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Socioeconomic dimensions, migration, and deforestation: An integrated model of territorial organization for the Brazilian Amazon

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Abstract

The territory organization of the Brazilian Amazon, understood as a socioeconomic network of municipalities, reflects the diversity of human settlements and their potentials for environmental changes, especially deforestation. This paper characterizes the urban network in the Brazilian Amazon through a model that integrates the levels of socioeconomic organization of municipalities and their interrelationships, as determined through migratory movements. The model of territorial organization combines five components: (i) the hierarchy of central places (poles) established by the concentration of urban specialized services, (ii) the geographical distance between central poles and other centers, (iii) the poles' populations, (iv) the migratory movements among them, and (v) a socioeconomic dimension index. These components are combined into a gravitational model to produce measures and maps of the socioeconomic municipality network of the Brazilian Amazon. As a result, out of 792 municipalities in the Brazilian Amazon, 9 were classified as macro-poles, 29 were classified as meso-poles and 48 as micro-poles. The areas of influence of these poles were determined according to the three hierarchy levels. The Amazon region network comprises a nested spatial pattern of municipalities not constrained by the state boundaries. Socioeconomic space and population movements influence the mobility of the deforestation frontier. This analysis provides insights to predict deforestation as well as to guide formulation of sustainable development policies suitable for each region's specificity.

Keywords: Socioeconomics; Migration; Territorial organization; Deforestation; Amazon

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1. Introduction

Although socioeconomic dynamics drive the fast pace of deforestation in the Brazilian Amazon, the intensity of the deforestation process varies greatly across the basin due to regional differences, including physiographic attributes, access to infrastructure such as paved roads, population characteristics and dynamics and socioeconomic organization, as well as age of the frontier. Hence the understanding of the territorial distribution of both economic activity and socio-demographic dynamics is a starting point to evaluate a region's potential for environmental changes, such as deforestation (Soares-Filho et al., 2006). This fact is implicit in the concept of *anthropic* pressure, which is the pressure imposed on the environment by the socioeconomic conditions of human settlement (Monteiro and Sawyer, 2001). Additionally, the establishment of a territorial hierarchy, representing nested spatial levels of socioeconomic and demographic organization, provides a basis for design of sustainable development policies according to each region's specificities. This spatial organization can be represented in terms of the urban network and the space under its influence. According to Becker (2001), the Brazilian Amazon can be regarded as an urban forest. Indeed, IBGE (Brazilian Institute for Geography and Statistics) census data for 2000 show that more than 68% of its population lives in urban centers. Although this view stresses the need for understanding the Amazon socioeconomic space in terms of its urban network, only a few studies (e.g. Wood and Porro, 2000; Carpentier et al., 2000; Armenteras et al., 2006) have so far addressed the deforestation process in the light of the urban network and its associated socioeconomic and demographic dynamics.

Other previous studies have provided methods to map the urban network layout and its associated socioeconomic space in Brazil in order to direct regional development policies (e.g. IPEA/IBGE/NESUR, 1999; Lemos et al., 1999, 2003; Garcia, 2002). It is worth mentioning that the three first studies did not explicitly involve migration, the only variable from census data able to measure flows over time and space. Only Garcia (2002), using the same framework as Lemos et al. (1999) proposed a regionalization for the Brazilian territory based on population movements among central poles and areas under their influence. Nevertheless, none of these studies provided a methodology specifically addressed to the potential of socioeconomic and demographic dimensions for environmental changes in the Amazon region.

2. Objective and rationales

The main objective of this study is to establish a model of territorial organization for the Brazilian Amazon based on the characteristics of its municipalities. The model consists of two components. The first is a measure of hierarchy of cities as a function of urban specialized services and is used to identify poles of influence. The theory of central places (Christaller, 1966) refers to a nodal urban hierarchy consisting of larger centers polarizing surrounding smaller centers. The main rationale is that the largest population centers, in which urban services are concentrated, have the largest potential for attracting socioeconomic activities and for spreading them to surrounding centers. Considering the territory as a plastic space made up of interactions among places through flows of people, resources and information (Harvey, 1989), the second component is a measure of interaction among those previously identified poles and municipalities under their influence. This measure of interaction considers: (1) for each municipality, its population size weighted by a socioeconomic dimension index (SDI); (2) for each municipality in relation to the economic poles, its distance and the overall migratory flow between them.

To assess the influence of socioeconomic dimensions on the environment, we hypothesize that SDI can be used to infer the *anthropic* pressure exerted by a population within a specific territory unit – such as the municipalities or larger regions formed by their aggregation – on the deforestation process. We combine the following five dimensional axes to produce the SDI summary: (1) population concentration and dynamics, i.e. total growth rate; (2) economic development; (3) agrarian infrastructure; (4) agricultural and timber production; (5) social development. A positive effect on the deforestation process is ascribed for the first four dimensions and a negative effect for the fifth. The rationale for establishing these components is that population growth and migration, together with economic growth, stimulate deforestation (Skole et al., 1994;

Laurance, 1999; Soares-Filho et al., 2004). In addition, logging (Nepstad et al., 1999) plus agriculture and ranching expansion are listed as major current causes of deforestation in the Brazilian Amazon (Margulis, 2002; Mertens et al., 2002; Alencar et al., 2004). Conversely, social development, as illustrated in the inverted U-shape Kuznets curve (Stern et al., 1996), could represent frontier governance (Nepstad et al., 2002), counteracting environmental degradation resulting from economic development.

SDI is interpreted as a proxy for the *anthropic* pressure on deforestation. As a measure of attraction, the population, strengthened by SDI, is employed in a gravitational model, in conjunction with the total migratory movement among the poles and the surrounding municipalities to make up their areas of influence. Therefore, this study characterizes the level of *anthropic* pressure and the interrelationships among municipalities, given by migratory movements, to establish a network of regions, aiming to shed light on the way these regions interconnect to influence the mobility of the deforestation frontier across the basin.

3. Methodology

The measure of the hierarchy of the cities is assessed by the index of services (IS). The urban centers were identified and ranked according to their supply of services, referred to here as the "service economy", as follows:

$$IS_i = \frac{SDP_i}{GDP_i}(1 - e^{\ln(0.05)SDP_i/SDP_{ref}}) \quad (1)$$

where IS_i is a ratio between the service economy domestic product (SDP_i) and the gross domestic product (GDP_i) of a municipality i, standardized by a reference service economy domestic product (SDP_{ref}), specifically the largest regional SDP_i. As depicted in Fig. 1, a municipality tends to concentrate more urban services as its economy grows. Thus, IS measures the potential of a municipality to act as a regional center, influencing surrounding municipalities.

We established three categories of centers by defining threshold values for IS: macro-poles, meso-poles, and micro-poles. Municipalities with IS higher than 20% are the macro-poles. This upper limit was defined to include all capital cities, except for Palmas,

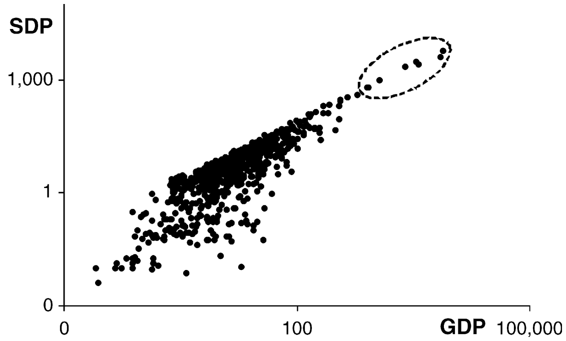

Fig. 1. Scattergram of gross domestic product (GDP) vs. service economy domestic product (SDP). Ellipse embraces all macro-poles, except for Palmas. Both axes are in logarithmic scale.

Tocantins state capital. Two more thresholds were set by determining the natural breaks of IS distribution frequency. Those with IS between 3.2 and 20% were classified as meso-poles and those with IS between 0.5 and 3.2% were the micro-poles, while municipalities with IS below 0.5% were not considered as poles. Furthermore, the qualitative aspects related to the importance of a municipality as a regional administrative center, its geographical location with respect to neighboring poles, namely its contiguity with other municipalities classified as poles, would add or subtract municipalities from poles defined by the IS thresholds. For example, Palmas, with IS of 7.8%, was ranked as a macro-pole because of its political importance, and Jarú was excluded from meso-poles due to its contiguity to Ji-Paraná, which presents higher IS. Once a hierarchy of regional poles is established, which can include a varying number of economic poles depending on a chosen cut-off threshold for IS, the measure of interaction between a pole and a municipality is calculated according to a gravitational model, as denoted:

$$Iv_{ij} = \frac{P_i(1 + SDI_i)P_j(1 + SDI_j)}{d_{ij}^{\xi}} \quad (2)$$

where Iv_{ij} represents the interaction between pole i and municipality j, given by their populations (P_i and P_j) and socioeconomic dimension indices (SDI_i and SDI_j), weighted by the distance (in this case, the geodetic distance) between them raised to the power of ξ, an attrition coefficient so that:

$$\xi = 1 + e^{(\ln(0.001)/vmt_{ref})vmt_{ij}} \quad (3)$$

where vmt_{ij} is the overall migratory flow between pole i and municipality j and vmt_{ref} is the reference migratory flow, namely the largest intermunicipal migratory flow.

The socioeconomic dimension index is calculated by applying the grade of membership (GOM) fuzzy classification method – see Manton et al. (1994) for theory and Gold et al. (1990); Sawyer and Beltrão (1991); Hughes et al. (1996) for application examples – to socioeconomic and agriculture census data, such as population density and growth rate, urbanization level and rate; gross domestic products, municipal income taxes and budget; number and types of agricultural implements; production from animal husbandry, agriculture, and forestry; education, habitation, and health parameters. SDI was built as a proxy of the *anthropic* pressure. As such, this index combines the following five dimensional axes: (1) population concentration and dynamics, (2) economic development, (3) agrarian infrastructure, (4) agricultural and timber production, and (5) social development. High levels of the first four dimensions are combined with low level of social development to produce the socioeconomic dimension index for each municipality. Only this synthetic index is presented in this paper. Variables for each of the dimensions are listed in Table 1. Their data sources are IBGE, 2000 demographic census; IBGE, 1996 population tally; IBGE, 1999 municipal database; IBGE, 1999 profiles of the Brazilian municipalities; Andrade and Serra (1999); IBGE, 1995–1996 agricultural census; IBGE, 2000 municipal cattle herd survey; IBGE, 1997 municipal cattle herd survey; IBGE, 2000 municipal agricultural survey; IBGE, 1997 municipal agricultural survey; and logging data from Veríssimo et al. (2001).

Migratory flows were calculated based on a matrix with information for the residents in a municipality and the municipality of residence 5 years prior to August 1st, 2000 (collected in the 2000 Demographic Census). Those residing outside the municipality in the reference period are considered in-migrants; conversely those residing in the municipality in the reference period but outside it in 2000 are the out-migrants. The difference between the two is the net migration and the sum is the overall volume of population exchange (Garcia, 2002). As a measure of interaction between pole and a municipality, the overall migratory volume is employed in Eq. (3).

Table 1
Variables used for the socioeconomic dimension index, according to their dimensional axis, year of reference, and source of information

I. Population concentration and dynamics
Total population (2000)[a]
Population density (2000)[a]
Level of urbanization (2000)[a]
Population growth rate (1996/2000)[a,b]
II. Economic development
Domestic gross product (1996)[c]
Domestic gross product: primary sector (1996)[c]
Domestic gross product: secondary sector (1996)[c]
domestic gross product: tertiary sector (1996)[c]
Number of banks (1998)[d]
Total deposits in banks—thousand *Reais* (1998)[d]
Total investments—thousand *Reais* (1998)[d]
Municipality revenue (1997)[d]
Municipality total expenditure (1997)[d]
Share in the federal funds of the municipality (1998)[d]
Land taxes (1998)[d]
III. Agrarian infrastructure
Agricultural aggregated value (1995–1996)[e]
Number of tractors (1995–1996)[e]
Sowing machines (1995–1996)[e]
Harvesters (1995–1996)[e]
Number of trucks (1995–1996)[e]
Total of farming machinery (1995–1996)[e]
IV. Agricultural and timber production
Total area of agricultural establishments with less than 200 ha (1995–1996)[e]
Total area of agricultural establishments with 200 ha or more (1995–1996)[e]
Land tenure concentration (1995–1996)[e]
Livestock (2000)[f]
Annual rate of increase of the livestock (1997–2000)[f,g]
Density of cultivated area (2000)[h]
Annual rate of increase of the cultivated area (1997–2000)[h,i]
Number of milling companies (1997)[j]
Timber log volume per year (1997)[j]
Area affected by logging (1997)[j]
V. Social development
Years of schooling—population age 7–14 (1996)[b]
Years of schooling—population age 15–24 (1996)[b]
Years of schooling—head of household (1996)[b]
Hospitals per 1000 population (1999)[d]
Hospital beds per 1000 population (1999)[d]
Ambulatories per 1000 population (1999)[d]
Health posts per 1000 population (1999)[d]
Health centers per 1000 population (1999)[d]
Medical doctor offices per 1000 population (1999)[d]
Dentist offices per 1000 population (1999)[d]
Ambulatories in general hospitals per 1000 population (1999)[d]
Health posts per 1000 population (1999)[d]
Hospital bedridden patients per 1000 population (1999)[d]
Number of households (2000)[a]

Table 1 (*Continued*)

Improvised private household (2000)[a]
Collective household (2000)[a]
Water supply (2000)[a]
Bathroom or sanitary installation (2000)[a]
Garbage collection/destination (2000)[a]
Electricity (2000)[a]
Average number of television sets per household (2000)[a]
Telephone sets in the household (2000)[a]
Paved streets (1999)[k]
Streets with illumination (1999)[k]

[a] IBGE 2000 demographic census.
[b] IBGE 1996 population tally.
[c] Andrade and Serra (1999).
[d] IBGE 1999 municipal database.
[e] IBGE 1995–1996 agricultural census.
[f] IBGE 2000 municipal cattle herd survey.
[g] IBGE 1997 municipal cattle herd survey.
[h] IBGE 2000 municipal agricultural survey.
[i] IBGE 1997 municipal agricultural survey.
[j] Veríssimo et al. (2001).
[k] IBGE 1999 profiles of the Brazilian municipalities.

Hence Iv_{ij} measures the dependence of a municipality on a regional center, defined as the attraction exerted by the center's population. In this case, the population attraction of a central place is stressed by its socioeconomic dimension index, as we assume that larger populations with higher anthropic pressure – as determined by SDI – have more impact on the environment. In this gravitational model, the dependence of a municipality to a pole is strengthened by two-way migratory flows and weakened by geographical distance. Finally, we mapped the poles' areas of influence by assigning to a particular pole all municipalities where its respective Iv_{ij} is greatest.

4. Results

4.1. Urban hierarchy

Out of 792 municipalities in the Brazilian Amazon, 9 were classified as macro-poles, 29 as meso-poles and 48 as micro-poles. Municipalities with IS higher than 20% are the macro-poles. These include eight state capital cities with IS values above 20%: São Luis, Cuiabá, Porto Velho, Rio Branco, Manaus, Boa Vista, Belém, and Macapá. Palmas, the capital city of Tocantins state, with IS of 7.8%, was added to this list because of its administrative and political functions (Table 2).

The non-contiguous municipalities classified as meso-poles, with IS above 3.2%, comprise the above macro-poles, as a meso-pole is also a micro-pole – thus a macro-pole is also a meso-pole and a micro-pole – plus the cities of Rondonópolis, Ji-Paraná, Imperatriz, Santarém, Sinop, Cacoal, Marabá, Cáceres, Barra do Garças, Vilhena, Ariquenes, Tangará da Serra, Paraupebas, and Gurupi. Additional six municipalities (Caxias, Bacabal, Tucuruí, Araguaína, Cruzeiro do Sul, and Tefé) were added to this level because of their known importance as regional administrative centers (Table 2).

One hundred and sixteen municipalities were initially classified as micro-poles, with IS above 0.5%. After excluding contiguous poles with lower IS, they were reduced to 48: the above-mentioned macro and meso-poles plus Parintins, Guarantã do Norte, Breves, Colíder, Juara, Alta Floresta D'Oeste, Balsas, Pontes e Lacerda, Almeirim, Barra do Corda, Paragominas, Juína, Itaituba, Codó, Altamira, Redenção, Jaru, Guajará-Mirim, and Alta Floresta (Table 2).

4.2. Socioeconomic dimension index

Each municipality is assigned to a grade of membership within the extreme profiles that encompass the highest and lowest categories of variables constituting each of the five axes—population concentration, economic development, agrarian infrastructure, agricultural and timber production, and social development. The grade of membership varies from 0 to 1 depending on the number of equal characteristics between the municipality and the extreme profile. The higher the grade of membership of a municipality, the closer is it to the extreme profile. These indices are then combined to produce the synthetic index of Socioeconomic Dimension; high SDI values correspond to high-ranking positions in the first four dimensions and low in the fifth. For example, the municipality with grade of membership close to 1.0 for population concentration and dynamics axis is similar to its top profile, which has the largest urban population in 2000, highest population density, lowest urbanization level and rate, and highest rate of population growth. Top profile for social development index has high educational level, good medical care and garbage collecting systems, high percent of water and electricity supplies, street paving and illumination, and large number of households with

Table 2
Populations, service domestic products (SDP) and gross domestic products (GDP) in 10^6 *Reais*, indices of service (IS), net-migration, in-migrants and out-migrants among the Amazon economic poles and other Brazilian municipalities within 1995 and 2000

State	Macro-poles/ meso-poles	Population	Out-migrant	In-migrant	Migratory volume	Net migration	SDP	GDP	IS
PA	Belém[a]	1,280,614	105,809	57,432	163,241	−48,377	5668.53	7676.87	70.1
MT	Cuiabá[a]	483,346	34,696	24,201	58,897	−10,495	2956.53	3399.54	63.9
RO	Porto Velho[a]	334,661	19,087	20,935	40,022	1,848	2307.70	2472.55	57.8
MA	São Luís[a]	870,028	48,333	55,479	103,812	7,146	2636.66	3630.90	55.0
MA	Manaus[a]	1,405,835	44,964	85,569	130,533	40,605	4166.10	7159.99	54.6
AC	Rio Branco[a]	253,059	11,922	15,888	27,810	3,966	947.21	1155.32	29.8
AP	Macapá[a]	283,308	12,364	28,764	41,128	16,400	651.05	826.72	21.7
RR	Boa Vista[a]	200,568	10,157	28,817	38,974	18,660	616.92	798.68	20.7
MT	Rondonópolis[b]	150,227	12,627	8,520	21,147	−4,107	349.90	448.51	12.5
RO	Ji-Paraná[b]	106,800	15,080	8,423	23,503	−6,657	298.23	358.41	10.9
MA	Imperatriz[b]	230,566	32,005	17,020	49,025	−14,985	276.10	360.78	10.1
TO	Palmas[a]	137,355	8,308	38,759	47,067	30,451	207.97	221.69	7.8
PA	Santarém[b]	262,538	31,228	12,212	43,440	−19,016	208.68	354.03	7.6
MT	Sinop[b]	74,831	6,456	12,081	18,537	5,625	137.01	173.48	5.2
RO	Cacoal[b]	73,568	11,836	5,955	17,791	−5,881	135.71	219.28	5.1
PA	Marabá[b]	168,020	18,327	18,246	36,573	−81	134.56	248.53	5.0
MT	Cáceres[b]	85,857	7,728	6,832	14,560	−896	121.51	149.80	4.6
MT	Barra do Garças[b]	52,092	5,694	4,221	9,915	−1,473	118.26	140.41	4.5
RO	Vilhena[b]	53,598	5,573	8,844	14,417	3,271	112.46	147.79	4.3
RO	Ariquemes[b]	74,503	9,442	6,806	16,248	−2,636	105.78	145.04	4.0
PA	Parauapebas[b]	71,568	6,266	12,721	18,987	6,455	90.98	345.40	3.3
MT	Tangará da Serra[b]	58,840	6,719	6,776	13,495	57	86.19	127.74	3.3
TO	Gurupi[b]	65,034	7,535	5,328	12,863	−2,207	82.31	97.57	3.2
MT	Alta Floresta	46,982	8,874	3,348	12,222	−5,526	75.70	102.52	2.9
MA	Caxias[b]	139,756	8,845	6,265	15,110	−2,580	70.02	104.68	2.7
RO	Guajará-Mirim	38,045	3,248	2,126	5,374	−1,122	69.66	83.18	2.7
RO	Jaru	53,600	11,411	3,272	14,683	−8,139	64.16	109.52	2.5
MA	Bacabal[b]	91,823	9,579	4,302	13,881	−5,277	59.38	89.16	2.3
PA	Tucuruí[b]	73,798	7,892	9,597	17,489	1,705	54.38	168.74	2.1
PA	Redenção	63,251	10,141	6,545	16,686	−3,596	50.94	89.04	2.0
AC	Cruzeiro do Sul[b]	67,441	4,290	2,665	6,955	−1,625	49.91	73.70	1.9
TO	Araguaína[b]	113,143	14,176	10,982	25,158	−3,194	48.58	72.25	1.9
PA	Altamira	77,439	9,794	5,977	15,771	−3,817	47.52	94.38	1.8
MA	Codó	111,146	6,692	3,902	10,594	−2,790	43.32	70.05	1.7
MT	Juína	38,017	4,697	3,305	8,002	−1,392	41.96	54.40	1.6
PA	Itaituba	94,750	21,247	5,651	26,898	−15,596	41.35	72.35	1.6
MA	Barra do Corda	78,147	7,742	3,468	11,210	−4,274	40.06	59.97	1.5
PA	Paragominas	76,450	10,615	11,108	21,723	493	39.00	198.63	1.5
MA	Tefé[b]	64,457	4,874	3,170	8,044	−1,704	36.17	68.15	1.4
PA	Almeirim	33,957	6,644	2,834	9,478	−3,810	34.10	120.08	1.3
MT	Pontes e Lacerda	43,012	5,640	4,856	10,496	−784	32.06	65.49	1.2
MA	Balsas	60,163	3,085	5,448	8,533	2,363	28.21	54.55	1.1
RO	Alta Floresta D'Oeste	26,533	2,038	2,034	4,072	−4	25.04	72.79	1.0
MT	Colíder	28,051	6,162	2,525	8,687	−3,637	23.38	39.70	0.9
MT	Juara	30,748	3,231	1,742	4,973	−1,489	23.07	39.39	0.9
PA	Breves	80,158	7,590	3,567	11,157	−4,023	14.77	102.07	0.6
MA	Parintins	90,150	6,153	3,709	9,862	−2,444	14.26	63.11	0.5
MT	Guarantã do Norte	28,200	2,934	3,256	6,190	322	13.52	24.10	0.5

Source: IBGE 2000 demographic census. Andrade and Serra (1999).
[a] Macro-poles.
[b] Meso-poles.

telephone and TV sets. Similar interpretation is valid for the grades of membership of the other three axes, whose variables show a direct relation to the top profiles. High values of the synthetic index SDI, therefore, combine high population concentration and growth with low urbanization, high economic development, high agrarian infrastructure, large agricultural and timber production, and low social development.

Levels of socioeconomic dimensions were established using the natural breaks in the frequency distribution of this variable: low for values from 0 to 0.25; medium-low from 0.25 to 0.33; medium from 0.33 to 0.66; high medium from 0.66 to 0.75 and high from 0.75 to 1.00. Fig. 2c shows the distribution of municipalities according to the level of socioeconomic dimension. Of 729 municipalities, 7% have high socioeconomic dimension, whereas 22% have low.

A comparison between the maps of density of deforested land (Fig. 2a) and the socioeconomic dimension index (Fig. 2c) demonstrates that there is a close match between municipalities with high deforested percentage and those with high to moderate SDI, notably in states of Mato Grosso, Rondônia and Acre, and more specifically in Eastern Pará and Western Maranhão state. Other municipalities with high SDI but low deforested density can be associated to regions with high deforestation within 2000 and 2001, such as the municipalities along the Cuiabá-Santarém highway in Southern Pará (Fig. 2b). In this way, this analysis also indicates that other areas with high SDI, but still low current deforestation, such as Santarém's nearby municipalities, the municipalities surrounding Manaus towards Roraima and along the Amazon river, Aripuanã in Mato Grosso state, and Huimatá, in Amazonas state, along the Porto-Velho/Manaus highway, may potentially become hotspots of deforestation in the near future (Fig. 2c). Data recently released by DETER, INPE's deforestation alerting system, agree with this interpretation (Valeriano et al. (2005). Moreover, the state of Mato Grosso, in which municipalities present the highest SDI, accounts for 48% of 26,130 km^2 of deforestation estimated by INPE for the Brazilian Amazon in 2003–2004 (INPE, 2005).

4.3. Economic poles' migration data

Table 2 shows data for the number of in-migrants and out-migrants, the net migrants, and the overall

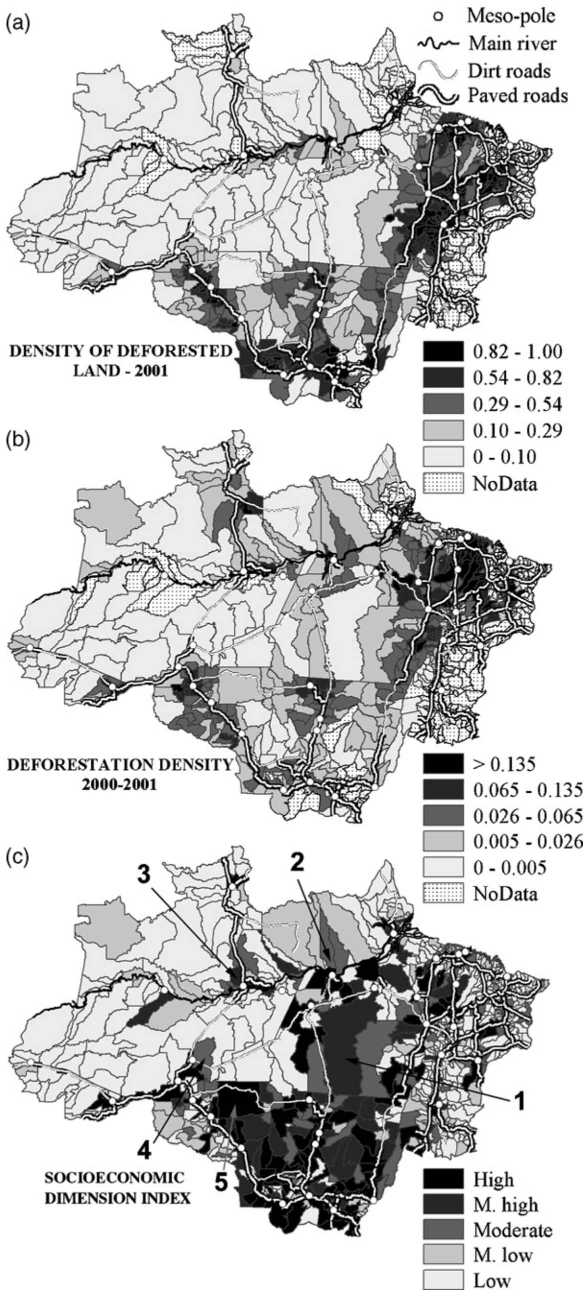

Fig. 2. (a) Density of deforested land % by 2001 (deforested land/(municipality's area—non-forest)), (b) 2000/2001 deforestation density % (deforestation/municipality's area), and (c) socioeconomic dimension index for the Brazilian Amazon's municipalities. Deforestation data come from PRODES (INPE, 2005). (1) Cuiabá-Santarém highway, (2) Santarém, (3) Manaus, (4) Huimatá, and (5) Aripuanã.

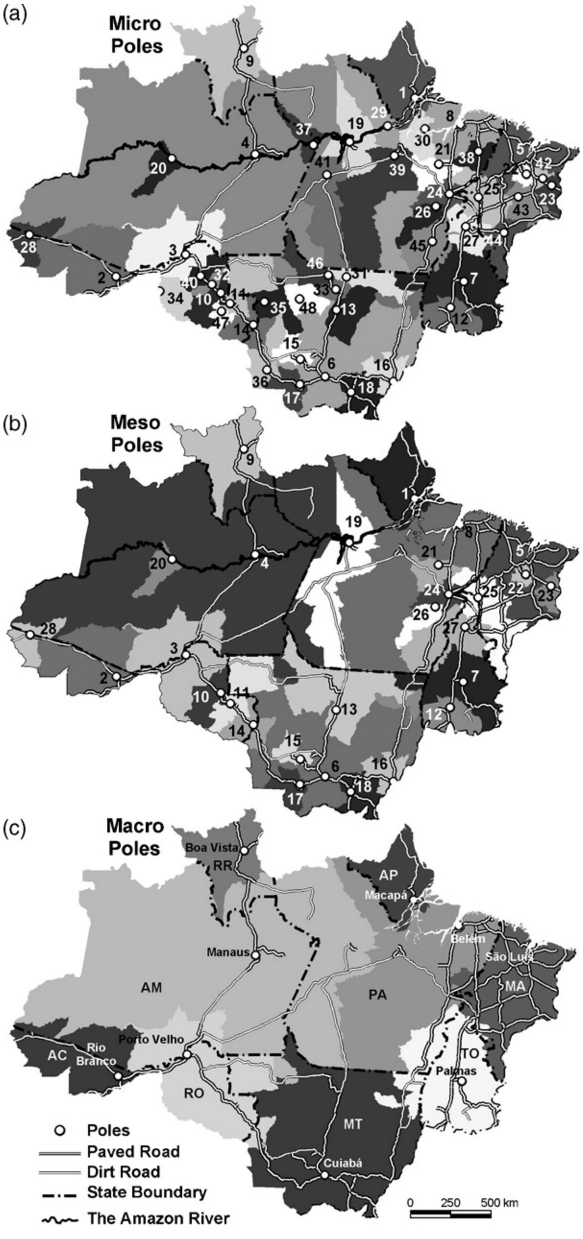

Fig. 3. The micro- (a), meso- (b) and macro-poles (c), and their areas of influence for the Brazilian Amazon in 2000. Poles: Macapá, 1; Rio Branco, 2; Porto Velho, 3; Manaus, 4; São Luís, 5; Cuiabá, 6; Palmas, 7; Belém, 8; Boa Vista, 9; Ji-Paraná, 10; Cacoal, 11; Gurupi, 12; Sinop, 13; Vilhena, 14; Tangará da Serra, 15; Barra do Garças, 16; Cáceres, 17; Rondonópolis, 18; Santarém, 19; Tefé, 20; Tucuruí, 21; Bacabal, 22; Caxias, 23; Marabá, 24; Imperatriz, 25; Parauapebas, 26; Araguaína, 27; Cruzeiro do Sul, 28; Almeirim, 29; Breves, 30; Guarantã do Norte, 31; Jaru, 32; Colíder, 33; Guajará-Mirim, 34; Juína, 35; Pontes e Lacerda, 36; Parintins, 37; Paragominas, 38; Altamira, 39; Ariquemes, 40; Itaituba, 41; Codó, 42; Barra do Corda, 43; Balsas, 44; Redenção, 45; Alta Floresta, 46; Alta Floresta D'Oeste, 47; Juara, 48. Acronyms for the Brazilian States: TO, Tocantins; PA, Pará; GO, Goiás; MT, Mato Grosso; RO, Rondônia; RR, Roraima; AP, Amapá; AC, Acre.

migratory volume among each of the 48 regional poles and the remaining Brazilian municipalities between 1995 and 2000. There is an association between the polarizing capacity of a pole and its overall migration volume. In other words, the higher the economic importance of a pole, measured in terms of its IS, the larger is its overall migratory volume, even if its net migration is relatively low (Garcia et al., 2004). For example, although the macro-pole of São Luis and the micro-pole of Parauapebas possess similar net migration figures (7100 and 6400, respectively), São Luis's overall migration is five-fold that of Paraupebas, which makes evident the greater importance and dynamism of São Luis.

4.4. Areas of influence of the economic poles

The index of interaction (Iv) measures a two-way influence: of the pole over remaining municipalities and of these over the pole. High values of this index mean high socioeconomic dimensions – translated as a high *anthropic* pressure – and large populations, both for the pole and municipality, as well as short distance and large migration exchange. Thus, high Iv can be interpreted as a strong connection between these two regions facilitated by proximity and population movement. As a result of this connection, an *anthropic* pressure gradient, influencing the deforestation process, is established from the pole to the satellite regions. The highest Iv between a given municipality and an economic pole defines which center is the pole of influence for this municipality. After the calculation of the Iv, a network of regions under influence of the economic poles was identified (Fig. 3).

Of the 48 micro-poles, the municipality of São Luis polarized the highest number of municipalities; a total of 109. This effect may be ascribed not only to its economic importance but also to the large number of small municipalities in Maranhão state. The second pole was Belém, with 72 municipalities under influence, followed by Palmas, with 67. The centers with smallest number of municipalities were Almeirim

(2), Guajará Mirim (3) and Tefé (2). But, in terms of area, the poles influencing the largest regions were Manaus, Cuiabá, Belém, Altamira and Rio Branco. Manaus, a burgeoning economic metropolis situated in the heart of the forest, is a particular case, due to voluminous fiscal incentives conveyed to its industrial park. Altamira, the largest Brazilian municipality and thus an anomaly in itself, hinders a detailed view of the migratory flows within this region, and Rio Branco, in spite of its low economic importance, is the most remote Brazilian state capital. The set of municipalities polarized by the same micro-pole defines the micro-regions of influence, as depicted in Fig. 3a.

Like the micro-pole regions, the meso-pole of São Luis had the highest number of influenced municipalities (143), followed by Belém (87) and Palmas (69). The 29 meso-poles polarize directly the non-pole municipalities, the other micro-poles and consequently the municipalities polarized by the micro-poles. The set of micro-poles and the area of influence polarized by the same meso-pole configure the meso-regions. Fig. 3b illustrates this configuration, in which the meso-region of São Luis comprises the micro-region of São Luis (109 municipalities) and the 26 municipalities of the micro-regions of Barra da Corda and 8 municipalities of the micro-region of Codó.

The regional macro-poles directly polarize the non-pole municipalities plus other meso-poles and indirectly their micro-poles of influence. The set of municipalities polarized by a macro-pole is the macro-region of influence. Fig. 3c exhibits the state capital macro-poles and their areas of influence. One can observe that their areas of influence are not constrained by state boundaries.

5. Conclusion

The urban network, in conjunction with the regional patterns of migration and the municipal socioeconomic dimensions, helps identify the Amazon frontier mobility, pointing out the current hotspots of deforestation – the deforestation arc – along with the emerging new frontiers. Fig. 4b portrays this integrated view, in which arrows indicate the deforestation trend towards the Amazon innermost frontiers. The bigger the arrow, the stronger is the front. Patterns of migration also indicate that most of the in-migrants to these inner fronts are coming from nearby consolidated frontiers, showing the way the frontier perpetuates itself (Fig. 4a). Two particular regions stand out from these results. First, the high SDI values assigned to municipalities along the Cuiabá-Santarém highway in Southern Pará may account for the expectation of paving this road (Fig. 2c). Second, Manaus, although with high SDI, concentrates much of its potential for deforestation nearby, namely on its urban–rural fringe. This can be attributed to its large flow of urban in-migrants, who are attracted to the numerous jobs offered by its burgeoning industry park (Table 2). This effect also demonstrates that the economic model of Manaus is exogenous to the region under its influence.

The integrated model presented here, considering the flow of people over economic poles and other centers, has added a new dimension to the grand regional compartments of the Brazilian Amazon, as first drawn up by Becker (1990) and later developed by Kampel et al. (2001) and Becker (2001). This type of model also has great potential for predicting environmental changes due to *anthropic* pressure, considering that the socioeconomic space network plays a decisive role in governing human settlement patterns. For example, its framework provides a basis for forecasting deforestation at different spatial levels, equivalent to the regions defined at each hierarchy level (Soares-Filho et al., 2006).

In comparison to the previous regionalization methods of Lemos et al. (2003) and Garcia (2002), the approach presented here is more sensitive to territorial diversity, providing a wider range of spatial arrangements, as it employed, instead of micro-regions, municipal census data. Also, as exhibited in Fig. 3, all municipalities assigned to a particular region in each of the three hierarchy levels form continuous spatial clusters, demonstrating that the adopted method is highly consistent in terms of spatial continuity, a prime requirement for any regionalization method.

The set of equations used in the present methodology was conceived to provide a general framework to map territorial organization and thus can be modified to incorporate different views of the urban network and its associated socioeconomic space. For example, geodetic distance could be replaced by other measures of distance that embody the concept of accessibility. In

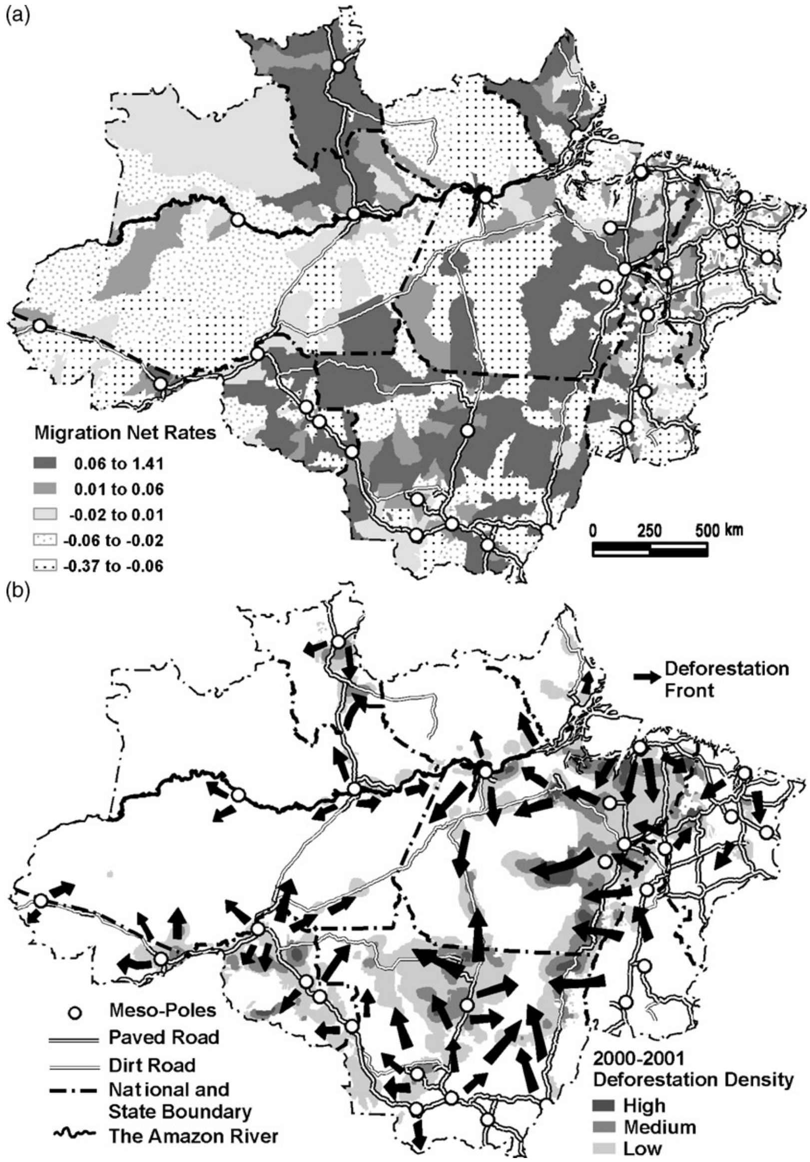

Fig. 4. (a) 1995–2000 migration net rates for the Brazilian Amazon municipalities and (b) major deforestation fronts, derived from the integrated analysis of the Amazon urban network, population movements and socioeconomic dimension index, laid over 2000–2001 deforestation hotspots from Alencar et al. (2004).

addition, the gravitational mass, in the numerator of Eq. (2), can be modified to address different geographic approaches. Still, further population studies can incorporate patterns of migration Brazil, especially in Peru, Bolivia, and Guiana.

The maps of the poles' areas of influence, presented in Fig. 3, are not meant to define regions in a strict sense, but rather to depict the way the Amazon socioeconomic space is structured in relation to its urban network and, consequently, how this spatial organization influences the deforestation process. In reality, there are no clear-cut boundaries between those regions, as all municipalities hold multiple interactions among themselves and with the identified poles. Moreover, the territorial organization presented here reflects the Amazon socioeconomic space at the turn of the millennium; this picture is expected to change as new economic centers emerge and other urban connections are established. It is particularly interesting to note that the identified regions depict a nested spatial pattern not constrained by state boundaries. This socioeconomic layout not only highlights the diversity of Amazon territory, but may also be useful for redirecting interstate public policies and other proactive measures aiming to conciliate socioeconomic development with the conservation of the Amazon's natural heritage.

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