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Who is responsible for deforestation in the Amazon? A spatially explicit analysis along the Transamazon Highway in Brazil

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A B S T R A C T

Understanding actor-specific responsibility for deforestation in the Brazilian Amazon is key in adjusting policy and resource allocation in the face of current forest destruction. However, previous research shows that there is great variability in such assessments. To contribute to the ongoing discussions on forest conservation and rural development policies in the Amazon, this paper studies actor-specific deforestation and its environmental effects in four municipalities situated along the Transamazon Highway. We used spatially explicit methods that integrate a database of 8281 georeferenced properties with a time series of remote-sensing data covering four periods between 1986 and 2007. We also included landscape ecology metrics as improved indicators of the complex environmental effects of forest fragmentation. The analysis demonstrates that smallholders (defined as colonists who own less than 100 ha of land) were responsible for 23% of total deforestation in the study region while accounting for 55% of the total properties. We also explored the relationship between property size and deforestation at the property level, finding that it closely follows a power distribution. Property deforestation increased with property size, while the percentage of property deforestation decreased. In spite of this, compliance with current legal requirements to maintain 50% of property forest cover was not statistically different between smallholders and largeholders. In comparison to municipalities dominated by medium- and large-scale ranchers, the smallholder-dominated municipality of Medicilândia showed better performance in all applied landscape metrics with well-established relationships with the provision of important environmental goods and services. Although all studied municipalities showed severe accumulated deforestation, Medicilândia experienced an abrupt decrease in municipal deforestation after 1999 to just 0.03% year^{-1}, while municipalities dominated by larger holders maintained or increased their previous deforestation rates to between 0.90% and 1.34% year^{-1} in the same period. This indicates that the smallholders' productions schemes in our study area might present potential for agricultural frontier stabilization based on improved land-use efficiency. The policy implications of our findings are discussed, especially with regard to the role of smallholders in productive forest conservation.

1. Introduction

Intense deforestation has followed government efforts to colonize the Brazilian Amazon since the 1970s. Today, one-fifth of the Legal Brazilian Amazon has been deforested (INPE, 2011), particularly in the so-called "arc of deforestation" and along the main roads hosting colonization projects (Soares-Filho et al., 2004). Although initially considerable colonization efforts were directed toward smallholders practicing family agriculture, under economic and demographic pressures the steady process of land accumulation transformed vast areas into capitalist frontiers controlled by large landowners (Pacheco, 2005). Inadequate state control over frontier development and monetary/tax incentives for colonization and large-scale cattle ranching has led to a race for land appropriation by people from all over Brazil (Ozorio de Almeida, 1992). As a result of those economic and demographic pressures, most of the colonized areas in the Brazilian Amazon today are contested landscapes (Schmink, 1982) in which the frontier is characterized by complex spatial interspersion of smallholders and largeholders. Extensive cattle ranching on large properties and family agriculture on small properties are considered the most prevalent land-use models in colonized areas of the Amazon (Kirby et al., 2006). More recently also industrial-scale agriculture (i.e., soy farming) has gained importance (Morton et al., 2006).

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The colonization of the Brazilian Amazon has resulted in a process of intense deforestation. The associated environmental and social problems, including biodiversity loss, degradation of soils, regional and global climate change, violence, social unrest and poverty, are of national and global concern (Alston et al., 2000; Foley et al., 2007; Laurance, 1999; Malhi et al., 2008; Rodrigues et al., 2009; Walker et al., 2011). Thus, governments and international organizations invested significant efforts to reduce deforestation, however, so far with only modest success. One of the reasons for these shortcomings results from insufficient information about the differential effects caused by the behavioral models of the many types of actors involved in the complex processes causing deforestation. A more accurate understanding of these actor-specific deforestation outcomes would help to design more effective environmental policies.

Against this background, this paper intends to contribute with a regional perspective on actor-specific deforestation, to help establishing better foundations for improved policies and resource allocation towards halting Amazonian deforestation. We focus in one of the most prototypical colonization efforts in the Brazilian Amazon, the Transamazon Highway, which offers four decades of frontier and colonization dynamics, a large diversity of actors and intraregional variability. The analysis applies a multi-scalar and multi-temporal methodological approach, attempting to address some of the shortcomings and successful approaches of previous deforestation studies (Section 2). Section 3 describes in detail the study area and methods used. Section 4 presents our findings with regard to actor-specific contributions to land accumulation and deforestation at the property and landscape levels, and the relationships between property size and deforestation. Based on the insights gained, in Section 5 we discuss the responsibility of each actor type for deforestation, and present in Section 6 the implications of our findings for future policies.

2. Actor-specific deforestation assessments in the Brazilian Amazon: methodological approaches

In the scientific literature, the relative contribution of smallholders vs. largeholders to overall deforestation is controversial (Table 1). Fearnside (1993) analyzed data from the Brazilian Institute of Geography and Statistics (IBGE) to conclude that smallholders caused only around 30% of the total deforestation in the Brazilian Legal Amazon, while Alencar et al. (2004) used data of IBGE 1995/1996 to show that 18% deforestation was attributed to properties of less than 100 ha. Pacheco (2005) derived data from the National Institute for Space Research (INPE) of 2002 to conclude that 47% of the deforestation could be attributable to smallholders. By crossing census information and INPE data, the same author estimated a 35% contribution of smallholders to deforestation by 2003 (Pacheco, 2009a). Chomitz and Thomas (2003) also used IBGE census tracts to estimate that about three quarters of deforestation is attributable to pastures, and that most part of it is due to cattle-oriented largeholders. Homma et al. (1998) suggested that half of the deforestation may be due to subsistence farming. On the other extreme Faminow (1998) affirmed that the share of deforestation of largeholders is just of 25%. Logically these numbers vary extremely if specific colonization projects are considered (Mertens et al., 2002; Walker et al., 2000).

This diversity of assessments arises from several factors. Beyond the diversity of conditions in the Amazon and the inherent variability of results at different scales, there are indications that also methodological shortcomings may decrease the feasibility of the assessments to adequately inform policy-making. In particular, we considered four critical aspects:

(i) In some studies, datasets obtained at large scales were used to derive results at finer scales. For example, given the limited data available in the Brazilian Legal Amazon, the study of Pacheco (2005) had to rely on non-spatially explicit agricultural census at the municipal level from IBGE overlaid with official municipal deforestation data. Although generating good results at a large scale, the lack of intra-municipal discrimination between colonist types limits the reliability of the results, because the interspersion of different colonist types requires caution in assuming that a certain colonist type characterizes a whole municipality. As shown by the same author (Pacheco, 2009a), more accurate estimates could be achieved by crossing the environmental data of INPE with the information from the census units underlying the aggregated IBGE information at municipality level. Some authors have managed to zone actor-specific areas through interpretation of landscape patterns in land cover change maps (Mertens et al., 2002, 2004), or by crossing settlement history, visual interpretation of landscape footprint and field surveys (Killeen et al., 2008). Such methods permit the study of large areas with very good results, but incur in a certain oversimplification since they operate at large scales, and the identification of actor-specific areas requires a strong first hand expertise which derives in difficulties for replication. At finer scales, only a complete register of georeferenced property grids and socio-economic surveys in each property would permit a detailed zoning. However large socio-economic surveys at the property level are expensive to obtain, while georeferenced property grids are rare and also difficult to obtain. Thus, the authors that have crossed land use maps with property grids to assess actor-specific deforestation in the Amazon had to rely on small samples that did not include the entire colonized areas in a municipality (e.g., Ludewigs et al., 2009; Michalski et al., 2010). They often developed property grids partially or completely based on the more often available information about the original properties (McCracken et al. (1999) and Aldrich et al. (2006), respectively). This method, however, assumes that property ownership and distribution have not changed in decades, thereby disregarding the historically intense processes of land accumulation and land grabbing (Alston et al., 2000; Chomitz and Thomas, 2003). Intense land accumulation dynamics have been demonstrated in parts of the Transamazon Highway by Ludewigs et al. (2009), who described a fourfold increase of the Gini coefficient of land distribution. Margulis (2003) indicated that in average 88.9% of the land belonged to properties larger than 100 ha in the entire Legal Amazon during the 1970–1995 period. As a consequence, the consideration of original properties probably bias deforestation assessments against smallholders.

(ii) In view of the importance of historical deforestation dynamics and long-term trends (Ferraz et al., 2009), many studies also suffered from insufficient observation periods, producing a static picture of deforestation. But frontier expansion is a dynamic process in which actors carry out deforestation at different intensities according to livelihood cycles, market dynamics and productive conditions. In particular, the potential for improved land-use efficiency of certain actors is often overseen (Pacheco, 2009b), and initially intense deforestation dynamics can sometimes be reversed during the final stages of colonization (Pfaff, 1999). The capacity of an actor for long-term adaptation of production schemes to the resources available within a spatially limited property is key in determining future deforestation responsibility and dynamics. Thus, at least

Table 1
Summary of relevant actor-specific deforestation assessments in the Brazilian Amazon.

Bibliographic References	Data source	Scope	Deforestation attributed to smallholders
Alencar et al. (2004)	IBGE 1995/1996 agrarian census	1996, Brazilian Legal Amazon. Smallholders < 100 ha	18%
Chomitz and Thomas (2003)	Census tract data from IBGE 1995/1996 agrarian census	1996, Brazilian Legal Amazon	More than three quarters of the land is in pasture. Most pasture is concentrated in large holdings.
Fearnside (1993) and Fearnside (2005)	IBGE 1985 agrarian census integrated with satellite estimations through multiple regressions.	1991, Brazilian Legal Amazon	30%
Margulis (2003)	Remote-sensing information from the National Institute for Space Research (INPE) and the Brazilian Institute of Environment and Renewable Natural Resources (IBAMA).	1997–1999, Brazilian Legal Amazon. Smallholders < 100 ha	Undetermined. As a proxy, deforested patches of less than 100 ha comprise 36.5% to 54.3% of the total deforestation, using respectively IBAMA and INPE data.
Pacheco (2005)	Author estimate based on the IBGE 1995/96 agricultural census and INPE data from 2002	2002, Brazilian Legal Amazon. Smallholders < 100 ha	47%
Pacheco (2009a)	Agricultural census information for 1995/1996 crossed with INPE data from 2003	Brazilian Legal Amazon. Smallholders < 100 ha	35%
Homma et al. (1998)	Interpretation of non-spatially explicit data from the IBGE 1995/96 agricultural census and the author's estimation of the number of smallholders in the Amazon Basin	Brazilian Legal Amazon. Smallholders < 100 ha	50%
Michalski et al. (2010)	Field and remote-sensing data over 300 georeferenced rural properties.	Nine municipalities in Northern Mato Grosso. Smallholders < 150 ha	Smallholders retain less forest cover per area owned, but contribute very little to absolute deforestation (<2% total deforestation in the studied properties)
Walker et al. (2000)	Size of cleared patches; visual inspection of remote-sensing data to attribute deforestation to large-scale ranching.	Four municipalities in the State of Pará, including Uruará along the Transamazon Highway. Largeholders > 1000 ha, smallholders < 100 ha	64% on average; between 0 and 92% depending on the municipality.
Mertens et al. (2002)	Land cover maps obtained from LANDSAT images, crossed with polygons representing actor dominated zones. Zoning was carried out by visual interpretation on land cover change maps.	SãoFélix do Xingú, Southern Pará	Aprox. 40% for small-scale directed colonization and 10% for small-scale spontaneous colonization.
Faminow (1998)	Estimates derived from various IBGE datasets	Brazilian Legal Amazon	75%
Aldrich et al. (2006)	Field cadastral and remote-sensing data	Uruará, Transamazon Highway. Smallholders < 3000 ha	96%

the initial colonization phase and the advanced frontier consolidation phase should be considered for reliable assessment. Ideally, a panel dataset with many years of data collection with the same landholders would ensure attributing deforestation to the responsible landowner (i.e., Aldrich et al., 2006; Ludewigs et al., 2009). This is an important issue, because in the Amazon settled or sold land may have been already deforested. Most critical, however, is that property size has often been considered as a mere scaling factor in understanding land-cover change (D'Antona et al., 2006). This simplistic notion that multiplying the number of colonists of a certain type by their current average property size provides an assessment of their deforestation impact within a given area is misleading, since it disregards possible long-term effects of actor-specific strategies for improved land-use efficiency at the property level, as well as the degree of environmental compatibility of their production strategies at the landscape level.

(iii) The large diversity of contexts and realities in the Amazon makes it difficult to establish valid basin-wide actor definitions. However, in an attempt to allow for regional comparisons and to facilitate conceptualization and discussion in the policy arena, there have been several attempts to classify Amazonian actors according to criteria, such as livelihood strategies (Chomitz et al., 2006; Fearnside, 2008), production systems (Browder et al., 2004; Walker et al., 2002), property size (Margulis, 2003; Walker et al., 2000), land-tenure dynamics (Browder et al., 2008), as well as combinations of these criteria (Pacheco, 2005). As seen in Table 1, much research considers property size for discriminating between actor types, since it is assumed that this criterion reflects the level of capitalization, which largely determines the productive strategy of a given colonist (D'Antona et al., 2006). Furthermore the size of properties is easy to measure, and permits a straightforward integration with geographical databases. Most commonly, an area of 100 ha is used as upper limit of smallholder properties in the Transamazon Highway (e.g., Mertens et al., 2004; Walker et al., 2000; Pacheco, 2005), in other Amazonian areas (Siegmund-Schultze et al., 2007) or even in the entire Brazilian Amazon (Fearnside, 1993). However, a number of studies use other values, including obviously unsuitable thresholds, as in the case of Aldrich et al. (2006), who, for the municipality of Uruará (also located along the Transamazon Highway), used a property size of 3000 ha to differentiate between small and large-holders in spite of the average property size in Uruará being less than 200 ha (IBGE, 2006). Such threshold implies that smallholders comprised 99.7% of the colonists in a municipality with significant presence of medium and large-scale cattle ranching enterprises, in which according to official figures family farming accounted for 87.1% of the properties and 43.5% of the farming land by 2006 (IBGE, 2006).

(iv) Raw deforestation figures do not sufficiently represent the real implications of deforestation. The effects of forest fragmentation on biodiversity, greenhouse gas emissions and microclimatic conditions are of great importance in the Amazon (Laurance, 1999). Considering that two landscapes with the same composition but with different configurations potentially result in different levels of provision of ecosystem goods and services (Schmit et al., 2006), landscape configuration metrics are more appropriate than simple deforestation area estimates for assessing the complex implications of deforestation. Thus, deforestation area figures should be complemented with landscape indicators of forest fragmentation, edge effects and forest functional thresholds (Skole and Tucker, 1993). Although the biological implications of these metrics are not fully understood, their relevance in strictly assessing deforestation dynamics has been confirmed by several studies (Imbernon and Branthomme, 2001; Peralta and Mather, 2000; Trani and Giles, 1999). In spite of that, most deforestation assessments in the Amazon have focused on landscape composition, which does not provide a reference to spatial attributes and interrelationships.

3. Data and methods

With the aim of improving our understanding of the specific contributions of relevant actor groups to deforestation in the Brazilian Amazon, we tried to address the identified shortcomings of existing deforestation studies by adopting a spatially explicit and multi-temporal approach at the property and landscape levels, which we applied in four municipalities along the Transamazon Highway in the State of Pará. The landscape level permitted a comparison among the four studied municipalities, each of which is broadly characterized by a different composition of actors and related production models. The property level permitted a finer, aggregated analysis of colonists' effects on deforestation using data obtained through remote sensing. The two levels of analysis were based on crossing municipal and rural property boundaries, respectively, with multi-temporal land-cover maps (Browder et al., 2008).

Our analysis used original datasets obtained through extensive fieldwork, including a detailed database of rural properties obtained through GPS surveying after inquiring land ownership *in situ*. This allowed to take into account land accumulation by representing actual current ownership (whether legally backed or not) in almost the entire area of the studied municipalities (see Section 3.4), and enabled the comparison with the original land tenure data from National Institute for Colonization and Agrarian Reform (INCRA). By including a multitemporal perspective based on remote sensing of satellite images covering four time periods between 1986 and 2007, we explored deforestation trends and assessed temporal land-use efficiency dynamics. Moreover, we used adapted landscape ecology metrics to better address the spatial and temporal dimensions of deforestation processes, in particular to (i) compare the effects of human disturbance on the landscape and the forest condition of four municipalities (Colson et al., 2011) and (ii) as generic indicators of the provision of environmental goods and services in these municipalities (Lindenmayer et al., 2002).

Nonparametric significance tests were used to test the null hypothesis that two independent samples come from the same population, because our sample of properties did not meet the assumption of normality. Given their robustness, methods that compared the sum of ranks were used (Mann–Whitney *U* and Wilcoxon tests). Equally, Spearman's rho was also used for assessing correlations, avoiding the normality assumption. Non-linear regressions were used to obtain a relationship between property size and deforestation.

3.1. Characterization of the study sites

The Transamazon Highway is the most paradigmatic colonization project in the Brazilian Amazon, offering ideal conditions for analyzing the aftermath of the colonization initiated by the Brazilian Government in the 1970s. Its foundation was the construction of a 3300-km road (the Transamazon Highway), along both sides of which INCRA aimed to settle colonists in a 100-km band, previously expropriated to prevent land speculation (Smith, 1976). The enormity of the project soon clashed with reality, and colonization was reduced to just three *Integrated Colonization Projects*. In these areas, colonists settled in 10-to-20-km wide stretches on both sides of the road. This plan was mostly directed towards family agriculture in small properties of approximately 100 ha, although some larger properties (mostly of 500 and 3000 ha) were granted soon afterward (Moran, 1981). However, the abandonment of the initial plans and the lack of governmental control led to frontier expansion and land accumulation. Today, many properties of up to several thousand hectares are found as far as 100 km from the road.

This study centers around the municipality of Medicilândia, which due to the predominance of small colonists, the existence of well known local initiatives for the small-scale production of cocoa and timber plantations, and outstanding socio-economic indicators was selected by the international research project ForLive[3] as one of their case studies for analyzing promissory smallholder initiatives with potential for sustainable rural development in the Amazon (Pokorny et al., 2011). In fact, 71.1% of the municipal colonized land belonged to properties of less than 200 ha, and intensive agriculture, often in agroforestry systems on small family-managed properties made Medicilândia the main producer of cocoa and bananas, and the second largest producer of coffee in the state of Pará (Table 2). According to IBGE (2006) it presented also the highest municipal percentage of family farming area in the Transamazon Highway (65.4%), which doubled the regional average (32.9%). Compared with neighboring municipalities, Medicilândia enjoyed a higher GDP per capita, a better human development index (HDI) and a lower Gini inequality income (Table 2).

For the purpose of comparison, we also considered in our analysis the three nearby municipalities of Brasil Novo, Anapú and Pacajá, where, in contrast to Medicilândia, properties over 200 ha occupied most of the colonized land. The total surveyed area of the four municipalities corresponds to 38,358 km^2 at the core of the Transamazon Highway. The studied municipalities have fairly similar physiographical conditions, a predominance of moist humid upland forests and a short dry season from July to October.

However, Medicilândia, with a large patch of *terra roxa* soils (euthrophic nitisols) of about 58,400 ha along the main road, generally enjoys better soil fertility than Brasil Novo and specially Anapú and Pacajá (SIPAM, 2004). Nevertheless, patches of *terra roxa* between 2600 and 69,600 ha are also found in the neighboring municipalities of Altamira, Brasil Novo, Uruará and Senador José Porfírio. In these municipalities, however, most of the fertile soils are dominated by large ranches and agricultural enterprises, and not by small family farmers.

While in Medicilândia the government granted properties of 100 ha, in Brasil Novo larger properties (*glebas* of 500 ha) were additionally conceded. Nowadays Brasil Novo is dominated by medium landowners, with almost half the properties having sizes between 200 and 600 ha. This municipality depends almost exclusively on cattle ranching, and there is very little family agricultural production. Approximately one-fourth of its territory is composed

[3] EU/ForLive project (PL 510903) "Forest management by small farmers in the Amazon, an opportunity to enhance forest ecosystem stability and rural livelihood"

Table 2
General characterization of the studied municipalities.

	WEST		EAST	
	Medicilândia	Brasil Novo	Anapú	Pacajá
Area (km^2)	8274	6368	11,858	11,858
Protected/indigenous reserves (km^2)	302 (3.6%)	1557 (24.4%)	5189 (43.8%)	0 (0%)
Population density[a] (inhabitants/km^2)[a]	3.3	2.8	1.7	3.4
% of colonized area dedicated to family farming[b]	65.4	45.6	32.5	42.8
% of colonized area in properties of <200 ha	71.1	35.0	46.4	30.6
% of colonized area in properties of between 200–600 ha	8.3	46.3	10.5	28.5
% of colonized area in properties of >600 ha	20.6	18.7	43.1	40.9
Predominant initial lot size	100 ha	100 and 500 ha	100 and 500–3000 ha	100 and 500–3000 ha
Initial INCRA investments	High	High	Low	Low
Deforestation (km^2)[c]	1806.9 (21.8%)	2408.1 (37.8%)	1836.2 (15.5%)	4330.4 (36.5%)
Deforestation *per capita* (ha)	6.6	13.4	9.0	10.8
Productive vocation	Agrarian predominant	Cattle	Cattle predominant	Cattle predominant
Livestock (1000 heads) [b]	127.4 (1.0%)	257.4 (2.0%)	132.3 (1.0%)	271.1 (2.1%)
Cocoa (1000 Tn)[d]	14.3 (37.6%)	2.3 (6.0%)	0.4 (1.1%)	1.0 (2.7%)
Banana (1000 Tn)[b]	51.3 (9.3%)	4.6 (0.8%)	21.6 (3.9%)	14.4 (2.6%)
Coffee (Tn) [b]	7574 (45.5%)	221 (1.3%)	350 (2.1%)	140 (0.8%)
GDP *per capita* (R$)[d]	11,835	5265	9910	4271
Human development index[e]	0.71	0.67	0.64	0.66
Gini inequality income index[f]	0.41	0.46	0.48	0.53

[a] Based on IBGE (2010).
[b] Data from IBGE (2006). Family farming definition according to federal law Lei No. 11.326 of 2006. Percentage with respect to Pará State shown in parenthesis.
[c] INPE (2011). Calculated in the same year as the fieldwork in this study, 2007.
[d] Data from the Secretaria de Estado de Planejamento, Orçamento e Finanças do Estado do Pará (SEPOF). SEPOF (2007). GDP for 2004 in Brazilian R$. Percentage with respect to Pará State shown in parenthesis.
[e] Data from year 2000. United Nations Development Programme Brazil. URL: http://www.pnud.org.br/atlas/tabelas/index.php.
[f] Calculated using http://www.wessa.net/co.wasp and information from SEPOF (2007).

of the Arará indigenous reserve. Unlike the municipalities to the west of the city of Altamira, the municipalities of Anapú and Pacajá received fewer initial investments and were less intensively considered by colonization projects, as the government did not foresee such an active role for small settlers. Instead, after 1975, the government authorized contracts for the "alienation" of public lands (*contratos de alienaçao de terras públicas*), granting areas of 3000–5000 ha to cattle ranchers and agribusiness. In these two municipalities, a lack of governmental control in combination with the availability of significant subsidies for cattle ranchers favored a more intense process of invasion by large cattle ranchers and agribusinesses, who grabbed thousands of hectares of land (IPAM, 2006), in addition to constant colonization by poor smallholders practicing subsistence agriculture. Currently, more than 40% of the colonized area in these municipalities is composed of properties of more than 600 ha. In Anapú, there are also protected indigenous areas accounting for more than two-fifths of the municipality's area.

3.2. Characterization of actor types

In accordance to most deforestation studies, we used property size as a proxy for actor types. Smallholders were defined as colonists with less than 100 ha following the traditional view within Amazonian research in our study area (e.g., Mertens et al., 2002, 2004; Walker et al., 2000), and the typical lot size allocated by INCRA to family farmers. The suitability of this threshold for our study area was assessed by calculating the median property size in the smallholder dominated municipality (Section 5). Property size thresholds for medium and large landholders in our study area were obtained from hierarchical clustering of socio-economic and productive information from 93 surveyed landowners (Godar, 2009; Godar et al., in press). The surveys gathered information on 38 parameters (i.e., production, soil fertility, landuse composition, family working load and demographics, distance to markets, landuse history and credit). The resulting groups were clearly aggregated by property size and pointed out to three colonist groups: (i) Smallholders who own properties of up to 100 ha and practice small-scale, family agriculture using a wide diversity of livelihood strategies that often include some cattle ranching (Walker et al., 2000; Margulis, 2003; Siegmund-Schultze et al., 2007). (ii) Medium landholders with properties of between 100 and 600 ha. These property owners most often practice extensive, family-managed cattle ranching. Because production success is often compromised by the need to periodically create new pastures following soil exhaustion, their capitalization is generally low. (iii) Largeholders who own properties of over 600 ha that may be up to several thousand hectares in size. These landholders exclusively practice large-scale cattle ranching. Although production is extensive and requires low investment per head of cattle, the scale of production does require external labor. Capitalization levels vary greatly according to the production circumstances of each property.

3.3. Multi-temporal land-cover mapping

Land-cover maps were obtained through remote sensing using sixteen dry-season Landsat TM and ETM + images, covering four time periods in each studied municipality between 1986 and 2007 (1987, 1991, 1999 and 2007 for Medicilândia and Brasil Novo; 1986, 1996, 2001 and 2007 for Anapú and Pacajá). The images and dates were selected according to their cloud cover and general quality.

Forest types were mapped in 2007 (last date of the time series) by integrating forest inventories and spectral data (Lu, 2005; Vieira et al., 2003). This was accomplished by correlating vegetation structure data from 65 field forest inventories of 20 × 20 m and reflectance data extracted from 2 × 2 pixel windows at the same locations. Four forest successional stages were discriminated using canonical discriminant analysis (Lu et al., 2003), which resulted in numerical scores derived from the canonical functions that characterized each plot. The numerical scores strongly reflect the aboveground biomass and other parameters that increase with forest maturity. Stand aboveground biomass varied between 2 and

14 kg/m^2 for the less advanced group in the forest succession SS1 (6.6 ± 3.9), to respectively 7–15 kg/m^2 (11.2 ± 3.1), 15–30 kg/m^2 (20.6 ± 3.9) and 31–70 kg/m^2 (41.0 ± 12.2) for the other three more advanced successional stages (SS2, SS3, and SS4). A strong correlation between the forest data and the spectral values was observed using multivariate regression. It depended mostly on TM-band 5, but also on spectral indices ND57 and ND47 ($R^2 = 0.85$ for the municipalities covered by the images located along path 226 and $R^2 = 0.70$ for the municipalities covered by path 225). Broadly similar relationships between biomass and TM5 have also been found in other studies in the Amazon (Lu et al., 2004; Steininger, 2000). Non-forest land uses were discriminated through unsupervised classification using the ISODATA algorithm and ground-truthed using a GPS device at 212 field locations. Farmland, urban areas, roads, water, alluvial sediments and clouds were differentiated.

Extrapolating the obtained relationship to the full extent of the 2007 satellite images resulted in forest maps that were overlaid onto the previously obtained maps of non-forested areas. To produce the older maps, histogram matching using 2310 spectrally time-invariant pixels in deep-water bodies was performed (Du et al., 2002), transforming the histograms of the older images to resemble those of the 2007 images. The differences between the median spectral responses of the control points were measured for each TM band and then added to the respective histograms. The global accuracy of the 2007 maps (using 300 randomly allocated points) was 87.3%. For deforestation assessments, as result of field work and post-control of those 300 random points, the two forest groups with higher biomass were considered as forest, whereas the other two successional stages and all human-made land uses were considered deforestation. The municipal

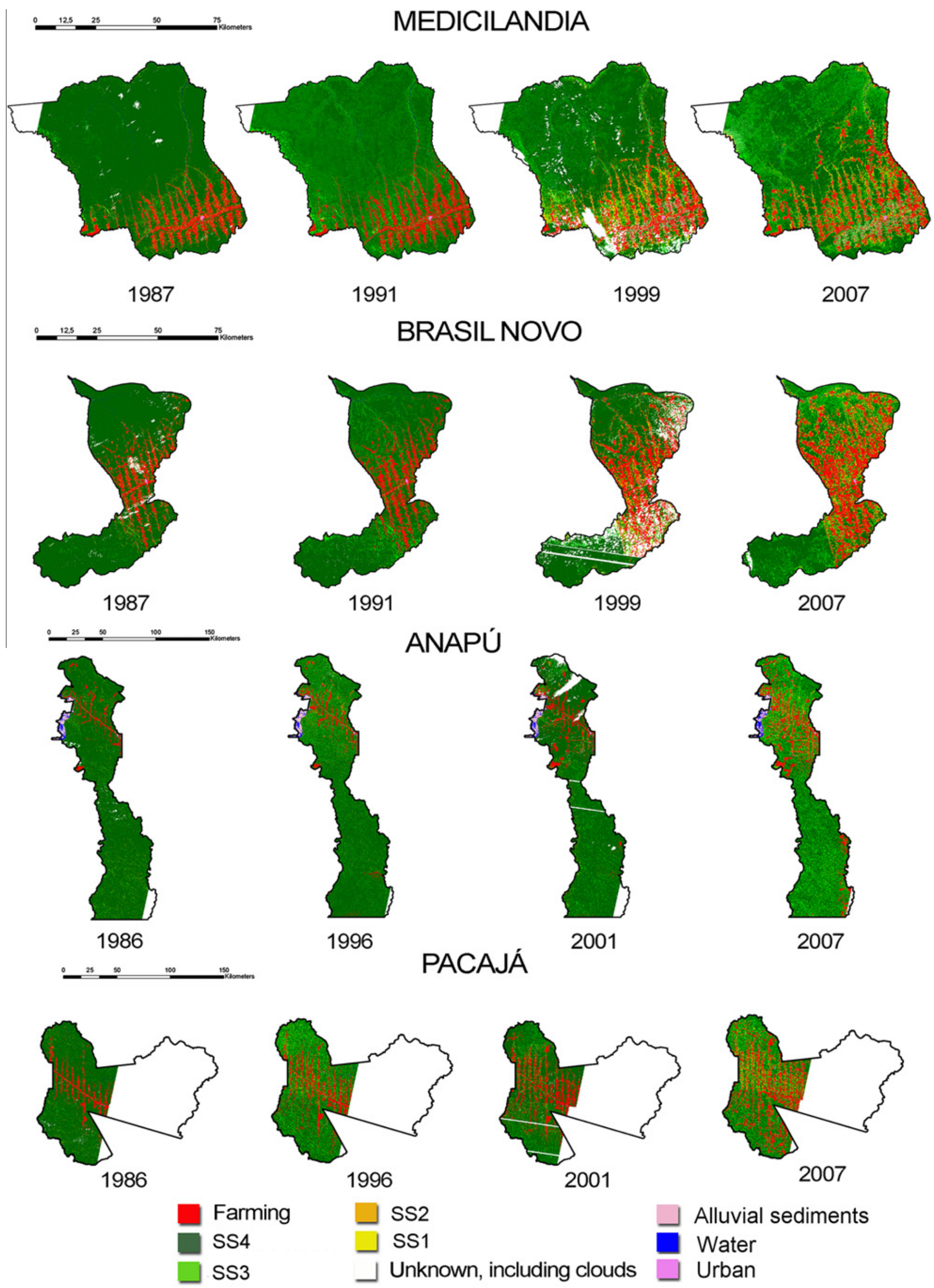

Fig. 1. Multitemporal land cover maps of the four studied municipalities between 1986 and 2007.

deforestation figures were very similar to the INPE deforestation data but were between 2% and 9% lower depending on the municipality. More details of the methodology used can be found in Godar (2009).

Fig. 1 represents land-cover within the four municipalities since 1986/1987. Multitemporal change maps were calculated to facilitate understanding of long-term dynamics and spatially explicit degradation/restoration processes. Image areas degraded by cloud cover or stripping were considered unknown land uses. Degradation was defined as the conversion of any pixel representing forest to farming, less-advanced stages of forest succession, roads or urban classes. The opposite changes were considered as restoration.

3.4. Property data

To account for the property level, 5294 property boundaries in Anapú and Pacajá were kindly provided by the INCRA/Brazilian Army (Technical cooperation project TCT-INCRA-4a DL). These property boundaries were obtained using a GPS device during the exhaustive identification of rural properties, which followed the violent land conflicts and the murder of Sister Dorothy Stang in Anapú in the year 2005 (Campos and Nepstad, 2006). Properties partly situated in Anapú and Pacajá and/or closely neighboring their boundaries were allocated to them for the purpose of analysis. An additional 2987 digital properties were obtained by the authors in collaboration with local farming unions in Medicilândia and Brasil Novo using GPS. In the case that any of the corners of a given property was not identifiable through GPS in the field, its location was interpreted using field indications provided by the owner, and when possible also title documentation and analysis of geometrical land-use shapes in satellite images.

The complete property database of 8281 properties included both legal properties and *de facto* occupied properties (Fig. 2). They represented current ownership, since field teams of the Brazilian Army visited each of their surveyed properties, while for our own database we interviewed property owners, neighbors or obtained ownership information from knowledgeable field assistants from the municipal Land Worker Unions (Sindicatos dos Trabalhadores Rurais – STR). Properties were defined as land owned or occupied by a single family unit (husband, wife and children). All properties nominally belonging to different members of the same family were merged into a single and unique property. This is due to some interviewed colonists declaring ownership of different lots to different family members due to legal suspicions. Hence in our database a property may be composed of geographically separated parts, better representing real ownership/occupation and hence better reflecting possible land accumulation. The grid included the great majority of colonized areas in Medicilândia (74.4% of the municipal pasture and farming areas lay within our property database), Brasil Novo (73.1%) and Anapú (83.6%). However, in Pacajá they accounted for only 22.0% of the total because property grids and land-use mapping for this municipality were incomplete. The deforestation per property was obtained by extracting land uses from the obtained maps.

The boundaries of the original lots granted by INCRA to individual colonists in the 1970s were only available for the municipalities of Medicilândia and Brasil Novo, and we digitized them from printouts provided by INCRA and the municipality of Brasil Novo, respectively. For these locations we were able to calculate the

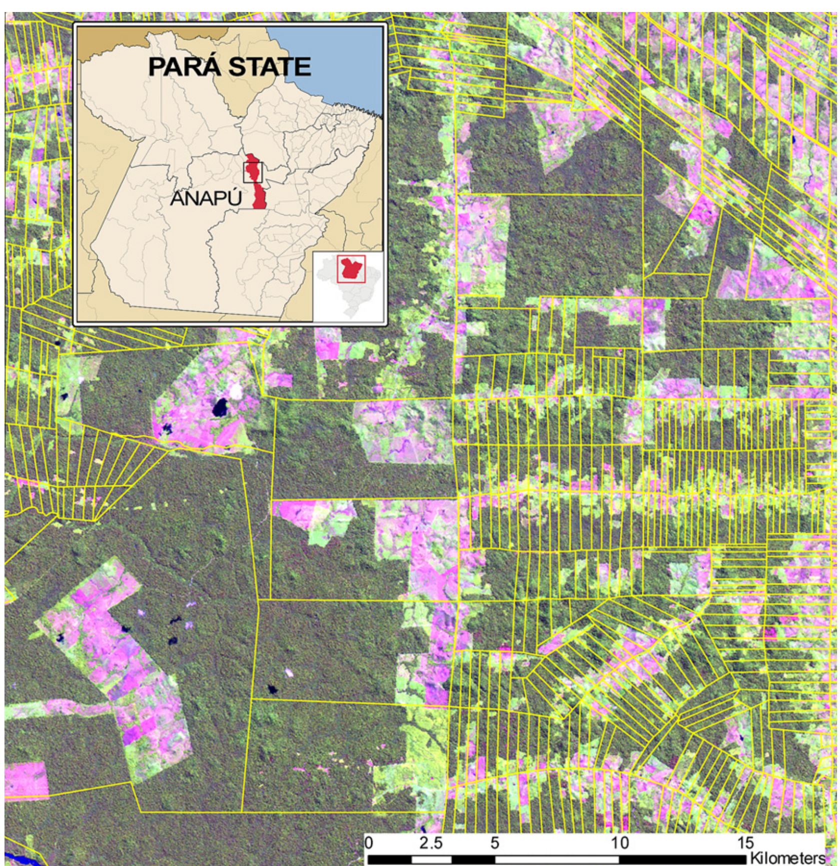

Fig. 2. Detail of the georeferenced property network in the municipality of Anapú. The background corresponds to a LANDSAT TM5 image (path/row 226/63, 2007-06-23) showing bands 5, 4 and 3.

Table 3
Land tenure and deforestation by actor type and municipality in 2007.

Actor	Land tenure				Distance to the road[b]	Deforestation	
	Area[a]	n	Mean ± SD (per property)	Gini	Mean ± SD	Area[a]	Mean ± SD (per property)
Smallholders (<100 ha)	336.7 (22.8%)	4547 (54.9%)	74 ± 22	n.a.	17 ± 12	126.5 (23.2%)	28 ± 22
Medium landholders 100–600	630.5 (42.7%)	3459 (41.8%)	182 ± 132	n.a	18 ± 14	265.0 (48.7%)	77 ± 84
Largeholders >600	508.8 (34.5%)	275 (3.3%)	1850 ± 1873	n.a.	32 ± 17	152.8 (28.1%)	555 ± 615
Medicilândia	235.8	1776	133 ± 262	0.32	9 ± 6	112.5	63 ± 122
Brasil Novo	271.1	1211	224 ± 263	0.45	16 ± 11	166.2	137 ± 169
Anapú	609.1	3660	166 ± 584	0.57	31 ± 16	177.5	49 ± 165
Pacajá	360.0	1634	220 ± 480	0.61	26 ± 12	88.0	54 ± 147

Property grid coverage: Medicilândia: 74.4%; Brasil Novo: 73.1%; Anapú: 83.6%; Pacajá: 22.2%.
[a] In thousands of hectares.
[b] Distance in kilometers between the georeferenced polyline representing the Transamazon Highway road and the centroids of all the georeferenced properties.

variation of the Gini coefficient of land distribution since initial colonization. For Anapú and Pacajá we relied on bibliography, and secondary indicators to assess land accumulation, such as the differential extent of the largest continuous deforested patches between different dates. However since we had no continuous panel dataset with many years of data collection with the same landholders, our database does not consider the fact that large landholdings may be created by consolidating previously deforested small landholdings, or that some recent settlements for smallholders have been created by redistributing previously deforested large properties (e.g., PDS Anapú).

3.5. Landscape metrics

The municipalities were used as landscape proxies, reflecting the outcomes of their respective actor type dominance. We selected metrics to measure forest fragmentation, forest core area and forest connectivity. Although landscape metrics have been surprisingly underused in Amazon deforestation research, they have been directly linked to the provision of environmental goods and services:

– Habitat fragmentation poses one of the greatest threats to biodiversity worldwide (otequilha-Leitão and Ahern, 2002). Forest fragmentation negatively affects gene flow (Degen et al., 2006) and interacts synergistically with hunting, fires and logging, favoring processes of intense degradation (Laurance et al., 2002). Related edge effects cause higher tree mortality rates, which were observed by Laurance et al. (2000) to occur within a maximal distance of 300 m from the forest edge. The resulting changes in forest ecology provoke a declining interior gradient of environmental goods and services provision (Mesquita et al., 1999), including increased greenhouse gas emissions (Laurance et al., 1998). To assess fragmentation and edge effects, forest patch density and forest edge density metrics were calculated.
– Forests situated at greater distances from highly anthropized land uses are better preserved and potentially provide more environmental goods and services (Skole and Tucker, 1993). Thus, a core forest area located at a minimum of 300 m from anthropic land uses was defined to estimate the area of potentially lightly degraded forests (Laurance et al., 2000). The impact of large cleared areas was assessed using the median of the 10 largest patches of continuous farmland in each municipality. Largest patch indices were used to assess the integrity of municipal forest stocks.
– Habitat connectivity affects the persistence and movement of plants and animals in fragmented landscapes and influences energy fluxes related to hydrological services (Pringle, 2001) and gene flow/conservation (Manel et al., 2003). Connectance and interspersion/juxtaposition indices were used to assess connectivity between forest patches and the intermixing of patch types, respectively. The connectivity distance between two given forest patches was defined as 500 m, considering the implications outlined in Laurance et al. (1997).

To avoid the use of dependent metrics, a principal component analysis was performed, resulting in the selection of eight landscape metrics. They were calculated using FRAGSTATS (McGarigal and Marks, 1995) in each municipality. Only areas potentially subjected to colonization were considered. Thus we excluded indigenous reserves which generally show much lower deforestation rates (Nepstad et al., 2006; Soares-Filho et al., 2010) to avoid a possible bias resulting from the comparison of municipalities with different percentages of preserved areas.

4. Results

4.1. Land tenure and land accumulation

As shown in the upper panel of Table 3, largeholders owned just over 3% of all properties in the year 2007, but occupied more than one-third of the colonized land. Despite being outnumbered by smallholders, medium and large landowners (who generally raise cattle exclusively) occupied more than three-quarters of the area. A family of large-scale cattle ranchers owned in average approximately 1850 ha, which is equivalent to the space occupied by 25 smallholder families, while a family of medium landowners occupied an average area equivalent to that of 2.5 smallholder families.

The average and maximum distances of the various property classes to the main road reflect the intense process of expansion that occurred during the last four decades. While the original properties were situated at a maximum distance of 20 km from the road (due to initial INCRA planning), in 2007 largeholders were found as far as 98 km from the road and smallholders at more than 60 km. The average distance to the road among the original INCRA properties were close to 10 km for all landholder types (as described in Ludewigs et al., 2009), whereas in the year 2007, this distance varied between 17 for smallholders and 32 km for largeholders. The strong increase of the Gini coefficient for land distribution from 0.14 for the original INCRA settlement (Ludewigs et al., 2009) to 0.53 for the year 2007, also indicates an intense process of land accumulation which provoked a great inequality in land distribution. However, as seen in the lower panel of Table 3 the smallholder dominated municipality of Medicilândia (0.32) exhibited a much more equalitarian land distribution than the municipalities dominated by medium and large cattle ranchers (0.45–0.61). Also the average property size and average distance to road were significantly lower in Medicilândia than in the rest of the municipalities (Mann–Whitney U test; $p < 0.001$).

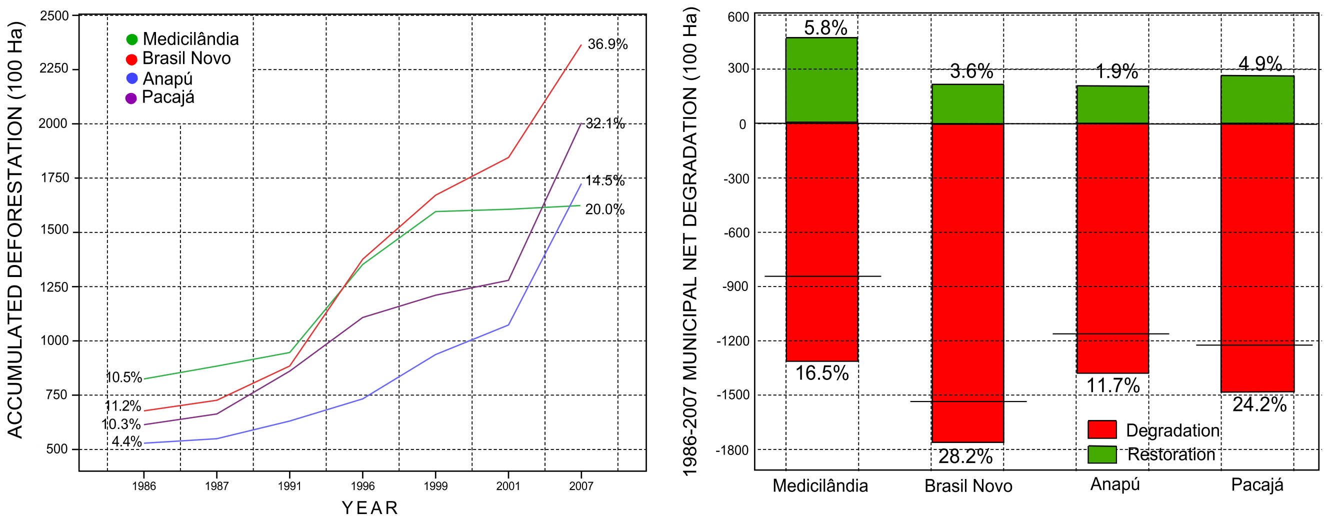

Fig. 3. Municipal deforestation and degradation-restoration dynamics between 1986 and 2007. The municipal deforestation percentages were calculated by extrapolating the area mapped to the total municipal area. Total area mapped with respect to municipal area: Medicilândia: 97.7%; Brasil Novo: 99.6%; Anapú: 99.3%; Pacajá: 53.7%. The municipal degradation/restoration was calculated with respect to the total area mapped. Degradation is defined as the conversion of any pixel representing forest (primary or secondary) to farming, less-advanced stages of forest succession, roads or urban classes. The opposite changes were considered as restoration. Note that the net result represented by the black horizontal lines does not equal total accumulated deforestation, as degradation/restoration dynamics can happen between land-uses that are considered deforestation.

4.2. Actor-specific deforestation

In the entire study area, large and medium landowners were responsible for more than three-quarters of the total deforestation until 2007 (Table 3). Furthermore, in average a property of large cattle ranchers had an accumulated deforestation of 555 ha, which is 20 times the area deforested in a property owned by a smallholder family. As a consequence, the 275 properties owned by largeholders in our study area accounted for 28.1% of the total deforestation, while the 4547 smallholder properties were responsible for 23.2%. Thus, most of deforestation was caused by some few hundreds of large properties, while the colonists with property sizes of less than 200 ha representing 88% of all land owners, accounted for just 47% of total deforestation.

Adherence to the *reserva legal* (RL), a legal obligation currently requiring the preservation of at least 50% of the forest on a property, was generally poor (approximately 65% on average). The difference in adherence between smallholders and largeholders was

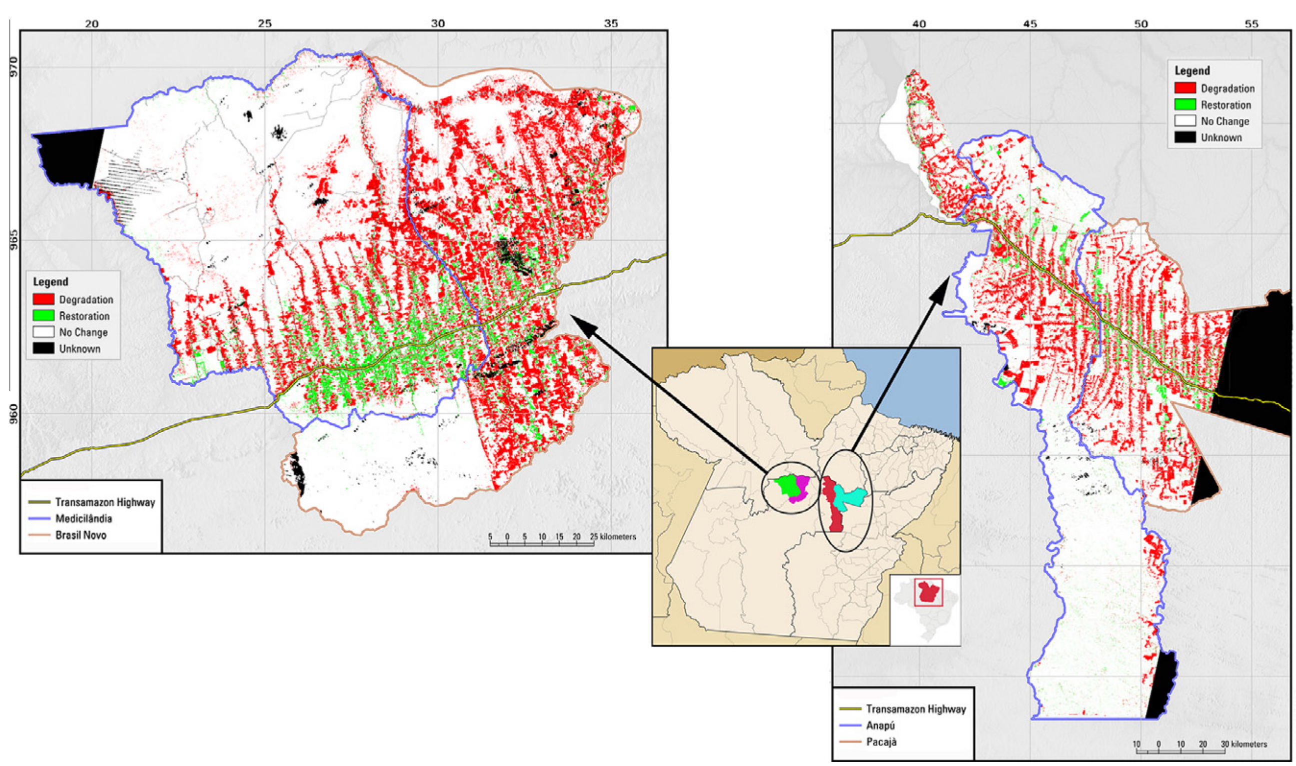

Fig. 4. Map of municipal degradation-restoration between 1986 and 2007. Degradation is defined as the conversion of any pixel representing forest (primary or secondary) to farming, less-advanced stages of forest succession, roads or urban classes. The opposite changes were considered as restoration.

not statistically significant using a Wilcoxon test (67.8% vs. 72.5%; $p = 0.138 > 0.001$). However, in comparison to medium landholders, smallholders respected the RL significantly more often despite their greater spatial constraints (67.8% vs. 60.6%; $p < 0.001$). In average, smallholders deforested 38% of their properties in comparison to 42% of medium landholders and 30% for large landholders.

The two more recently colonized municipalities (Anapú and Pacajá) presented lower average property deforestation, while among the initially colonized municipalities, Medicilândia presented an average property deforestation less than half that of Brasil Novo. Despite being a smaller municipality and including more protected area, Brasil Novo exhibited a higher level of deforestation than Medicilândia, both in absolute and relative terms (Fig. 3). In Brasil Novo as well as in Pacajá, considerably more than one-third of the municipal area was deforested by 2007, followed by Medicilândia, with around one-fifth. Deforestation was lowest in Anapú (one-seventh of the area), a municipality that is larger, less populated and has a greater proportion of land in indigenous reserves (44% compared to 4% in Medicilândia). Deforestation was considerably higher in municipalities with the least area occupied by smallholders, both in terms of the percentage of the municipal area and *per capita* rates (Table 2). The analysis of land-use change maps revealed that most of the deforestation occurred in large rectangular patches of several hundreds of hectares, most often in remoter areas characterized by greater availability of unoccupied land (Fig. 4). This pattern typically corresponds to large cattle ranches installed on (public) forest land.

In all municipalities, highly significant positive correlations were found using Spearman's rho between the size of the properties and the total deforested area (Medicilândia: 0.39; Brasil Novo: 0.73; Anapú: 0.62; Pacajá: 0.69; $p < 0.01$; entire study area: 0.65, $p < 0.01$). The relationship between property size and accumulated property deforestation closely follows a power distribution, considering both all individual properties ($R^2 = 0.96$) and aggregated size classes ($R^2 = 0.99$) (Fig. 5a). The classified size categories were 50 ha for the 1–600 ha range, 100 ha for the 600–1200 ha range and 200 ha for larger property areas. The regression curve indicates that although total deforestation clearly increases with property size, smaller properties show higher percentages of relative deforestation within their properties. Thus, a small increase of size in small properties would provoke a comparatively greater increase of deforestation compared to larger properties, as shown by the derivate of the regression curve (Fig. 5b). However, the individual responsibility of a given property for the region's deforestation increases exponentially with property size, as illustrated in the representation of the integral of the regression curve (Fig. 5c). In particular the analysis indicates that, if the size of a property doubles, its individual contribution to total deforestation increases by 80% more than what would be expected if deforestation contribution and property size were strictly proportional.

4.3. Deforestation dynamics

Until 1991, Medicilândia exhibited more deforestation than the other municipalities, and presented similar deforestation rates until 1999. Since then, as indicated by the abrupt flattening of the

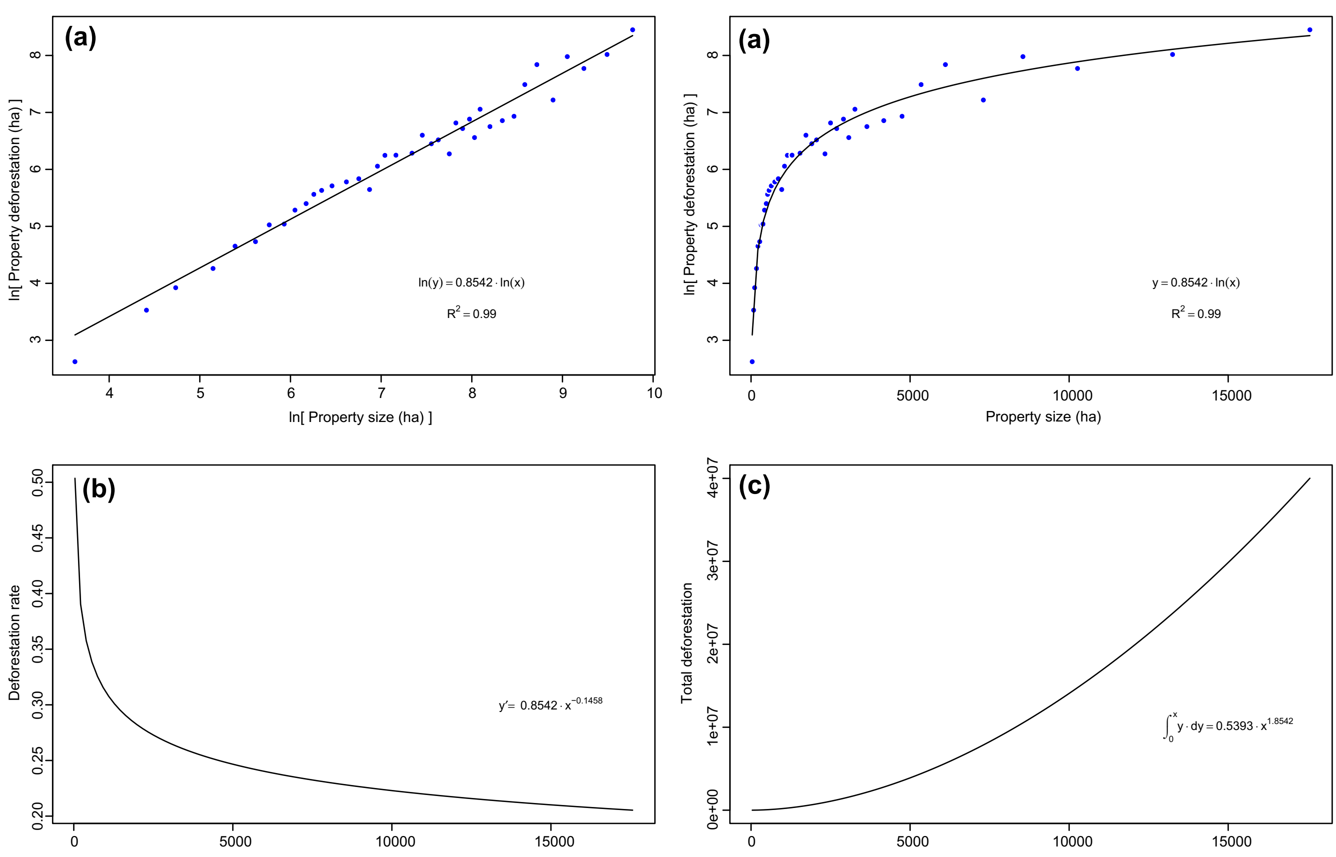

Fig. 5. Regression curve between property area and total property deforestation. Only the properties with deforestation higher than 5% of the property area were considered, thereby eliminating properties without obvious management. The properties were aggregated into 39 size classes. (a) The regression curves represent the relationship between property size and property deforestation based on data of 8281 properties classified in 39 size groups. (b) The curve represents the derivate of the obtained regression curve (instant percentage rate of deforestation for a given property size). (c) The curve represents the integral of the obtained regression curve. The area below the integral curve represents the total accumulated deforestation in the sample properties vs. property size.

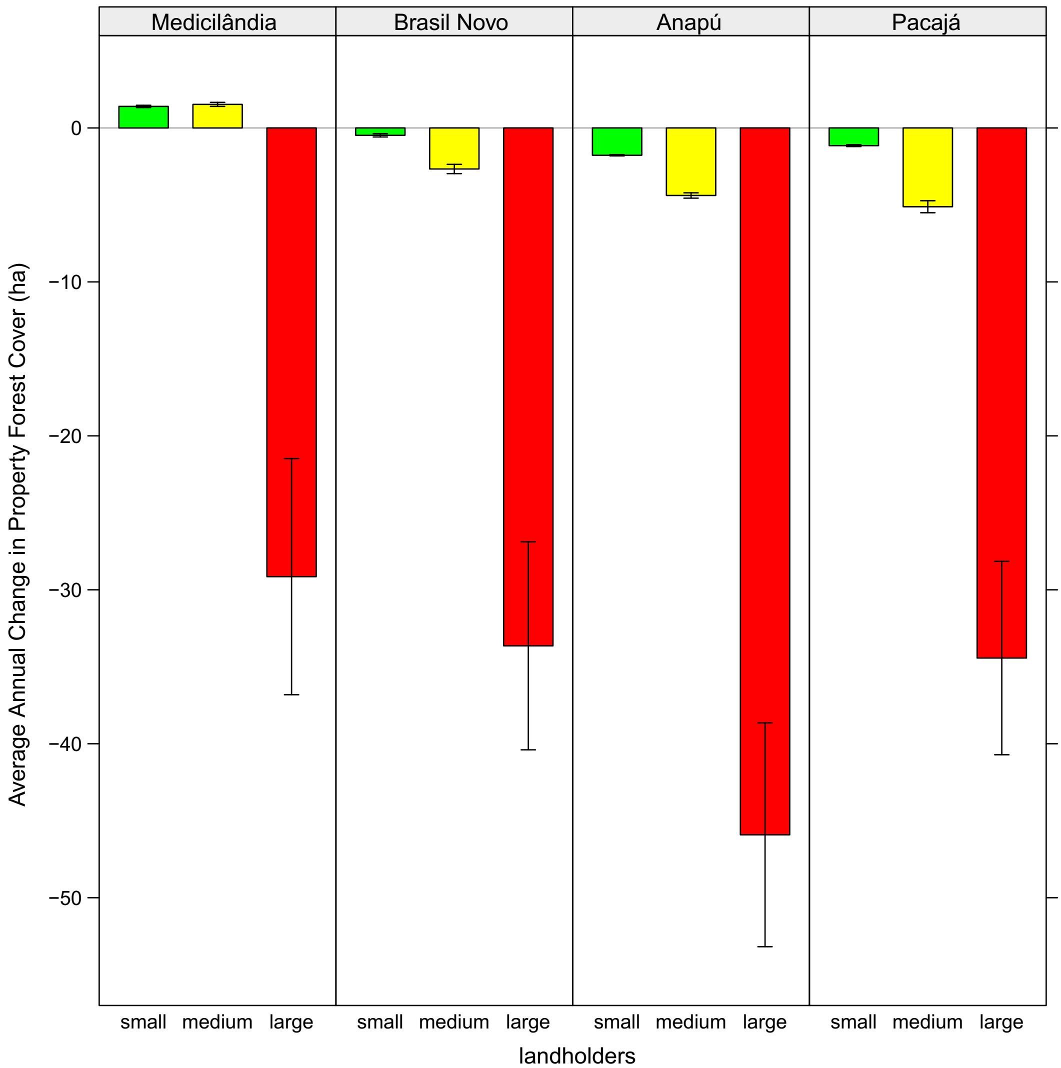

Fig. 6. Average annual change in property forest cover by actor type and municipality between 1999 and 2007. The studied period is 1999–2007 for Medicilândia and Brasil Novo, and 2001–2007 for Anapú and Pacajá.

Table 4
Results of landscape metrics by municipality.

	Medicilândia		B. Novo		Anapú		Pacajá [a]	
Index	2007	1987–2007 (%)[e]	2007	1987–2007 (%)[e]	2007	1986–2007 (%)[e]	2007	1986–2007 (%)[e]
Forest patch density	0.74	250.4	1.69	448.2	1.07	312.7	1.58	369.8
Forest edge density	26.55	170.2	42.42	217.0	32.79	169.7	42.12	200.7
Forest core area (300 m distance)[b,c]	342.5	70.6	54.5	22.8	234.5	63.4	227.7	51.1
Largest forest patch[c]	251.6	39.6	98.3	34.8	251.6	92.3	215.2	77.7
Largest farming patch[c]	1.9	45.0	7.8	323.9	25.3	731.9	14.5	129.4
Median of the 10 largest farming patches[c]	1.09	76.9	4.22	370.8	4.14	246.3	3.99	222.6
Connectance (500 m distance)[d]	0.11	48.6	0.07	28.3	0.11	31.1	0.07	27.7
Interspersion and juxtaposition index	76.85	110.0	55.66	77.6	53.19	93.0	53.71	84.2

[a] Only 53.7% of Pacajá was mapped; thus, the core areas and largest patches do not correspond to the entire municipality. The remaining measurements are good indicators of the municipal values because they are calculated by area unit.
[b] Distance calculated from any anthropic land use.
[c] In thousands of hectares.
[d] Maximal distance between forest patches.
[e] Value in 2007 as a percentage of the respective index calculated in 1986/1987.

deforestation line for Medicilândia in Fig. 3, deforestation in Medicilândia decreased to only 0.03% of the municipal area per year. This contrasts with the situation in the municipalities dominated by medium and large cattle ranchers, where the already high deforestation rates even increased in the last studied period. Correspondingly, the highest level of restoration and the lowest level of degradation during the analyzed period were found in Medicilândia. In this municipality, the net degradation was similar to that in the municipality of Anapú (10.7% vs. 9.8%), which, however, had a much lower population density. In general, the few areas that showed indications for restoration were smaller and often aggregated along the main road, largely corresponding to the original lots of about 100 ha granted by INCRA in a 10-km wide stretch along the main road (Fig. 4).

As seen in Fig. 6, recent deforestation (1999–2007 respectively, 2001–2007 depending on the municipality) was much higher for the larger properties, regardless of the municipality. A Wilcoxon test ($p < 0.001$) demonstrated that large and medium landholders contributed significantly more than smallholders to recent deforestation, and their relative deforestation responsibility has increased since 1986. Remarkably, small and medium landowners in the municipality of Medicilândia managed to not only reduce property deforestation from 1999 to 2007, but also to recover a tiny portion of their forests. This was the only net recovery of forest associated with any actor type in the studied municipalities, which suggests for Medicilândia a trend towards increased land-use efficiency in small properties.

4.4. Landscape metrics performance

Deforestation analysis at the municipal level was complemented with a more subtle landscape-metric qualitative analysis (Table 4). The values presented are not statistical samples but correspond to the entire municipal areas. Brasil Novo and Pacajá showed the highest rates of forest fragmentation by 2007, which were more than 50% greater than the rates in Anapú and double those in Medicilândia. Brasil Novo also exhibited the greatest increase in forest fragmentation since 1987 (approximately 4.5-fold), followed by Pacajá and Anapú (each showing a well over threefold increase). Medicilândia suffered a comparatively smaller increase (approximately 2.5-fold), reflecting the fact that all the municipalities have undergone strong environmental degradation, but that it was far less intense where smallholders prevailed. The forest edge density results indicate a similar pattern.

The remaining forest core area and the sizes of the largest patches of forest and farmland also indicated a higher quality of forest assets in Medicilândia compared to the other municipalities. In the year 2007, Medicilândia presented a larger area of lightly degraded forests in areas potentially dedicated to colonization (3425 km^2 or about 1.5 times more than in Anapú or Pacajá). This area represents approximately two-thirds of the same type of forest that existed in 1987. In contrast, Brasil Novo had lost most of its potentially lightly degraded forests due to pasture expansion, so that less than 550 km^2 remained. Since 1987, more than three-fourths of the non-protected forests in Brasil Novo have been eliminated or subjected to strong edge effects.

Also, the environmental impacts associated to large and continuous land clearing were greater in the three municipalities where medium and large-scale ranching predominated. In these municipalities, the median of the 10 largest farming patches was approximately 4000 ha, which is four times greater than in Medicilândia. Furthermore, in Medicilândia, the size of the largest cleared patch considerably decreased since 1987, whereas in Pacajá and Anapú these patches increased more than twofold, and almost fourfold in Brasil Novo.

Connectivity metrics confirmed that smallholder-dominated areas performed better in environmental terms. Forest connectivity was found to be similar in Medicilândia and Anapú, being approximately 50% greater than in Brasil Novo and Pacajá. The colonists of Medicilândia retained approximately half of the forest connectivity that was found in 1987, whereas in Anapú, connectivity decreased to one-third, and barely one-fourth in Brasil Novo and in Pacajá. The fact that also the forest interspersion index of Medicilândia was almost 50% greater than that of the other municipalities indicates that smallholdings were associated with a more diverse and intertwined mosaic of forested landscapes per hectare, whereas the landscapes created by largeholders were more dual and homogeneous.

5. Discussion

This paper addresses the controversial issue of how much deforestation is attributable to smallholders and largeholders. Our analysis covering four municipalities along the Transamazon Highway agrees with the general view that large-scale cattle ranching is the main activity causing deforestation in the Brazilian Amazon (Fearnside, 1993; Margulis, 2003). Furthermore we conclude for our study area that the deforestation share of largeholders has rapidly increased in the last decades. This contrasts with the remarkable decreasing of recent deforestation rates in some areas dominated by smallholders, indicating that the main trend in the Transamazon Highway is towards an accelerated conversion of forest into pastures within large consolidated properties.

The completeness and size of our property database permitted a detailed assessment of actor-specific deforestation responsibility in four of the core municipalities of the Transamazon Highway. The significantly better performance of Medicilândia against the other municipalities could be interpreted to produce a bias in our assessment. However Medicilândia contributed with just 20.3% of the total smallholder properties and 21.4% of the total properties to our analysis. In fact if we would have excluded Medicilândia from this study, the responsibility of smallholders for deforestation would be 20% of the total, smaller than the 23% figure obtained in this study.

To assure a thorough analysis and double-check our findings we performed analysis at the municipal level (using municipalities as proxies for actor-specific landscapes) and at the property level by aggregating properties according to actor-specific property size thresholds. This is a very delicate issue since those thresholds are as diverse as the large variability of productive conditions and regional realities in the Amazon, and therefore cannot be directly extrapolated to other areas. However the suitability of the chosen 100 ha threshold for the definition of smallholder properties in our study area was confirmed by the median property size of 99.1 ha ($n = 1776$) for all properties in Medicilândia, the municipality characterized by smallholderś dominance.

The use of landscape metrics to assess forest condition dynamics in the four municipalities confirmed the tendency described above. Although the specific implications of the calculated landscape metrics for biological conservation are not the focus of this study, our findings indicated that landscape metrics provide an effective way to assess explicit patterns of deforestation that have potential implications for the provision of environmental goods and services, especially if analyzed in a comparative fashion.

As shown in this study, actor-specific deforestation studies can benefit from the use of large databases of updated land-tenure information, integrated with the powerful remote-sensing and GIS tools that are currently available. Property grids are basic for monitoring actor-specific deforestation in an incontrovertible manner. Thus, the development of digital property databases should be prioritized as an indispensable tool for better governance and deforestation monitoring. A multi-temporal methodological approach that accounts for long-term dynamics is also key, as shown by the fact that in Medicilândia deforestation rates significantly changed over time.

5.1. Responsibility for deforestation along the Transamazon Highway

Our findings indicate that although the Transamazon Highway colonization project was preferentially planned to install colonists carrying out family agriculture in the vicinity of the main road, a process of land accumulation has changed the land tenure situation and spread out colonization much farther from the road. Forty years after the directed colonization of the region started, only approximately 23% of the land remained in the hands of smallholders, while the rest was mostly devoted to cattle mono-cultivation on large properties. In 2007, three-quarters of the land belonged to properties over 100 ha and more than half to properties over 200 ha, although the later accounted for just 12% of the total number of properties. Thus, inequality in land distribution has increased almost fourfold since initial colonization, and the ongoing boom of cattle ranching (Cattaneo, 2008) suggests that this tendency may continue. This has resulted in an increasing deforestation, with smallholders being responsible for approximately one-fourth of the total. These figures are consistent with those of Fearnside (1993) for the whole Brazilian Amazon, and Michalski et al. (2010) for frontier areas in the state of Mato Grosso. Moreover, the analysis indicated that the responsibility of largeholders for total deforestation is increasing. This might be a general trend in other old Agrarian Reform settlements, given the expansion of cattle ranching and recent case studies confirming that generally where largeholders prevail, annual deforestation rates are higher than in areas where diversified family agriculture predominates (Pacheco, 2009a).

The results at the municipal level confirmed this observation. The smallholder dominated municipality of Medicilândia was found to be the least deforested municipality in absolute terms and *per capita*, performing better than the other municipalities in all calculated landscape metrics. It maintained a larger area of functional forest, and its landscape was composed of a mosaic of interspersed land uses in which forest still constitutes the landscape matrix. In contrast, the municipalities characterized by a predominance of large-scale ranching presented more homogeneous landscapes associated with an abundance of large cleared areas, showing much more intense forest fragmentation dynamics and potentially providing fewer environmental goods and services.

5.2. Smallholder potential for landscape stabilization

Although the results of this study cast the blame on medium and large landholders for most of the observed deforestation, the smallholders in the study areas also heavily transformed their landscapes. This was demonstrated by the fact that Medicilândia was the most deforested municipality in absolute terms until 1991. However, it was exactly in this municipality where, in the last observation period from 1999 to 2007, deforestation nearly stopped, declining to a rate of only 3 km^2/year. In contrast, the municipalities with a predominance of larger landholders presented annual deforestation rates of approximately 100 km^2/year, thus remaining at least as high as during earlier frontier stages.

Only in Medicilândia the total area of large contiguous cleared areas for farming decreased since 1987, while in the cattle ranching-dominated municipalities it increased between 2.2- and 3.7-fold. Obviously, the dominance of smallholders may have, at least in the long term, a positive effect on the deforestation dynamics at landscape level. However, largeholders in Medicilândia presented similar deforestation rates per unit area owned as largeholders in other municipalities, while smallholders in other municipalities did not achieve a freezing of deforestation rates on their properties. The first finding suggests that large cattle monocultivations may require high annual deforestation rates in all our study area, regardless of contextual factors, such as fertility or good access to markets. This supports the idea that the continuous expansion of pastures may be inherent to extensive cattle ranching systems (Muchagata and Brown, 2003), at least as practiced in the Transamazon Highway. However, the second finding suggests that among the smallholders in the studied municipalities only those situated in Medicilândia have enjoyed contextual factors and favorable conditions supporting their success and predominance. One important factor for this could be that INCRA in this municipality did not grant large properties of more than 100 ha during initial colonization, thereby hampering the creation of large properties. Additionally the better soil fertility in Medicilândia could have contributed strongly to the success of family farming. Hence the potential of smallholders for landscape stabilization has been just observed in Medicilândia. In the other municipalities it can merely be concluded that smallholders are less responsible than largeholders for total accumulated deforestation.

A closer look at the dynamics that have occurred during the last decade confirmed that the halting of deforestation in Medicilândia was strongly related to those smallholders situated close to the main road. There, many areas that were cleared decades ago, mostly to satisfy government requirements to demonstrate productive use of the land for land-tenure acquisition, gradually recovered to secondary forests or were converted into agroforestry systems and tree plantations (Hoch et al., 2009). One of the factors contributing to this recovery process was that smallholders often abandoned the frequently enforced technological packages that required large tracts of cleared land, especially related to industrial rice cultivation, cattle ranching and sugar cane (Stewart, 1994). Probably the clearest example is the Abraham Lincoln sugar cane factory, which in the year 1974 was installed by the government at a cost of 6 million US$ (Stewart, 1994). To ensure supply, 270 surrounding colonists were forced to clear most of their 100 ha properties for producing sugar cane in fertile *terra roxa* soils. Only after the failure of the factory, the colonists were able to reorient their production, mostly towards cocoa (IBGE, 2006). Today, in several parts of the municipality, the landscape of the original colonization stretches is shaped by a complex mosaic of cocoa plantations grown under the shadow of trees, other agroforestry systems, pastures, tree plantations, secondary forests, and mature forest remnants. Remarkably, the shift in productive strategies obeyed productive and market logics, linked to demand for cocoa, banana and other agricultural products, despite strong governmental incentives for cattle-ranching (Fearnside, 2005). Nevertheless, cattle ranching is an important activity for smallholders in the Transamazon Highway (Walker et al., 2000; Pacheco, 2009b), in particular in Medicilândia (Table 2). Our results, however, suggest that cattle ranching as a complementary component of the diversified livelihood strategy of the smallholders in Medicilândia may be compatible with landscape stabilization.

5.3. Land use efficiency

In view of the well-known social and environmental hazards of large-scale cattle ranching in the Amazon (Faminow, 1998; Sauer, 2005), it is worth noting that according to our data, just 42% of the colonized land by 2007 could have supported the same number of colonists if they were smallholders. Therefore, a considerable amount of land has been deforested to sustain a reduced number of medium and largeholder families. For example, as shown in Fig. 5, deforestation in our study area would have increased to 51% if all properties would have been small (100 ha), compared to only 21% deforestation in the case of a standard property size of 15,000 ha. In the first case, however, the area would have provided livelihoods for 14,760 families, while in the second case, only 99 families and some employees would have benefited. This perspective has often been disregarded in previous studies focusing on the simple fact that smallholders deforest a comparatively larger percentage of their properties (Michalski et al., 2010), but neglecting a *per capita* analysis of deforestation. In particular, most studies of deforestation in land reform settlements do not sufficiently contrast the observed deforestation impacts with the important role of settlements in providing socio-economic opportunities for poor families (Brandão and Souza, 2006).

In accordance with Fearnside (1993) and Michalski et al. (2010), our findings also indicate that the percentage of property deforestation decreased with property size. This, however, does not necessarily imply less responsibility of the largeholders for the region's deforestation, because the lower relative deforestation of largeholders resulted in larger absolute deforested areas than would be associated with smaller properties. In particular our findings show that the participation of a given property in total deforestation increased exponentially with its size. Remarkably, the smallholders presented statistically similar level of respect of the legal obligation to preserve at least 50% of the forest on a property as largeholders in spite of their bigger spatial constraints.

In view of the large increase of the Gini coefficient of land distribution in our study region, the higher deforestation rates in largeholder dominated areas and the growing deforestation responsibility of largeholders, we argue that the continuous land accumulation by largeholders may explain, at least partly, their lower deforestation per area unit. Largeholders would show a certain tendency to disregard land use efficiency within a property and favor instead the expansion to other areas, accepting the periodical degradation of pastures as an inherent production factor. Smallholders on the contrary would have adapted better in the long term to the conditions of the study area and the available space. Nevertheless the links between property size and deforestation are in practice mediated by an array of factors affecting land-use decision making that are out of the scope of this paper, including the adoption of production systems (Perz, 2003), household demographics (Walker et al., 2002), access to capital (Walker et al., 2002), soil quality and market access (Chomitz and Thomas, 2003).

6. Conclusions

Largeholders and smallholders appear to be antagonists within the study area, as demonstrated by the dramatic change in land ownership relative to the initial domination of smallholders that resulted from the original INCRA colonization policies. This study not only demonstrates that large-scale cattle ranching is the main cause of deforestation in the Transamazon Highway region, but also that smallholders have the capacity to improve their land-use efficiency and decrease deforestation rates while creating a stable landscape composed by a mosaic of different land use elements embedded in a forest matrix. This process, however, takes time and requires specific conditions. In the municipality of Medicilândia, for example, smallholders may have benefited from the availability of good soil fertility near the main road in combination with a favorable institutional context for the development of cocoa production and other permanent cultivations. However, the fact that smallholders outside of Medicilândia did not achieve the same level of success calls for further multi-disciplinary research to understand the specific drivers and necessary conditions that cooperate with smallholder success and landscape stabilization. In particular, it is necessary to determine to what extent the successful model of diversified family agriculture in Medicilândia can be applied to other parts of the Amazon.

This, however, does not imply that substituting largeholders for smallholders in the Amazon would prevent deforestation *per se* and immediately, since that is dependant on their relative numbers and the specific local productive conditions, among many other key explanatory variables of deforestation. Obviously actor contribution to deforestation depends on who is the dominant actor that holds the land in a specific study area, but our findings provide with an example of the potential of smallholders for the stabilization of a cultivated forested landscape. A similar dynamic is largely unknown in largeholder dominated areas in the Brazilian Amazon, including neighboring areas of the Transamazon Highway with similarly good soil fertility conditions and general characteristics. Hence our findings go beyond the mere assessment of actor specific responsibility for deforestation in the Transamazon Highway context, and have wider implications for policy decision-making related to actor-specific deforestation in the Brazilian Amazon. In particular our findings suggest that policy-makers should acknowledge that although smallholders do deforest considerably, especially if settled in unfavorable areas, this is not incompatible in the long-term with a better deforestation performance than largeholders and a tendency to the creation and consolidation of cultivated forested landscapes. The better performance of Medicilândia in all applied landscape metrics with well-established relationships with the provision of important environmental goods and services suggests that those landscapes are more sustainable.

Given the rapid growth of cattle ranching in the Brazilian Amazon, particularly along the Transamazon Highway (IBGE, 2009), the alternative to family agriculture mosaics in our study area is most likely large farming patches created by large-scale ranchers. Under this premise, smallholders could be considered as key actors in preserving the Amazon (Campos and Nepstad, 2006), which obviously do not halt deforestation but significantly decrease its rates. This requires an understanding of forest conservation as "limited use" of the forested landscape, and of family agriculture as a tool for "productive conservation" (Perz, 2004). In this sense, pro-smallholder policies, at least in areas hosting adequate local conditions, could cooperate in deforestation alleviation with the already well-known conservation effects of the creation of reserves (Nepstad et al., 2006), generating important synergies for example through the creation of outer buffer areas. It deems necessary that policy-makers more systematically explore possibilities for supporting smallholders in the Amazon while reducing current productive and financial support to large-scale cattle ranching. A more effective land use planning and zoning would increase the chances of smallholders to settle in suitable areas, cooperating with their consolidation. Since the struggle between smallholders and largeholders has historically focused on land distribution and legal tenure, pro-smallholder efforts should probably be directed toward Agrarian Reform.

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