro-industrial and mining projects, by extending economic growth and migratory attraction to smaller municipalities. Moreover, there is a fragmented group of less-populated municipalities exhibiting high in-migration rates (2005–2010) in the Center Brazilian Amazon, which are located close to environmentally sensitive areas and

Table 4
Standardized regression coefficients from the OLS and SLM explaining in-migration and out-migration rates in the Brazilian Amazon, 2005–2010.

Variables	In-migration		Out-migration	
	OLS	SLM	OLS	SLM
Intercept	0.000 (0.028)	0.020 (0.024)	0.000 (0.029)	−0.009 (0.026)
Demographic				
Population	−0.154*** (0.043)	−0.098** (0.038)	−0.211*** (0.046)	−0.121** (0.041)
Urban Population Growth (2000–2010)	−0.004 (0.028)	0.019 (0.025)	−0.099*** (0.030)	−0.072** (0.027)
% Population with 20–39 years	0.205*** (0.036)	0.185*** (0.031)	−0.192*** (0.038)	−0.164*** (0.034)
Economic and Development				
Variation in GDP (2000–2010)	0.171*** (0.031)	0.151*** (0.027)	−0.127*** (0.032)	−0.115*** (0.029)
% Services GDP	−0.182*** (0.032)	−0.112*** (0.028)	−0.189*** (0.034)	−0.093** (0.030)
HDI	0.391*** (0.044)	0.195*** (0.040)	0.523*** (0.047)	0.355*** (0.044)
Variation in HDI (2000–2010)	−0.042 (0.039)	0.005 (0.034)	−0.039 (0.041)	−0.068 (0.037)
Inequality				
Gini	−0.058 (0.034)	−0.040 (0.030)	−0.026 (0.037)	0.013 (0.033)
Connectivity				
Distance to the closest major center	−0.062 (0.046)	−0.080* (0.040)	0.099* (0.049)	0.059 (0.044)
Distance to a paved road	−0.012 (0.031)	−0.011 (0.027)	0.047 (0.033)	0.036 (0.030)
Environment				
% Deforested area (2005–2010)	0.102*** (0.030)	0.047 (0.026)	0.185*** (0.032)	0.129*** (0.029)
% Forested area	0.044 (0.033)	0.045 (0.029)	−0.162*** (0.036)	−0.085** (0.032)
N = 740				
Adj R^2	0.438***		0.364***	
Rho		0.513***		0.469***
Akaike Information Criterion (AIC)	4383.17	4236.37	4018.07	3900.48

Standard errors are in parentheses.
***$p < 0.001$.
**$p < 0.01$.
*$p < 0.05$.

conservation units, such as Apiacás, Novo Mundo, Camaru do Norte, Curubim and Candeias do Jamari. In these areas, a more nuanced understanding of migration patterns and their drivers might be vital to curb deforestation and forest degradation triggered by multiple factors, especially ranching, soybean production and mining (Fearnside, 2008; Soares-Filho, 2006).

The high in-migration rates (above 15%) in 118 less-population municipalities, with less than 30,000 inhabitants, suggests that economic and demographic changes in the Brazilian Amazon are significantly comprehensive in the territory. Even though some large and medium-sized municipalities (in terms of population) in the Brazilian Amazon presented higher migration volume in absolute terms between 2005 and 2010, less-populated municipalities exhibited higher proportional changes in population (IBGE, 2010). Expressive migratory rates in these municipalities might cause acute logistic and social challenges (Guedes et al., 2012), especially in the major in-migration frontiers, which demand specific public policies since local governments in the Brazilian Amazon are usually not prepared to deal with severe territorial changes.

Furthermore, related literature reveals that inter-municipal migration is predominantly an urban phenomenon in the Brazilian Amazon (Becker, 2005; Monte-Mór, 2013). In this specific analysis, the following aspects are very relevant: urbanization is highly disseminated in the Amazonian territory (Vicentini, 2006), which clearly impacts the association between response variables and urban growth; urban population growth between 2000 and 2010 also depends on inter-municipal migration in the first quinquennium, which can partially explain the absence of significance in the SLM explaining in-migration rates; several municipalities in the rainforest frontier exhibited similar levels of in-migration and out-migration rates between 2005 and 2010, which impacts the estimated coefficients; finally, the most stagnated municipalities presented low migration rates between 2005 and 2010, especially in the regional interior. In these areas, rural-urban migration and high fertility rates have shaped the urban population growth (Sathler et al., 2018).

Moreover, significant migration rates have a substantial impact on population age structure (Khoo & McDonald, 2011; McDonald & Temple, 2006). Related literature shows that the propensity to migrate changes by age and tends to be higher among the adult population (UN, 2011; Rogers, 2015). We find that both in-migration and out-migration effects on age structure might be relevant, given the significant associations between response variables (2005–2010) and the percentage of population between 20 and 39 years (2010). Further research might investigate this finding with some detail, by considering the effect of previous migration (2000–2005) on this explanatory variable and changes in age structure between the two latest census (2000 and 2010). In addition, the general decrease of regional fertility rates in the past decades is also relevant, affecting unequally the percentage of adult population among the explored municipalities (Carvalho & Wong, 2006; Paiva & Wajnman, 2005).

The economic and development variables also dominated the spatial regression models. The significant association between variation in GDP and both in-migration rates (positive) and out-migration rates (negative) confirm the empirical evidences presented by the most prominent literature on economic drivers of migration (Massey et al., 1993). Neoclassical economics explores the impacts of the unequal economic growth on internal and international migration at the regional and local levels (Harris & Todaro, 1970; Todaro, 1976; Todaro and Maruszko, 1987). The effect of variation in GDP on in-migration and out-migration rates between 2005 and 2010 is especially relevant in the Brazilian Amazon, given the systematic advancement of economic activities throughout the rainforest frontier. In general, our findings show a positive association between migration and economic dynamics. The main in-migration frontiers in the Brazilian Amazon correspond to groups of municipalities exhibiting impressive economic growth between 2000 and 2010. In the Southeast Pará, Canaã dos Carajás (39.63%) and Parauapebas (17.81%) presented high variation in GDP, and so did Nova Maringá (14.72%), Querência (17.75%) and Nova Lacerda (15.34%) in Mato Grosso state. In addition, Pedra Branca do Amapari (21.75%) and Rio Preto da Eva (15.01%) had high variation in GDP in the Northern in-migration frontiers (IBGE, 2010). In contrast, 175 municipalities in the Brazilian Amazon presented very low (just above 5%) variation in GDP between 2000 and 2010. These results would suggest that the Amazonian migration agenda should include policies seeking the reduction of the concentration of labor opportunities and economic growth from huge economic projects, incorporating the dissemination of jobs and social opportunities in sustainable activities throughout the most stagnated areas in the Brazilian Amazon.

In the Brazilian Amazon, most *small and medium-sized* municipalities (in terms of population) with a high percentage of services in their GDP composition have low levels of investments in the agricultural and industrial sectors, presenting an undiversified and stagnated economy. In contrast, high percentage of services GDP in *large municipalities* usually reflects a more specialized and diversified economy (IBGE 2000, 2010; Sathler et al., 2018). Our results demonstrate a negative association between the percentage of services GDP and both response variables by suggesting that in-migration and out-migration rates are lower among the most stagnated municipalities. In fact, related literature shows that the in-migration rates are traditionally lower in the most stagnated regions of Brazil (Cunha, 2011; Lima and Braga 2013). In addition, results suggest that a higher degree of low-income and social exclusion can hinder out-migration as an alternative to household adaptation to the local economic constraints (poverty trap and trapped populations) (Black, Stephen, Bennett, Thomas, & Beddington, 2011; Williamson, 2006). This effect tends to be stronger in some parts of the Brazilian Amazon because of the high economic costs necessary to cross the large distances involved in migration (IBGE, 2008). These include Northern Pará, where Breves (81.16%), Anajás (76.11%) and Afuá (72.93%) presented high percentage of services in their GDP and also negative net migration. These municipalities have hosted since the late XIX century extractive activities, such as timber, rubble and açai, and do not have developed large-scale industrial and agricultural projects (IBGE, 2010; Paula, 1980, p. 41).

The strong positive association between HDI and both in-migration and out-migration rates reflects the high developmental discrepancies among municipalities in the Brazilian Amazon (Guedes et al. 2012), which were created by the historically unequal spatial distribution of the private and public investments in the region (Fearnside, 2008; MMA, 2008). The significant positive association between HDI and in-migration rates is an expected result (Lucas, 1997; Todaro, 1980). In contrast, the high positive association between HDI and the out-migration rates reflects some relevant regional particularities, such as the spatial distribution of socioeconomic variables and the low-income effects among specific population groups. Finally, two common effects of out-migration on local income levels should be further investigated given their potential impacts on HDI: a) the decrease of pressure on sharing scarce resources (Taylor, 2002); b) the effects of remittances on local economy (World Bank, 2016; Brown and Jimenez-Soto, 2016).

Changes in development levels do not follow variations in economic growth at the same pace in the Brazilian Amazon, especially in the rainforest frontier, where investments can immediately improve some economic indicators, such as HDI income, but also create demands for local governments by negatively affecting other HDI components, such as HDI education and HDI longevity (Sathler et al., 2018). As an example, Presidente Figueiredo and Rio Preto da Eva presented high in-migration rates (20.41% and 15.49%, respectively) while exhibiting moderate values of HDI (0.65 and 0.61, respectively). These two municipalities are close to the state capital, Manaus, which concentrated most of the state population (1,802,014 inhabitants) and GDP (R$ 48.5 billion) in 2010. Census data show that Presidente Figueiredo and Rio Preto da Eva exhibited high variation in GDP between 2000 and 2010 (10.42% and 15.00%, respectively), which is probably driven by migration flows in the assessed period. In the Northeast Amazonas, further studies might need to investigate in some detail the migration dynamic by also exploring possible pull factors in the state capital. In addition, the relative impact of social improvements on social indicators depend on the previous level of social development in the assessed area (Hutcheson & Sofroniou, 1999). In the less developed Amazonian municipalities, lower improvements in social conditions often cause significant variations in HDI. Social inequality within the municipalities measured by the Gini index is not significant in the spatial regression models. Although HDI differences among municipalities are very relevant in the spatial regression models, we do not find any evidence of effect of local social inequality on in-migration and out-migration rates.

In these analyses, the *distance to the closest major center* is particularly important given the long distances involving many cities and population agglomerations in the Brazilian Amazon, especially in the regional interior (Sathler et al., 2009). This variable is negatively and significantly associated with in-migration rates and indicates the relevance of localization of the main districts within the regional urban network. Although the effects of paved roads on facilitating in-migration in rainforest frontiers have been described in previous literature (Chomitz & Gray, 1995; Rudel, 1983), SLM do not reveal any significant association between the distance to a paved road and in-migration rates. Our results are not reflecting only the rainforest frontier dynamic and its relationship with the regional interior, but also the effect of hundreds of municipalities in the Southern and Eastern Brazilian Amazon, whose migration dynamic strongly depends on their interactions with other Brazilian regions, such as the Brazilian Northeast and Center-West. Further studies might explore the association between roads and migration by considering distinctly the rainforest frontier and the regional interior.

The OLS and SLM models demonstrate that the association between the percentage of deforested area and in-migration rates become insignificant after controlling for spatial structure in the data. Although the spatial regression model does not show any evidence of association between in-migration rates and environment variables by considering all the Amazonian territory, previous studies show significant linkages between these variables within the rainforest frontier (Caviglia-Harris et al., 2012; Brondizio et al., 2002). Therefore, confounding effects might affect the estimated coefficients when considering all the Amazonian territory. Moreover, deforestation rates have strongly declined between 2004 and 2010 in the Brazilian Amazon as a result of federal policies, such as the Deforestation Detection System and the expansion of indigenous reserves and protected areas (Nepstad, 2009; Soares-Filho et al., 2010), while inter-municipal migration levels remained at high levels (Cunha, 2011), which can directly affect the estimated coefficients in the SLM explaining in-migration rates.

On the other hand, the associations between out-migration and the environmental variables in the spatial regression model are consistent. The positive association with the percentage of deforested areas and the negative association with the percentage of forested area suggest that environmental depletion is shaping out-migration rates in the region. Although initial deforestation is positively associated with urban, economic, and population growth (Sathler et al., 2018), our results suggest that highly deforested areas, such as the stagnated municipalities within Maranhão state and several municipalities from the Southern Amazon, have presented significant levels of out-migration. In addition, examining developing countries in the late XX century, Bilsborrow (2002) shows that environmental deterioration plays an important role in out-migration from rural areas and small urban centers. In the Amazonian rainforest frontier, previous studies reveal that a decrease in social conditions stimulated by environmental depletion usually follows preliminary gains in welfare (boom-and-bust pattern), which can impact both in-migration and out-migration rates (Celentano et al., 2012; Rodrigues et al., 2009). Further studies might investigate in more detail the demographic, socioeconomic and environmental dynamism of the main migration hotspots in the Brazilian Amazon. Additional research on topological relations among migration, deforestation and other mapped elements, such as the main urban agglomerations, roads, rivers, protected areas and economic activities) could reveal relevant insights. Finally, integrating environmental, socioeconomic, demographic and spatial data are essential to understand the regional context of migration in the Brazilian Amazon. The PRODES project, as well as the Brazilian decennial demographic census and PNUD figures provided a rich and reliable database on compatible spatial units.

5. Conclusion

By investigating the associations between migration (2005–2010) and contextual socioeconomic, demographic, connectivity, and environmental factors, we find that there is significant spatial patterning in in-migration and out-migration rates among the 740 explored municipalities in the Brazilian Amazon, with most of the selected variables exhibiting spatial dependence. The literature suggests that the concentration of investments and demographic growth in the rainforest frontier have stimulated the spatial dependence among the selected variables (Sathler et al., 2018; Guedes et al., 2012). The spatial regression models demonstrate the multidimensional character of migration in the Brazilian Amazon. We find that demographic dynamism, economic growth, regional inequality and the environmental changes were associated with the intensity of migration flows between 2005 and 2010.

Our results show that the *Demographic* dimension is relevant in the spatial regression models, especially in the SLM explaining out-migration in which all the three incorporated variables (population, urban population growth and the percentage of population with 20–39 years) present significant coefficients. We find that the high in-migration rates among many less-populated Amazonian municipalities and the significant values of out-migration rates in the interior ensured territorial robustness for migration in the region. In addition, the urban nature of the population growth and the establishment of an urbanized forest in the Brazilian Amazon (Becker, 1995; Vicentini, 2006), which presented considerably high urbanization rates in 2000 (IBGE, 2000), impacted the association between urban growth and migration rates in the models. Moreover, internal migration was not relevant among stagnated municipalities, where rural-urban migration and the high fertility rates have a strong effect on urban population growth. We also find that in-migration and out-migration are significantly associated with age structure.

The economic and development variables also played an important role in the SLM explaining in-migration and out-migration. Our results demonstrate that the effect of variation of GDP on migration is especially relevant in the region because of the advancement of the rainforest frontier. In addition, the historically unequal spatial distribution of the economic growth and social development in the region is related to the positive association between HDI and in-migration and out-migration rates.

In the spatial regression model, in-migration rates are not significantly associated with the environment variables. However, literature demonstrate a strong association between these variables within the rainforest frontier, by not considering the complete Amazonian territory (Caviglia-Harris et al., 2012; Brondizio et al., 2002). Moreover, out-migration rates are clearly associated with both environment variables (the percentage of deforested area between 2005 and 2010 and the percentage of forested area in 2010), which suggest that environment depletion is driving out-migration rates in the Brazilian Amazon. In addition, this study provides key elements that support the design and improvement of policies seeking sustainable development growth and deforestation decrease in the region.

Notes

[1] In this study, the rainforest frontier is roughly represented in Fig. 1 by comprising an arc throughout the Northern Rondônia, Northern Mato Grosso and Eastern Pará. This dynamic area has been constantly changing its geographical coverage and also its socio-economic and demographic characteristics in the past decades.

[2] According to PNUD (2010), HDI is formed by the geometric mean of the following normalized indicators: mean years of schooling and expected years of schooling, per capita income and life expectancy at birth.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apgeog.2019.102042.

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